CHEMICALS IN WAR

A Treatise on Chemical Warfare

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BY

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ABOUT THIS BOOK

This book is complete except for irrelevant chapters such as: Relation of Chemical Industry to Chemical Warfare, International Situation, Chemical Technique and Tactics of Cavalry, Military Organization for Chemical Combat, Chemical Techniques and Tactics of Air Corps, etc.

Also left out was the extensive bibliography and hundreds of footnotes referring to books long out of print and generally unobtainable. For the most part, their subject matter concerned the historical record of the use of toxic substances in World War One and would have been of no use nor of any interest to one contemplating the making and use of chemical warfare substances in our time.

ABOUT TABLE IV.—PROPERTIES OF CHEMICAL AGENTS

The original chart was a large foldout of 14 by 28 inches. This was impractical to reproduce in the present format. However, the 25 substances and their characteristics have have been reproduced on the following six pages. For ease in following the chart, the substances have been numbered. To follow the chart, simply pick the substance of interest and follow its number across the chart, page by page.

PREFACE

The three outstanding developments of the World War were the military airplane, the combat tank, and chemical warfare. Each of these new instruments of war made its appearance on the battlefield at about the same time, each exerted an important influence in shaping the character of modern combat, and each is destined to play an even greater role in future warfare.

Since the World War, all nations have actively pushed the development of these new arms and much has been written concerning the first two—military aviation and mechanization—both in this country and abroad. But, for reasons not altogether clear, the literature of chemical warfare has not kept pace with its development since the war, although much has been done during the past few years in the principal countries of Europe to supply this deficiency. The dearth of publications on chemical warfare in this country is truly remarkable, considering the position of the United States among the industrial nations of the world, and particularly in view of the phenomenal growth of its chemical industry during the past fifteen years.

With the exception of one book by General Fries and Dr. West, which appeared in 1921 and was largely a narrative account of the Chemical Warfare Service in the World War, and one or two books concerning certain phases of gas warfare, no authoritative texts on chemical warfare have appeared in this country, despite the European literary activity in this field in the past few years.

There is perhaps no military subject that is so little understood and so much misrepresented as chemical warfare. During the late war it suffered much vilification and abuse which was not only wholly without

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Table IV. Properties of Chemical Agents

(See also page 174)

Agent, common name	Chemical name	CWS. symbol	Physiological classification	Tactical classification	Persistency (summer)	Persistency (winter)	Lowest irritant concentration, mg. per liter or oz. per 1,000 cu. ft., 10 min. exposure
Bromacetone..... (1)	Bromacetone (CH_3COCH_2Br)	BA	Lacrimator	Harrassing agent	1 to 2 hr. in open; 3 hr. in woods	2 days in open; 7 days in woods	0.0015
Brombenzyl cyanide (French: Camite) (2)	Brombenzyl cyanide ($C_6H_5CHBrCN$)	CA	Lacrimator	Harrassing agent	3 days in open; 7 days in woods	Several weeks	0.00015
Chloracetophenone..... (3)	Phenyl chlormethyl ketone ($C_6H_5COCH_2Cl$)	CN	Lacrimator	Harrassing agent	Solid for days; burning mixture, 10 min.	Several weeks in solid; burning mixture 10 min.	0.0003
Chlorine..... (4)	Chlorine (Cl_2)	Cl	Lung injurant	Casualty agent	5 min. in open; 20 min. in woods	10 min. in open; 1 hr. in woods	0.029
Phosgene..... (5)	Carbonyl chloride ($COCl_2$)	CG	Lung injurant	Casualty agent	10 min. in open; 3 min. in woods	20 min. in open; 2 hr. in woods	0.005
Diphosgene..... (German: Perstoff) (French: Surpolite) (6)	Trichlormethylchloroformate (diphosgene) ($ClCOOCCl_3$)	German Green Cross	Lung injurant	Casualty agent	15 min. in open; 60 min. in woods	30 min. in open; 3 hr. in woods	0.005
Chlorpicrin..... (vomiting gas) (7)	Trichlornitromethane (Cl_3CNO_2)	PS	Lung injurant and lacrimator	Casualty agent and harrassing agent	1 hr. in open; 4 hr. in woods	12 hr. in open; week in woods	0.009
Ethyldichlorarsine..... (German: Dick) (8)	Ethyldichlorarsine ($C_2H_5AsCl_2$)	ED	Lung injurant, sternutator, and vesicant	Casualty agent and harrassing agent	1 to 2 hr. in open; 2 to 6 hr. in woods	2 to 4 hr. in open; 12 hr. in woods	0.001
Hydrocyanic acid..... (9)	Hydrocyanic acid (HCN)	French 4	Systemic toxic	Casualty agent	5 min. in open; 10 min. in woods	10 min. in open; 1 hr. in woods	0.020
Cyanogen chloride..... (10)	Cyanogen chloride (CNCl)	French 4B	Systemic toxic	Casualty agent	10 min. in open; 20 min. in woods	20 min. in open; 2 hr. in woods	0.0025
Mustard..... (11)	$\beta\beta'$ Dichlorethyl sulfide $(ClCH_2CH_2)_2S$	HS	Vesicant	Casualty agent	24 hr. in open; 1 week in woods	Several weeks both in open and in woods	0.001
Lewisite..... (12)	β Chlorvinyldichlorarsine ($ClCH{:}CHAsCl_2$)	M-1	Vesicant	Casualty agent	24 hr. in open; 1 week in woods	1 week	0.0008
Methyldichlorarsine..... (German: Methyldick) (13)	(CH_3AsCl_2)	MD	Vesicant and lung irritant	Casualty agent	1 hr.	2 to 3 hr.	0.002
Diphenylchlorarsine..... (German: Clark I) (14)	Diphenylchlorarsine ($(C_6H_5)_2AsCl$	DA	Respiratory irritant (sternutator)	Harrassing agent	5 min. by H.E. detonation; 10 min. by candle dissemination	Same as summer	0.0005
Diphenylcyanarsine. (German: Clark II) 15	Diphenylcyanarsine ($(C_6H_5)_2AsCN$)	CDA	Respiratory irritant (sternutator)	Harrassing agent	Same as DA	Same as DA	0.0001
Adamsite..... (16)	Diphenylaminechlorarsine $(C_6H_4)_2NHAsCl$	DM	Respiratory irritant (sternutator)	Harrassing agent	10 min. in open from candles	10 min. in open from candles	0.00038
Crude oil..... (17)	Mixture of paraffin hydrocarbons	CO	None	Screening agent	While source is operating plus 5 min.	Same as summer	None
White phosphorus..... (18)	White phosphorus (P_4), yellow phosphorus	WP	None	Screening agent and incendiary agent	Depends upon size of burning particle; usually 10 min. or less in open	Same as summer	Smoke irritation negligible

Intolerable concentration, mg. per liter or oz. per 1,000 cu. ft., 10 min. exposure	Lethal concentration, mg. per liter or oz. per 1,000 cu. ft., 10 min. exposure	Melting point	Boiling point	Volatility, 20°C. (68°F.)	Vapor pressure, 20°C. (68°F.)	Vapor density compared to air	Density of solid, 20°C. (68°F.)	Solvents for
0.010 (1)	3.20	−54°C. (−65°F.)	135°C. (275°F.)	75 oz. 1,000 cu. ft. air	9 mm. Hg	4.7	1.60	Fats and organic solvents
10 min. exposure, 0.0008 (2)	30 min. exposure, 0.9; 10 min. exposure, 3.5	25°C. (77°F.)	225°C. (437°F.)	0.13 oz. 1,000 cu. ft. air	0.0112 mm. Hg	6.6	1.47	Chlorbenzene, chloroform, PS, CG
10 min. exposure, 0.0045 (3)	30 min. exposure, 0.34; 10 min. exposure, 0.85	59°C. (138°F.)	247°C. (476°F.)	0.106 oz. 1,000 cu. ft. air	0.013 mm. Hg	5.2	1.30	Chloroform, PS, ethylenedichloride, monochloracetone
10 min. exposure, 0.10 (4)	30 min. exposure, 2.53; 10 min. exposure, 5.60	−102°C. −(152.5°F.)	−34.6°C. (−28.5°F.)	19,369 oz. 1,000 cu. ft. air*	4,993 mm. Hg	2.5	1.46	CG, PS, CCl_4
10 min. exposure, 0.020 (5)	30 min. exposure, 0.36; 10 min. exposure, 0.50	−118°C. (−190°F.)	8.2°C. (46.7°F.)	6,370 oz. 1,000 cu. ft. air†	1,180 mm. Hg	3.5	1.38	Cl and PS
10 min. exposure, 0.40 (6)	30 min. exposure, 0.36; 10 min. exposure, 0.50 (U.S.); 0.05 (Germany)	−57°C.	127°C. (260.6°F.)	120 oz. 1,000 cu. ft. air	10.3 mm. Hg	6.9	1.65	CG, PS, DA
10 min. exposure, 0.050 (7)	30 min. exposure, 0.80; 10 min. exposure, 2.00	−69.2°C. (−92.4°F.)	112°C. (231.5°F.)	165 oz. 1,000 cu. ft. air	18.3 mm. Hg	5.6	1.66	Chloroform, CG, chlorine, CS_2, C_6H_6 C_2H_5OH
10 min. exposure, 0.01 (causes sneezing) (8)	30 min. exposure, 0.10; 10 min. exposure, 0.50	−30°C. (−22°F.)	156°C. (312°F.)	100 oz. 1,000 cu. ft. air	5.0 mm. Hg	6.5	1.70	Ethyl chloride
10 min. exposure, 0.030 (9)	30 min. exposure, 0.150; 10 min. exposure, 0.200	−15°C. (5°F.)	26°C. (79°F.)	873 oz. 1,000 cu. ft. air	603 mm. Hg	0.93	0.75	$ASCl_3$, $SbCO_3$
10 min. exposure, 0.005 (10)	30 min. exposure, 0,120; 10 min. exposure, 0.40	−6°C. (21°F.)	15°C. (59°F.)	3,300 oz. 1,000 cu. ft. air	1,000 mm. Hg	1.98	1.22 at 0°C.	Organic solvents
Eye-casualty concentration—1 hr. exposure, 0.001 (11)	30 min. exposure, 0.07; 10 min. exposure, 0.15	14°C. (57°F.)	217°C. (422.6°F.)	0.625 oz. 1,000 cu. ft. air	0.065 mm. Hg	5.5	1.27	Oils, PS, alcohol, carbon tetrachloride
Minimum irritating concentration, 0.0008 (12)	30 min. exposure, 0.048; 10 min. exposure, 0.12	−18.2°C. (0°F.)	190°C. (374°F.)	4.5 oz. 1,000 cu. ft. air	0.395 mm. Hg	7.1	1.88	HS-PS, oils, alcohol
1 min. exposure, 0.025 (13)	30 min. exposure, 0.125; 10 min. exposure, 0.75	54.8°C. (−66.6°F.)	132°C. (269.6°F.)	75 oz. 1,000 cu. ft. air	8.5 mm. Hg		1.85	Organic solvents
10 min. exposure, 0.0012 (14)	30 min. exposure, 0.60; 10 min. exposure, 1.50	45°C. (113°F.)	383°C. (720°F.)	0.00068 oz. 1,000 cu. ft. air	0.0005 mm. Hg	Practically no vapor; all solid particles	1.4	Acetone, chloroform, chlorpicrin
10 min. exposure, 0.00025 (15)	10 min. exposure, 1.00	31.5°C. (91°F.)	350°C. (662°F.)	0.0015	0.0001 mm. Hg	8.8	1.45	Organic solvents, chloroform
3 min. exposure, 0.005 (16)	30 min. exposure, 0.65; 10 min. exposure, 3.00	195°C. (387°F.)	410°C. (770°F.) Decomposes below boiling point	Negligible	Negligible	No vapor; disseminated as solid	1.65	Furfural acetone
None (17)	None	−20°C. (−3°F.)	200°C. (392°F.)	Negligible	Negligible		0.8	Benzene, gasoline
Smoke irritation negligible (18)	Smoke harmless	44°C. (111°F.)	287°C. (549°F.)	0.1728 oz. 1,000 cu. ft. air	0.0253 mm. Hg	Vapor negligible; disseminated as a solid	1.83	Carbon disulfide, ether, benzene

Action on metals	Stability on storage	Action with water	Hydrolysis product	Odor in air	Odor detectable at mg. per liter or oz. per 1,000 cu. ft.	Physiological action
Very corrosive to iron (1)	Unstable in heat or light	None	None	Pungent and stifling	0.0005	Vapor, severe lacrimation; liquid, produces blisters; often toxic
Very corrosive to iron; lead or enamel lined shells required (2)	Slowly decomposes	Slowly hydrolyses	HBr and various compounds	Like sour fruit	Irritates before odor can be detected	Severe lacrimation and nose irritation
Tarnishes steel slightly (3)	Stable	None	Not readily hydrolyzed	In low concentrations like apple blossoms	0.0002	Eye and skin irritation
None if dry; vigorous corrosion if wet (4)	Stable in iron cylinders, if dry	A little dissolves forming HCl, HOCl, and ClO_2	HCl; HOCl; ClO_2	Pungent	0.0100	Burns upper respiratory tracts
None if dry; vigorous corrosion if wet (5)	Stable in dry steel containers	Hydrolyzes rapidly	HCl; CO_2	Like ensilage; fresh-cut hay	0.0044	Burns lower lung surfaces, causing edema
None if dry, corrosion if wet (6)	Stable in dry steel containers	Hydrolyzes slowly	$ClCO_2$; CO_2; HCl	Disagreeable, suffocating	0.0088	Burns lower lung surfaces, causing edema
Produces slight tarnish only (7)	Stable for long periods in steel containers	Very slightly soluble	Hydrolyzes with difficulty	Sweetish, like flypaper	0.0073	Lacrimates; irritates nose and throat; produces nausea and lung irritation in order as concentration increases
None (8)	Stable	Hydrolyzes slowly	Ethylarseneous oxide and HCl (hydrolysis product is poisonous if swallowed)	Biting, irritant	0.0010	Vesicant, ⅛ as powerful as HS; powerful sternutator; causes paralysis of fingers
None except on copper, if dry; corrodes all if wet (9)	Stable when mixed with strong acid and dissolved in solvents	Miscible, slowly decomposes	Ammonium cyanide	Like bitter almonds	0.0010	Paralysis of central nervous system
None if dry; corrodes metals if moist (10)	Unstable; stability increased when mixed with $AsCl_3$	Slightly soluble	HCl; cyanuric acid		0.0025	Irritates eyes and lungs
None (11)	Stable in steel containers	Slowly hydrolyzes	HCl and $(HOCH_2CH_2)_2S$; not toxic	Like garlic or horse-radish	0.0013	Dissolves in skin or lung tissue, then produces burns
None (12)	Stable in steel containers	Hydrolyzes readily	HCl; MI oxide; (ClCH)(CHAsO); very toxic	Like geraniums, then biting	0.014	Dissolves in skin, then burns and liberates MI oxide which poisons body
None (13)	Very stable	Slightly soluble	None		0.0008	Asthma, dyspnea; lung injurant, skin vesicant
Vigorous corrosion on steel (14)	Slowly decomposes	Slowly hydrolyses	HCl; Da Oxide (Da oxide is poisonous if swallowed)	Like shoe polish	0.0003	Sneezing; vomiting; headache
Vigorous corrosion on iron and steel (15)	Very stable	None	None	Like garlic and bitter almonds	0.0003	Sneezing; vomiting; headache
Very slight (16)	Stable in steel containers	Insoluble, hydrolyzed with difficulty	HCl; DM oxide $[(C_6H_4)_2NHAs]_2O$; DM oxide is very toxic if swallowed	No pronounced odor	Almost no odor to average man, up to 0.0025	Headache, nausea, violent sneezing, followed by temporary physical debility
None (17)	Very stable	None	None	Slightly suffocating	None	None
None (18)	Stable out of contact with oxygen	None; stored under water in concrete tanks	Smoke in air; phosphoric acid (H_3PO_4) dissolved in water	Like matches		Solid particle burns flesh; vapors very poisonous, cause bone decay; smoke relatively harmless

Protection required	Method of neutralizing	First aid	Munitions suitable for use	American marking on munitions
Gas mask; absorbent only (1)	Alkali	Wash eyes with boric acid; wash skin with warm sodium carbonate solution	Projectiles and grenades	2 green bands BA gas
Gas masks; absorbents in canister only (2)	Alcoholic sodium hydroxide spray	Wash eyes with boric acid solution	75-mm. artillery shell or airplane spray	2 green bands CA gas
Gask masks; both absorbent and effective filter (3)	Strong hot sodium carbonate solution	Wash eyes with boric acid; wash skin with warm sodium carbonate solution	Candles and grenades as burning mixtures; grenades; artillery shell; 4.2-in. CM; 4-in. CM; airplane spray and bombs as solution	Burning type munitions, 1 green band, CN gas
Gask masks; absorbents in canister only (4)	Alkali, solution or solid	Keep patient quiet and warm and treat for bronchial pneumonia	Mixed with CG and PS in cylinders and LP shells	1 green band CG gas
Gas masks; absorbents in canister only (5)	Steam hydrolyzes; alkalies and amines react with CG	Keep patient quiet; administer heart stimulants; give oxygen in severe cases; treat like pleurisy	LP shells; cylinders; 4.2-in. CM; 4-in. CM; 155-mm. howitzer shell	1 green band CG gas
Gas masks; absorbents in canister only (6)	Steam hydrolyzes alkalies and amines react with CG	Keep patient quiet; administer heart stimulants; give oxygen in severe cases; treat like pleurisy	LP shells; cylinders; 4.2-in. CM; 4-in. CM; 155-mm. howitzer shell	
Gas masks with high-grade absorbents in canisters (7)	Sodium sulfite solution	Wash eyes with boric acid; keep patient warm; protect throat from infection	Mixed with CN in 75-mm. shell; air bombs; 4-in. CM and 4.2-in. CM shell; pure in spray; w/GG in LP and 4.2-in. shell	2 green bands PS gas
Gas masks and protective clothing (8)	Sodium hydroxide solution	Wash skin with warm sodium carbonate solution	Artillery shell; 4.2-in. CM shell; airplane spray	2 green bands ED gas
Gas mask; absorbents only (9)	None necessary	Fresh air; cold water in face; artificial respiration	Artillery shell	
Gas mask; absorbents only (10)	None necessary	Fresh air; cold water in face; artificial respiration	Artillery shell	
Gas masks and protective clothing (11)	Bleaching powder, 3 % sodium sulfide (Na_2S) in water; steam; gaseous chlorine; or bury under moist earth	Wash affected parts with kerosene or gasoline, then with strong soap and hot water; rub dry; rinse with hot clean water; agent must be removed within 3 min.	Airplane spray; airplane bombs; 75-mm. guns; 155-mm. howitzer; 155-mm. gun; 4.2-in. CM	2 green bands HS gas
Gas masks and best of protective clothing (12)	Alcoholic sodium hydroxide spray	Wash with oils, hot water, and soap; dry; first aid must be applied at once	Airplane spray; airplane bombs; 75-mm. shell; 155-mm. howitzer shell; 4.2-in. CM	2 green bands M-1 gas
Gas masks and best of protective clothing (13)	Sodium hydroxide solution	Wash with soap and water, then with sodium hydroxide (5 %); wash eyes with boric acid	Artillery and mortar shell	2 green bands MD gas
Best type of filter in gas-mask canister (14)	Caustic gaseous chlorine	Chlorine in low concentrations	Burning-type munitions	1 green band DA gas
Gas masks, best type of filter (15)	Caustic gaseous chlorine	Chlorine in low concentrations	Artillery shell	
Best type of filter in gas-mask canister (16)	Gaseous chlorine bleach liquor	Breathe low concentrations of chlorine from bleaching-powder bottle	Candle; destroyer smoke attack; burning-type air bombs	1 green band DM gas
None (17)	None necessary	None necessary	Incomplete combustion by naval vessels	1 yellow band CO smoke
None needed against smoke; fireproof suits against burning particles (18)	None needed; copper sulfate solution stops burning of particles, as does water	Apply copper sulfate solution; pull out solids; treat burn with picric acid; keep burning part under water until medical aid arrives if no $CuSO_4$ is available	Grenades; artillery shells; 4-in. CM; 4.2-CM; airplane bombs in.	1 yellow band WP smoke

Table IV. Properties of Chemical Agents

Agent, common name	Chemical name	CWS. symbol	Physiological classification	Tactical classification	Persistency (summer)	Persistency (winter)	Lowest irritant concentration, mg. per liter or oz. per 1,000 cu. ft., 10 min. exposure
Sulfur trioxide (19)	Sulfur trioxide $(SO)_3$		None	Screening agent	While container is operating	Same as summer	Smoke irritation negligible
Oleum (60 per cent) (20)	$(SO_3XH_2SO_4)$		None	Screening agent	While container is operating	Same as summer	Smoke irritation negligible
HC Mixture (21)	Hexachlorethane (C_2Cl_6)†, zinc and zinc oxide (ZNO)	HC	None	Screening agent	Only while burning	Same as summer	Smoke irritation negligible
Titanium tetrachloride (22)	Titanium tetrachloride ($TiCl_4$)	FM	None	Screening agent	10 min. in open	Same as summer	Smoke irritation negligible
Sulfur trioxide solution (23)	Sulfur trioxide (SO_3), about 55 per cent; chlorsulfonic acid ($HClSO_3$), about 45 per cent by weight	FS	None	Screening agent	While container is operating	Same as summer	Smoke irritation negligible
Thermite (24)	Thermite ($Al+Fe_3O_4$)	Th	None	Incendiary agent	None	None	None
Solid oil (25)	Mixture of paraffin hydrocarbons	SO	None	Incendiary agent	None	None	None

* This volatility is at 4,993 mm. Hg. At 760 mm. Hg, the volatility of chlorine is 3,708 oz./1,000 cu. ft
† This volatility is at 1,180 mm. Hg. At 760 mm. Hg, the volatility of phosgene is 4,420 oz./1,000 cu ft.

Intolerable concentration, mg. per liter or oz. per 1,000 cu. ft., 10 min. exposure	Lethal concentration, mg. per liter or oz. per 1,000 cu. ft., 10 min. exposure	Melting point	Boiling point	Volatility, 20°C. (68°F.)	Vapor pressure, 20°C. (68°F.)	Vapor density compared to air	Density of solid, 20°C. (68°F.)	Solvents for
Smoke irritation negligible (19)	Smoke harmless	40°F. (104°F.)	45°C. (113°F.)	Negligible	242.27 at 25°C.		1.94	
Smoke irritation negligible (20)	Smoke harmless	5°C.	Decomposes	Negligible	Negligible		1.99	
Smoke irritation negligible (21)	Smoke harmless	Hexachlorethane 184°C. (363°F.)	185°C. (sublimes) (365°F.)	2.85 oz. 1,000 cu. ft. air	0.22 mm. Hg	Vapor negligible; disseminated as a solid	2.0	Alcohol, ether (for hexachlorethane only)
Smoke irritation negligible (22)	Smoke harmless	−23°C. (−9°F.)	136°C. (277°F.)	86.4 oz. 1,000 cu. ft. air	8.32 mm. Hg		1.7	Ethylene dichloride
Smoke irritation negligible (23)	Smoke harmless	Below −30°C. (−22°F.)		About 80°C. (176°F.)			1.91	Strong sulfuric acid
None (24)	None	1,500°C. (2,732°F.)	None	None	None	None	3.3	None
None (25)	None	30°C. (86°F.)	None	None	None	None	0.9	Organic solvents

Action on metals	Stability on storage	Action with water	Hydrolysis product	Odor in air	Odor detectable at mg. per liter or os. per 1,000 cu. ft.	Physiological action
Corrosive unless dry (19)	Stable if dry	Hydrolyzes	H_2SO_3 and H_2SO_4	Acrid suffocating smoke		Hacking cough
Corrosive unless dry (20)	Stable if dry	Hydrolyzes	H_2SO_3 and H_2SO_4	Acrid suffocating smoke		Like strong acid
None if dry (21)	Stable	C_2Cl_6 slowly hydrolyzes; mixture ignites	Smoke in air; ($ZnCl_2$) zinc chloride in water solution	Acrid suffocating smoke		None from solid; slightly suffocating action by heavy smoke
Vigorous corrosion by smoke; none by liquid on steel if dry (22)	Stable in steel containers when dry	Hydrolyzes	Smoke in air; $TiCl_4 \cdot 8H_2O$; then HCl and $Ti(OH)_4$	Acrid		Liquid burns like strong acid; vapors and smoke irritating to throat
Vigorous corrosion if wet; vigorous corrosion in presence of moisture (23)	Stable in steel containers	Reacts violently like strong sulfuric acid	Smoke in air; hydrochloric acid (HCl) and sulfuric acid (H_2SO_4) mixed in water solution as fog particles	Acid or acrid		Liquid burns like strong acid; smoke causes pricking sensation on skin
None (24)	Stable	None	None	None		Burns like molten iron
None (25)	Stable	None	None	None		Burns like oil

Protection required	Method of neutralizing	First aid	Munitions suitable for use	American marking on munitions
None (19)	Wash freely with cold water		Artillery and CM shell; airplane spray	
None (20)	Wash freely with cold water		Smoke grenades; airplane tanks	
None (21)	None needed	None needed	Burning-type munitions only; grenades; candles; smoke floats; special air bombs	1 yellow band HC smoke
None for ordinary smoke clouds; gas masks needed for heavy concentration only (22)	Alkali; solid or solution	Wash with sodium bicarbonate solution, then with warm water; treat burn with picric acid	Artillery shell; 4-in. CM; 4.2-in. CM; airplane spray; airplane bombs; special munitions	1 yellow band FM smoke
None for ordinary smoke; gas masks for high concentrations, only rubber gloves for handling liquid (23)	Any alkali, solid or solution	Like an acid burn	From cylinders under gas pressure; airplane spray tanks; explosive shell	1 yellow band FS smoke
Fireproof clothes (24)	None	Like ordinary burn	Drop bombs; artillery shell	1 purple band Th incendiary
Fireproof clothes (25)	None	Like hot-liquid burn	Drop bombs; artillery shell	1 purple band SO incendiary

foundation in fact, but which was deliberately disseminated as propaganda to influence the neutral nations of the world against Germany, just as in the Middle Ages the first use of firearms was similarly excoriated.

Chemical warfare has been the favorite topic of discussion at international conferences because it is a popular subject of condemnation, and one concerning which treaties and conventions can be made without the slightest probability of being lived up to, as was the case in the World War.

Finally, the subject of chemical warfare has been the happy hunting ground for sensational newspaper and magazine writers whose imaginations have furnished lurid pictures of whole populations being wiped out at a single blow with poison gas dropped from airplanes.

In view of the general public interest in this question and its importance to our national defense, it seemed to the author that it was high time for someone to produce an authoritative American text on chemical warfare, and so he reluctantly undertook this task as a patriotic duty.

The purposes of this book are threefold: (1) to trace the development of the art and science of chemical warfare from its beginning in the World War to the present time; (2) to present an American viewpoint on chemical warfare; and (3) to make available to the public an authentic text on a much misrepresented and misunderstood subject of great importance to our future national security.

General acknowledgment is made in the reference notes to the many sources to which the author is indebted for much of his material.

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Many of the illustrations are reproduced by permission of the War Department, and the diagrams of the German gas bombardments in 1918 are reproduced by the kind permission of the British Royal Artillery Institution.

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AUGUSTIN M. PRENTISS.

WASHINGTON, D. C.,
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PART II
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INTRODUCTION

From the dawn of antiquity to the present century men have fought their battles by physical blows, and it was not until the World War that the history of organized conflict recorded a deviation from this fundamental principle of battle.

The blows by which man subdued his opponent were delivered by hand until his ingenuity devised instruments for adding distance to the striking power of the human arm. But the weakness of primitive devices for projecting missiles put on hand-to-hand fighting a premium that persisted down through the Middle Ages. The invention of firearms at last enabled soldiers to fight their battles at a distance, for by superseding brawn with the propulsive power of gunpowder it became possible to penetrate all known forms of protection and to strike fatal blows from a distance. It then became an important aim of tactics to weaken an enemy by means of missiles hurled at a distance before closing with him to accomplish his final defeat.

The attention lavished upon various types of guns made these weapons so tremendously powerful that at last they came to defeat the very purpose they served. Thus, the fire power of modern weapons of impact—machine guns, supported by artillery of various calibers—has grown so great that, when properly located in defensive positions, they are capable of repulsing every assault against them. Soldiers cannot advance under the withering fires of machine guns and artillery barrages without prohibitive losses and any attempt to do so only results in futile slaughter. Modern armies are forced to seek protection in trenches so deep and strong as to defy even the colossal power of modern artillery, and tactical movement is thus eventually paralyzed.

This result was foreshadowed in our own Civil War, to be grimly demonstrated in the World War. In the latter conflict there were, at least on the Western Front, no flanks to be turned. Yet the absence of exposed flanks was here no more than proof that, given sufficient modern rifles and guns, and enough soldiers to man them, a battle front may be extended until it defies outflanking. Linear formations are then reinforced in depth so that substantial penetration becomes prohibitive and the task of subduing a belligerent must be accomplished by economic instead of military force.

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In order to counteract the power of modern impact weapons and the resulting deadlock of trench warfare, toxic gas finally was resorted to. It was hoped by this new means to restore movement in battle and thus again permit tactical maneuver and fire power to open the way to victory.

But gas, for reasons which we shall presently discuss, did not immediately fulfill these early expectations, although the ensuing struggle for technical protection led to an examination of practically every compound in the whole catalogue of chemistry that offered any promise of military utility and to the actual trial in battle of scores of chemical agents. The results, *in toto*, was *chemical warfare*, and the opening up of a new field for the implementation of military effort.

History records numerous earlier but abortive attempts to utilize the powers of chemistry for military ends. It is not within the scope of this book to examine in detail such occurrences preceding the World War. With the exception of Greek fire, none of them produced important results and none permanently challenged the supremacy of existing weapons. They are of interest to us here only as indicating man's eagerness to experiment with any means that promises to promote his fortunes in battle and his final dependence upon technical knowledge to produce such means.

The value of chemicals as war weapons had attracted the serious speculation of military minds as early as our Civil War, but no practical progress was made in this field because of the then undeveloped state of the chemical industry. Many chemical substances having powerful physiological effects had already been discovered and classified before the commencement of the World War; a number of these were well known and had been manufactured in quantity before the war. It was only natural then that these substances were utilized as chemical-warfare agents in the war and no new chemical was specially developed for war purposes. Yet there is a wide gulf between *laboratory research* and the colossal production needed to supply modern armies in the field. The use of chemicals as warfare agents was not practicable, even though the possibilities may have been recognized, until the chemical industry had attained sizeable proportions.

But during the decades preceding the World War the chemical industry, particularly in Europe, had been expanding apace. A remarkable feature of this new major industry was the tremendous development of dye production, which during the early years of the twentieth century largely centered in Germany. In 1913 the world production of dyes reached approximately 150,000 tons, of which Germany controlled three-quarters, producing at the same time something over 85 per cent of the intermediates entering into the finished dyes. When it is remembered that these intermediate products may also be used in compounding

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military chemical agents and that the dye factories provide both technical skill and manufacturing equipment needed for the production of these substances, the peculiar military significance of this industry becomes apparent.

The basic chemical industries, producing nitrogen compounds, chlorine, sulfuric and nitric acids, and the alkalies, had attained major proportions before the beginning of the war, especially in Germany. Thus chlorine, which was used on an enormous scale, not only as a war gas itself, but as the basis for the manufacture of nearly all other chemical agents, was being produced in Germany at the rate of tens of thousands of tons annually. The highly developed coal-tar industry, as well as facilities for production of arsenic, bromines, and phosphorus, stood ready to furnish important contributions to war effort.

The immense chemical factories along the Rhine were producing these potentials of chemical warfare on a large scale and, what was equally vital, possessed the technical talent capable of directing the conversion of their products into warfare agents. With the stage thus set, it needed no more than the urge of dire military necessity to insure the advent of chemical warfare.

Not only was the military crisis of the winter of 1914–1915 brought about by the collapse of the classical methods of attack so successful in former wars of movement, but (as far as Germany was concerned) the situation was even more critical because of the serious depletion of supplies of explosive ammunition. Germany entered the World War with plans for but a few months of intensive campaign, for which she believed that her accumulated stocks of ammunition would suffice. As these stocks rapidly dwindled with victory still distant, Germany was obliged quickly to mobilize her national industries behind her armies. That the great German chemical industry should have been immediately utilized to this end was inevitable; the wonder is rather that the first German gas attack was such a surprise to the Allies.

The introduction of chemicals as active agents of war was readily recognized as a portent that in the future, military weapons are to be forged in laboratories as well as in foundries. Thus, even in 1915, few students of military technique failed to discern the dawn of a new era

in the long history of warfare. The two decades that have elapsed since the first German gas attack at Ypres have not only confirmed this early appreciation but have added greatly to the comprehension of both soldier and scientist as to the role and power of chemicals in war.

Not only has the introduction of chemicals in war changed the character of modern combat, but it has also vastly accelerated the evolution of military weapons. Thus, more than a century passed after the British first brought cannon into the field at Crécy without witnessing

substantial improvement in the technique of supporting artillery; yet within a few years chemical warfare has advanced from an untried theory to a recognized principle of modern war.

This progress has been marked by two distinct phases. First there was the crucible of war—more than three years of fierce struggle that taxed the chemical resources of the most highly industrialized nations. Then followed the postwar period of evaluation, research, and assimilation. The latter phase has probably contributed no less than the former to the early maturity of this new arm of war.

Notwithstanding the remarkable results achieved with chemicals during the World War, the means and methods employed in that conflict appear as crude and feeble beginnings when viewed in the light of our present knowledge and our cooler conceptions of the future. As we draw away from the late war we apprehend more clearly that the potential power of chemicals was then only dimly foreshadowed. Today we realize that all nations are facing new and powerful instrumentalities involving as profound changes in the art and science of war as were brought about by the invention of gunpowder. In a word, armies have already advanced well into the era of chemical warfare.

CHAPTER I

BASIC PRINCIPLES

COMPARISON OF CHEMICAL AND EXPLOSIVE WEAPONS

An understanding of the true character of chemical warfare can best be approached by a consideration of the action of combat chemicals as compared to that of explosive weapons.

Certain important differences between the effects of chemical and of explosive munitions emphasize the peculiarity and novelty of chemical warfare and suggest some of its potentialities. These differences are particularly noticeable in the mechanism of the action of chemical agents and their effects in terms of time and space.

Chemical substances used in war for their direct physiological or chemical effects are called *chemical agents*. A chemical agent does not exert its effect by direct physical impact upon its target, like a rifle bullet or a shell fragment. On the contrary, chemicals may be liberated in place, depending on wind to move them to their targets; they may be transported to a point of release over or on the target by airplanes or wheeled vehicles; or they may be carried to that point in projectiles. In any case, the container is merely a conveyance for the chemical agent.

The effect of a chemical agent then is derived from the reactions that take place after the agent is freed from its container. Tactical and technical considerations indicate the point of release; natural forces then complete the processes of dispersion and ultimate effect. Herein lies a fundamental difference between chemicals and explosives.

Also, chemicals do not strike a physical target—they pervade the atmosphere over an area. The area may be wide when a volatile gas is dispersed, or it may be restricted to a few acres saturated with slowly evaporating liquids. Yet always the effect is as permeating as the active range of the component molecules.

In contrast to this wide distribution of effect characteristic of chemicals, let us analyze the action of high explosives. As the high-explosive shell detonates, its effect is derived from the concussion of the explosion and from the striking force of flying fragments. This action, however, does not extend beyond a relatively small area surrounding the point of burst. Even within this danger area, of two soldiers standing side by side, one may be killed and the other escape unharmed.

Such uncertain and uncontrollable results are impossible with gas. When gas is released everyone within its compass becomes *equally* exposed to its effect. The soldier may counter that effect with artificial

protection, but otherwise he cannot escape it even though he is some distance from the point of release, for gas saturates the entire atmosphere overlying the target area.

Again, in the matter of *time*, gas offers a striking contrast to weapons of impact. The effect of the rifle bullet is instantaneous; a second after the bullet strikes it is spent and harmless. But even the most fleeting gas clouds are effective for a matter of many minutes, while persistent chemicals may continue to contaminate an area for days.

Another unique characteristic of gas is its searching effect. A hastily dug fox hole affords individual shelter from machine-gun bullets. A copse of trees may well protect a whole company of infantry from artillery fire. But gas follows no narrow trajectory; it permeates the air and overcomes all incidental obstacles of terrain to stalk its quarry relentlessly. These distinctive features combine to enhance the power and utility of chemical agents, particularly in their action against personnel.

Before examining the basic principles underlying the science of chemical warfare, it is important to understand the meaning and usage of certain technical terms.

DEFINITIONS

We have said that chemical substances used in combat are designated as chemical agents. Of these agents, three distinct groups—*gases*, *smokes*, and *incendiaries*—constitute what is generally understood as the matériel of chemical warfare.

Gases are chemical agents which produce physiological effects. These agents are used in war to incapacitate military personnel. Physically they are often dispersed as liquids and not infrequently as particulate clouds; yet the term *gas* has attained in military parlance a generic meaning that embraces any chemical used for its direct effect upon the human body. A gas which produces death is called a *lethal* agent, while a gas which, under field conditions, does not cause death or serious casualties is an *irritant* agent.

A *smoke* agent, as its name implies, is one capable of obscuring vision in sufficient measure to afford concealment. It may incidentally burn or corrode, yet primarily it screens.

Incendiary agents start destructive fires, igniting even materials that ordinarily are slow to burn.

A *toxic* is any substance which, by its direct chemical action, either internally or externally, on the human or animal organism, is capable of destroying life or seriously impairing normal body functions.

Toxicity is the measure of the inherent poisonous effect of a chemical agent and is the product of its concentration times the period of exposure to its action.

Lacrimators cause intense, though temporary, irritation of the eyes; they are commonly known as *tear gas* (see Chap. VI).

Lung injurants are those gases that particularly attack and injure the bronchial tubes and the lungs. The "injurant" gases are quite distinct from "irritant" gases; the former are highly toxic and frequently lethal in action, whereas the latter are characteristically nonlethal and include generally lacrimators and sneeze gases (see Chap. VII).

Systemic toxics are substances which by systemic action exert a direct paralyzing effect upon the heart and nervous system. They are usually the most deadly of all gases (see Chap. VIII).

Vesicants are agents which exert a blistering (vesicant) effect upon the skin (see Chap. IX).

Irritant gases (sometimes called *sneeze* gases or *sternutators*) attack the nasal passages, causing nausea and headache of a few hours' duration. They are never lethal in concentrations encountered in the field (see Chap. X).

Symbols.—During the World War, code symbols or names were used to designate the various chemical agents employed, without revealing their chemical identity. The symbols were usually two or three letters, arbitrarily chosen, to designate the chemical agent, and the names were generally fanciful and were derived from some place or event incident to the first use of the agent. As most substances used as chemical agents were complex compounds with long chemical names, the short symbols and names proved very convenient in referring to the agent and came

into general use even where secrecy was not essential. In the course of a short time, the chemical identity of the agents used on both sides in the war became generally known and the code symbols and names lost their secrecy value. They are, however, still employed as a matter of convenience in preference to the chemical names of the compounds.

Table I shows a list of the principal chemical agents used in the war and their code symbols or names. For convenience, chemical agents will generally be designated throughout this text by their symbols, as indicated in Table 1.

Concentration refers to the quantity of chemical vapor present in a given volume of air. It is expressed in four ways, as follows: (1) as parts of gas per million parts of air; (2) as grams of gas per cubic meter of air; (3) as milligrams of gas per liter of air; or (4) as ounces of gas per thousand cubic feet of air.

Numerically, grams per cubic meter is the same as milligrams per liter, and is almost the same as ounces per thousand cubic feet; all these are

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TABLE I.—NOMENCLATURE OF CHEMICAL AGENTS

Chemical name	Chemical formula	English name	American CWS symbol	French name	German name
Gases					
Acrolein	CH_2CHCHO	—	—	Papite	—
Arsenic trichloride	$AsCl_3$	—	—	Marsite	—
Benzyl bromide	$C_6H_5CH_2Br$	—	—	Cyclite	T-Stoff
Benzyl iodide	$C_6H_5CH_2I$	—	—	Fraissite	—
Bromacetone	CH_3COCH_2Br	BA	BA	Martonite	B-Stoff
Brombenzyl cyanide	$C_6H_5CHBrCN$	—	CA	Camite	—
Bromine	Br_2	—	—	—	Brom
Brommethylethyl ketone	$CH_3COCHBrCH_3$	—	—	Homomartonite	Bn-Stoff
Carbonyl chloride	$COCl_2$	Phosgene	CG	Collongite	D-Stoff
Chloracetone	CH_3COCH_2Cl	—	—	Tonite	A-Stoff
Chloracetophenone	$C_6H_5COCH_2Cl$	—	CN	—	—
Chloracetophenone	$C_6H_5COCH_2Cl$	—	CNS	—	—
Chloroform	$CHCl_3$	—	—	—	—
Chlorpicrin	CCl_3NO_2	—	—	—	—
Chlorine	Cl_2	Chlorine	Cl	Bertholite	Chlor
Chlorpicrin	CCl_3NO_2	Vomiting gas	PS	Aquinite	Klop
Chlorvinyldichlorarsine	$CHClCHAsCl_2$	Lewisite	M-1	—	—
Cyanogen bromide	$CNBr$	CB	—	Campellit (Italian)	Ce (Austrian)
Cyanogen chloride	$CNCl$	—	—	Vitrite	—
Dianisidin	$(NH_2(OCH_3)C_6H_3)_2$	—	—	—	X
Dibromethyl sulfide	$(BrCH_2CH_2)_2S$	—	—	—	Bromlost
Dibrommethyl ether	$(CH_2Br)_2O$	—	—	—	X
Dichlorethyl sulfide	$(ClCH_2CH_2)_2S$	Mustard gas	HS	Yperite	Lost; also Yellow Cross
Dichlormethyl ether	$(CH_2Cl)_2O$	—	—	—	X
Dimethyl sulfate	$(CH_3)_2SO_4$	—	—	Rationite	D-Stoff
Diphenylaminechlorarsine	$(C_6H_5)_2NHAsCl$	Adamsite	DM	—	—
Diphenylchlorarsine	$(C_6H_5)_2AsCl$	—	DA	—	Clark I
Diphenylcyanarsine	$(C_6H_5)_2AsCN$	—	CDA	—	Clark II
Ethylbromacetate	$CH_2BrCOOC_2H_5$	—	—	X	—
Ethylcarbazol	$(C_6H_4)_2NC_2H_5$	—	—	—	Blue Cross-1
Ethyldibromarsine	$C_2H_5AsBr_2$	—	—	—	X
Ethyldichlorarsine	$C_2H_5AsCl_2$	—	ED	—	Dick. also Green Cross-3
Ethyliodoacetate	$CH_2ICOOC_2H_5$	SK	—	—	—
Ethylsulfuryl chloride	$ClSO_2OC_2H_5$	—	—	Sulvanite	—
Hydrocyanic acid	HCN	JL and VN	—	Forestite	—
Iodoacetone	CH_3COCH_2I	—	—	Bretonite	—
Methyldichlorarsine	CH_3AsCl_2	—	MD	—	Methyldick
Methylsulfuryl chloride	$ClSO_2OCH_3$	—	—	—	X
Monochlormethylchloroformate	$ClCOOCH_2Cl$	—	—	Palite	C-Stoff, K-Stoff
Perchlormethylmercaptan	$SCCl_4$	—	—	Carbontetrachlorsulfide	—
Phenylcarbylamine chloride	$C_6H_5CNCl_2$	—	—	—	Green Cross-1
Phenyldibromarsine	$C_6H_5AsBr_2$	—	—	—	X
Phenyldichlorarsine	$C_6H_5AsCl_2$	—	—	Sternite	Blue Cross-1
Thiophosgene	$CSCl_2$	Thiophosgene	—	Lacramite	—
Trichlormethylchloroformate	$ClCOOCCl_3$	Diphosgene	—	Surpalite	Perstoff
Xylyl bromide	$CH_3C_6H_4CH_2Br$	—	—	—	T-Stoff
Smokes					
Chlorsulfonic acid	$HClSO_3$	X	X	X	X
Hydrocarbons	—	Crude oil	CO	—	—
Niter, sulfur, pitch, borax, and glue	$KNO_3 + S + C + Na_2B_4O_7$ + glue	Type S mixture	Type S mixture	—	—
Silicon tetrachloride	$SiCl_4$	—	—	—	X
Stannic chloride	$SnCl_4$	KJ	KJ	Opacite	—
Sulfur trioxide	SO_3	—	—	X	N-Stoff
Sulfur trioxide + chlorsulfonic acid	$SO_3 + SO_3HCl$	X	FS	X	X
Sulfuryl chloride	SO_2Cl_2	—	—	X	X
Titanium tetrachloride	$TrCl_4$	—	FM	Fumergerite	F-Stoff
White phosphorus	P_4	WP	WP	X	—
Zinc, carbon tetrachloride ammonium chloride, and magnesium carbonate	$Zn + CCl_4 + NH_4Cl + MgCO_3$	—	HM	—	—
Zinc plus carbon tetrachloride plus zinc oxide plus kieselguhr	$Zn + CCl_4 + ZnO$ + kieselguhr	—	—	Berger Mixture	—
Zinc plus hexachlorethane and zinc oxide	$Zn + C_2Cl_6 + ZnO$	—	HC	—	—
Incendiaries					
Barium nitrate, magnesium, and linseed oil	$Ba(NO_3)_2 + Mg +$ linseed oil	Incendiary mixture	—	—	—
Barium peroxide plus magnesium	$BaO_2 - Mg$	Incendiary powder	X	—	—
Modified thermite	$3Al + 6Ba(NO_3)_2 + 8Fe_2O_3$	Modified thermite	X	—	—
Potassium perchlorate and paraffin	$KClO_4 + C_nH_{2n+2}$	Incendiary mixture	—	—	—
Sodium	Na	Sodium	X	X	X
Solidified hydrocarbons	—	Solid oil	—	—	—
Sulfur thermite	$8Al + 3Fe_2O_4 + 9S$	—	—	Duisite	—
Thermite	$8Al + 3Fe_2O_4$	Thermite	Th	X	X
White phosphorus in carbon disulfide		Inflammable liquids	—	X	—

X denotes employment without special name or symbol.
— denotes nonemployment.

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Phenyldibromarsine	$C_6H_5AsBr_2$	—	—	—	X
Phenyldichlorarsine	$C_6H_5AsCl_2$	—	—	Sternite	Blue Cross-1
Thiophosgene	$CSCl_2$	Thiophosgene	—	Lacramite	—
Trichlormethylchloroformate	$ClCOOCCl_3$	Diphosgene	—	Surpalite	Perstoff
Xylyl bromide	$CH_3C_6H_4CH_2Br$	—	—	—	T-Stoff

Smokes

Chlorsulfonic acid	$HClSO_3$	X	X	X	X
Hydrocarbons	—	Crude oil	CO	—	—
Niter, sulfur, pitch, borax, and glue	$KNO_3 + S + C + Na_2B_4O_7$ + glue	Type S mixture	Type S mixture	—	—

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ratios between *weight* of gas and *volume* of air. On the other hand, parts per million is purely a volumetric ratio and differs essentially from the other three ratios, in that the molecular weight of the gas must be taken into consideration. As all four of these ratios are met with in the literature of pharmacology, toxicology, and other branches of science closely allied to chemical warfare, it is frequently necessary to convert one expression into another. Mathematical formulas for doing so are given in Appendix A.

An *irritating* concentration is one which produces an irritant effect upon a man without injuring his body functions or seriously impairing his working efficiency. The lowest irritant concentration is often called the *threshold of action* or *threshold concentration*.

An *intolerable* concentration is one which cannot be withstood for more than a very limited time without serious derangement of some body function. As applied to lacrimators, it is usually synonymous with the maximum concentration in which a man can maintain his vision without masking.

A *lethal concentration* is one which the average unprotected man cannot survive after a definite brief period of exposure. The numerical value of the lethal concentration decreases as the time of exposure increases.

Volatility refers to the capacity of a liquid to change into vapor in the open air. Quantitatively, the volatility of an agent is the amount held as a vapor in a unit volume of saturated air at any given temperature and pressure. Volatility increases with temperature. If the volatility of a chemical compound is considerably greater than its lethal concentration for a 10-minute exposure, it is possible to set up killing concentrations under field conditions and the substance is a casualty-producing agent. For relation of volatility to vapor pressure, see Appendix A.

Hydrolysis is the reaction of any chemical substance with water whereby new compounds are created. This is a reaction of great importance in chemical warfare, as many chemical agents are rendered harmless after a time by hydrolysis. If the hydrolysis product is itself a poison, as is the case with all agents containing arsenic, considerable effort is required to neutralize the agent effectively.

Vapor Pressure.—Evaporation is constantly taking place from the exposed surfaces of all liquids and volatile solids. The pressure exerted by the escaping vapor is called the *vapor tension* of the liquid or solid. When its vapor tension equals the surrounding atmospheric pressure, a liquid is said to boil and a solid to sublime, for at that temperature its vapor is able to lift the air above it and so freely escape. At all temperatures below the boiling point of a

solid, the vapor tension of the substance is less than atmospheric pressure,
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so that the escape of the vapor is opposed by the surrounding air. Much of the vapor is thus forced back into the liquid or solid. Under these conditions the vapor is in equilibrium with the liquid or solid. A vapor in equilibrium is said to be saturated, and the equilibrium pressure is called the *vapor pressure*, which for a given substance depends only on

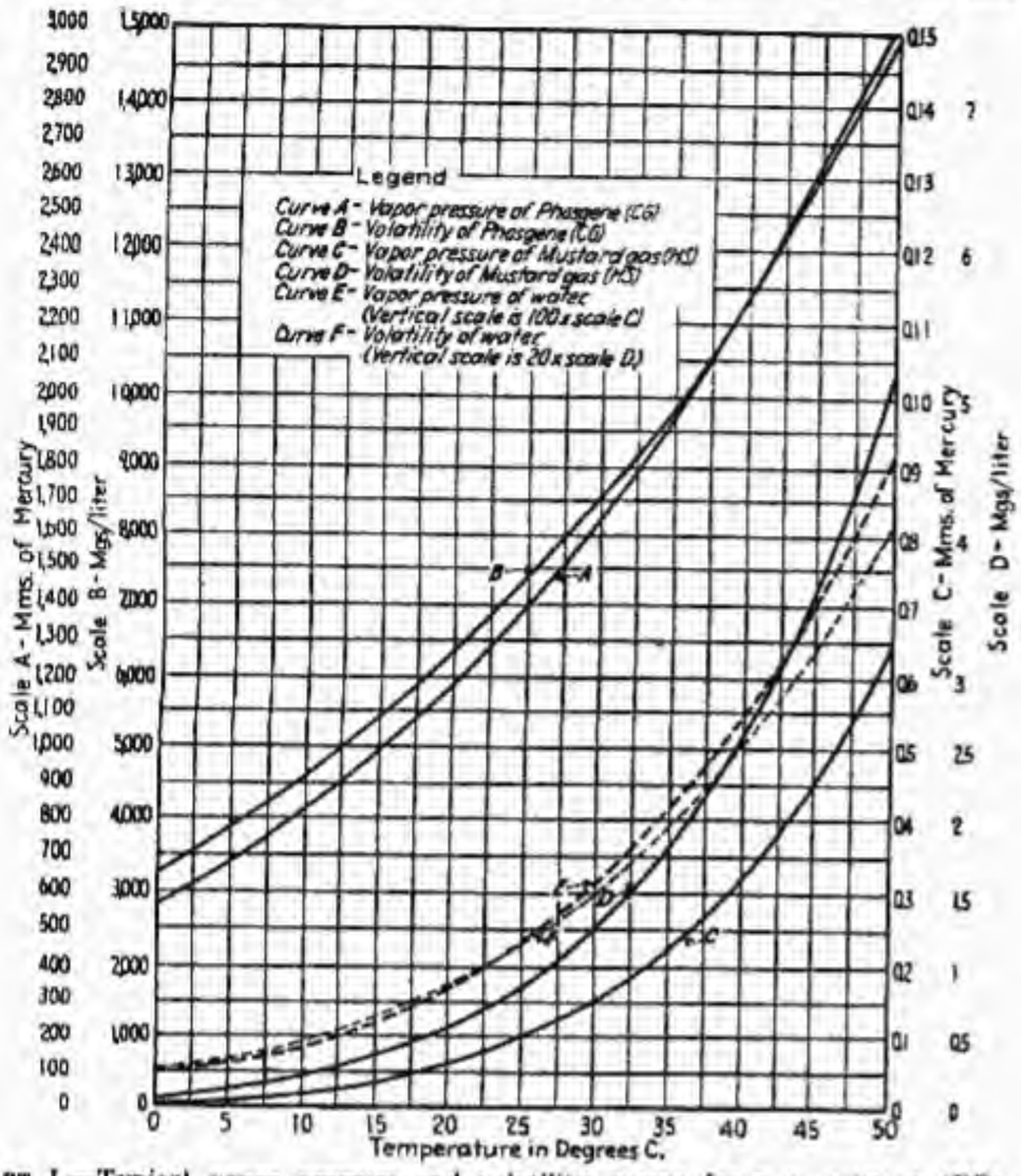

CHART I.—Typical vapor pressure and volatility curves for nonpersistent (CG) and persistent (HS) gases.

the temperature. If the vapor is not allowed to accumulate over the liquid or solid, it will remain unsaturated, equilibrium will not be reached, and the liquid will gradually disappear by evaporation. This is the usual case with chemical-warfare agents that are dispersed over the ground as liquids. No general relation is known connecting the vapor pressure and temperature, but curves showing this relationship have been determined by observation for a great number of chemical sub-
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stances that are liquids at ordinary temperatures. For purposes of comparison, the vapor-pressure–temperature curves for two of the most typical chemical agents, including the curve of water, are shown in Chart I.

Persistency is the length of time a chemical agent remains effective at the point of its release. If a gas remains in sufficient concentration to require protection of any kind at the end of 10 *minutes*, it is classed as *persistent*. If the concentration at the end of 10 minutes is too weak to require any protection, the gas is classed as *nonpersistent*. This is the American rule, but is not the same in other countries. In some foreign countries three classes of persistency are recognized, as follows:

Nonpersistent.
Moderately persistent.
Very persistent.

In such classifications the nonpersistent class is essentially the same as ours, while the moderately persistent and very persistent classes are in reality subdivisions of our persistent class. The advantage of such subdivision of the persistent class of gases is not apparent, as will be brought out in our further discussion of the subject of persistency.

The most important properties of a casualty-producing gas are toxicity and persistency, for upon the first depends its inherent power to incapacitate, and upon the second depends the extent of time during which the gas is effective in the field. The persistency of a gas also measures the length of time that must elapse before unprotected troops may occupy infected ground; thus it greatly influences the proper tactical use of the gas. As toxicity and persistency are not simple properties, but are functions which involve several other properties of a gas, they will be further considered at this point.

TOXICITY

Chemical agents have a wide range of toxicity, varying from simple local irritation, such as lacrimation, to fatal systemic poisoning, as from hydrocyanic acid. The measure of this toxicity, in terms of physiological reaction, may be determined with considerable scientific accuracy, not only within the laboratory, but also under the widely varying conditions encountered on the field of battle. Toxicities, thus established, furnish a criterion by which the most important agents of chemical warfare are judged and their tactical uses formulated. Since a general knowledge of the toxicity of agents is necessary to any comprehensive study of chemicals in war, a brief survey of the subject is presented at this point.

At the outbreak of the World War, German scientific research had produced, as a by-product of their chemical industry, extensive data on the toxicities of chemical substances. From these data, many
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chemical compounds were selected and tried out in military operations between 1915 and 1918. The majority of these substances were eventually discarded because the actual results obtained in the field failed to measure up to theoretical expectations. Yet the experience thus gained not only increased knowledge of the absolute toxicities of many chemical compounds, but also permitted the formulation of definite relations between the various factors entering into the problem, so that basic principles could be deduced and the whole subject established on a scientific foundation.

While the study of this field of toxicology has, since the war, engaged the attention of scientists generally, the interest and talent devoted to this subject in Germany continues to command respect. It is, therefore, believed that the German viewpoint on toxicity of war gases deserves consideration and we accordingly follow with some freedom the presentations of German authorities in this field, notably those of Drs. Haber, Flury, Meyer and Buscher.

The effects of chemical agents upon the human organism result either from internal contact, as inhalation, or from external contact with various body surfaces. Chemicals such as dichlordiethyl sulfide (mustard gas) combine both of these types of effect. Yet the two must be approached independently before cumulative toxicity may be quantitatively determined.

Considering first those agents whose vapors when inhaled produce deleterious internal reactions, it is found that a definite relation exists between the concentration of vapor present in the air, the amount of such contaminated air that is admitted into the body, and the toxic effect produced upon the body. This relation has been established by Haber as follows:

Most toxic substances on contact with the body react chemically with the living tissues and destroy them by forming chemical combinations therewith. The degree of intoxication or poisonous effect is proportional to the chemical reaction of the toxic substance on the body tissues. This reaction is a function of three independent variables:

1. The time of exposure to the toxic substance.
2. The concentration of the toxic substance.
3. The concentration of the living material (body tissues).

Let c = the concentration of the vapors or droplets of the toxic substance in the air, expressed in milligrams per cubic meter,
v = volume of air breathed in, per minute,
t = time of exposure to the contaminated atmosphere, in minutes,
G = weight of the body, in kilograms;

then the quantity of poison inhaled and generally retained in the body would be

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$$ctv \tag{1}$$

and the degree of intoxication or poisoning, I, is

$$I = \frac{ctv}{G} \tag{2}$$

Death occurs when the degree of intoxication, I, equals a constant

critical limit, W, which is specific for each kind of animal and for each toxic substance, *i.e.*, when

$$\frac{ctv}{G} = W \tag{3}$$

In general, the amount of air inspired per minute is proportional to the body weight of the higher animals, so that the ratio v/G is constant for a given species and may be written as unity for the purposes of comparing the toxicities of gases on the same kind of animals. Then

$$ct = W \tag{4}$$

The product $ct = W$ is called the *product of mortality* (*Tödlichkeitsprodukt*) or the *lethal index* of the particular toxic substance for the given animal. This product W varies inversely as the toxicity of the toxic substance, *i.e.*, the smaller the value of W, the more toxic is the substance.

By taking a large number of observations on various animals exposed to constant concentrations of toxic gases for definite periods of time under carefully controlled conditions and tabulating the mortality results, it has been found that the relation between the minimum lethal dose and time of exposure follows a definite curve for each toxic gas. Chart II shows this curve for phosgene on dogs and expresses the concentration required for each length of exposure in order to produce death. Such curves are generally known as toxicity curves and the form of curve shown in Chart II is typical of all such curves, and illustrates the tremendous increase in concentration required when the time of exposure is reduced below 10 minutes. For this reason, it is customary to base relative toxicity figures on 10 minutes for short exposures and 30 minutes for long exposures.

Upon examining internal physiological reactions to toxic vapors, it appears that some differentiation must be made between those substances characterized by *local* effects as distinguished from those that induce general *systemic* poisoning. Compounds of the latter category, such as carbon monoxide and hydrocyanic acid, are in part neutralized by certain physiological counterreactions, and their reactions with the body tissues are reversible up to a certain point. To allow for this

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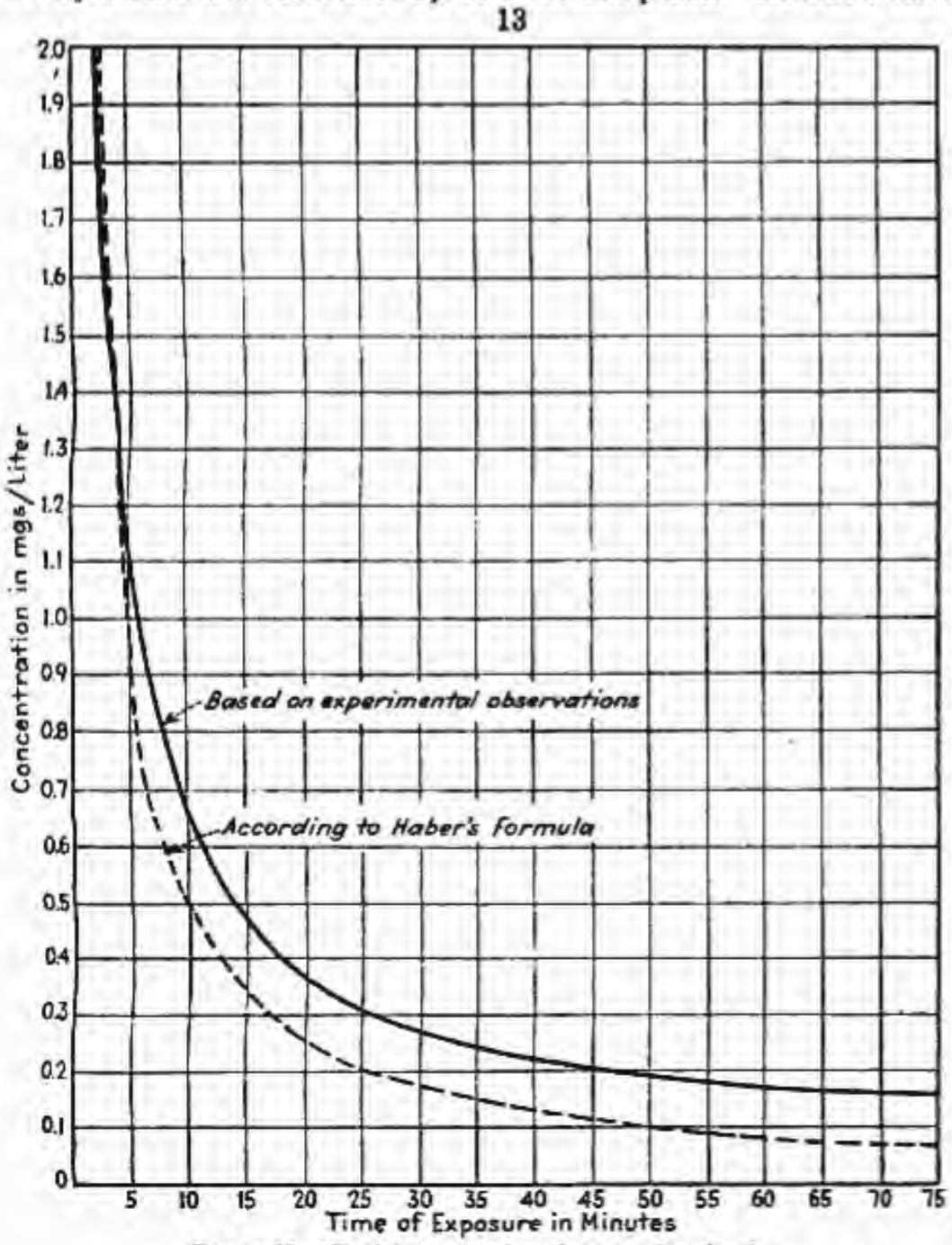

CHART II.—Toxicity curve for phosgene (on dogs).

phenomenon it is necessary to insert an "elimination factor," e, in the Haber formula, which then reads

$$(c - e) \times t = W \tag{5}$$

Here the relation between c and e demands a critical density of concentration below which systemic poisons are noneffective, and the observed data confirm this result.

In accordance with these formulas, toxicity data are experimentally determined by closely observing the physiological reactions of test

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animals under carefully controlled experimental conditions. While the effects on the higher animals are not in all cases absolutely parallel with human reactions, they do furnish valuable relative toxicological data as between various chemical agents. The following table presents lethal indices so computed for certain well-known chemical substances.

RELATIVE TOXICITY FROM INHALATION
(After Haber)

Agent	Lethal Index
Irreversible Reactions	
Phosgene	450
Diphosgene	500
Lewisite	1,500
Mustard gas	1,500
Chlorpicrin	2,000
Ethylsulfuryl chloride	2,000
Ethyldichlorarsine	3,000
Ethylbromacetate	3,000
Phenylcarbylamine chloride	3,000
Chloracetone	3,000
Benzyl iodide	3,000
Methyldichlorarsine	3,000
Acrolein	3,000
Diphenylchlorarsine	4,000
Diphenylcyanarsine	4,000
Bromacetone	4,000
Chloracetophenone	4,000
Benzyl bromide	6,000
Xylyl bromide	6,000
Brombenzyl cyanide	7,500
Chlorine	7,500
Reversible Reactions	
Hydrocyanic acid	1,000–4,000*
Carbon monoxide	70,000*

* The lethal indices of the *systemic* poisons depend upon the degree of concentration c, and the product $c \times t$ for these compounds is therefore not constant.

From the above table it appears that fatalities result from normal inhalation for 1 minute in an atmosphere contaminated with a concentration of 450 mg. of phosgene per cubic meter of air. The deadliness of agents of the phosgene type is further emphasized by the fact that they may be equally effective in smaller quantities when inhaled over longer periods, which does not hold true with the systemic toxics, such as hydrocyanic acid and carbon monoxide. In the case of phosgene, the absolute quantity of vapor required to produce death (toxicity index 450) is about 3.6 mg., based on a normal inspiration of 8 liters of air per minute, or $8 \times {}^{450}/_{1000} = 3.6$. Generally speaking this quantity of phosgene vapor introduced into the lungs will, as Flury (5) indicates, cause death even when inspired more slowly in a concentration correspondingly lighter than 450 mg. per cubic meter. The absolute quantity of hydrocyanic acid, according to the foregoing toxicity index, averages 20 mg.; but as dilution increases, the toxicity of gaseous hydrocyanic acid falls off rapidly, until at 0.03 gram per cubic meter the human organism is able finally to counteract wholly its toxicity; thus concentrations below this strength become actually innocuous. Considering the extreme volatility of carbon monoxide and hydrocyanic acid, and the resulting impracticability of creating effective concentrations of their vapors in the field, it is evident that these chemicals, while commonly regarded as highly poisonous, are unsuited to military usage.

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The foregoing toxicity figures must be accepted with reservations, as they apply to one set of conditions only, *i.e.*, to one animal (the cat) and to one rate of breathing. While experimental determinations of toxicity on animals yield valuable relative data as to certain classes of toxic agents, these data cannot always be applied to man, because

certain animals are more sensitive to certain gases than man and others are less so. Also the rate of breathing is a very important factor. Thus, a man at rest breathes on an average about 8 liters of air per minute, but, if he is exercising moderately, he will breathe 32 liters of air per minute, and with violent exercise he will breathe at a proportionally greater rate. Hence, when exposed to a toxic atmosphere of a certain concentration for the same length of time, he will take in four times as much poison when moderately exercising as when at rest. Body weight is another factor, for, in general, the larger the body, the greater the amount of a toxic substance required to produce the same degree of intoxication. Because of these factors, it is more accurate to state the specific amount of the toxic agent that will cause death when absorbed into the body. But such a criterion is impracticable of application in the field, and so an average constant concentration is assumed over a fixed time of exposure—usually 10 to 30 minutes for nonpersistent gases.

For comparison with the German toxicity data presented in the foregoing tabulation, the American data in the table on page 16, show the quantities of gases required to produce fatal effects on 10 minutes' exposure.

The wide discrepancy between the German and American toxicity data is strikingly shown in this tabulation. This discrepancy has been attributed to various causes, such as that the German data were based on cats, while most of the American data were based on dogs and mice; that cats are peculiarly susceptible to some gases and resistant to others; that the cats used in the German tests during the war were undernourished, and therefore less than normally resistant; that the degree of activity, and therefore the rates of breathing, may have been widely different in the German and American tests. While the subnormal

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condition of the German test cats would tend to explain partially the generally higher toxic effects obtained in the German experiments (*i.e.*, generally lower lethal indices), none of the reasons advanced are sufficient to explain the great number of widely divergent results.

LETHAL CONCENTRATIONS OF GASES
(10 Minutes' Exposure)

Agent	American data		German data
	Mg. per liter	Lethal index	Lethal index
Phosgene	0.50	5,000	450
Diphosgene	0.50	5,000	500
Lewisite	0.12	1,200	1,500
Mustard gas	0.15	1,500	1,500
Chlorpicrin	2.00	20,000	2,000
Ethylsulfuryl chloride	1.00	10,000	2,000
Ethyldichlorarsine	0.50	5,000	3,000
Ethylbromacetate	2.30	23,000	3,000
Phenylcarbylamine chloride	0.50	5,000	3,000
Chloracetone	2.30	23,000	3,000
Benzyl iodide	3.00	30,000	3,000
Methyldichlorarsine	0.75	7,500	3,000
Acrolein	0.35	3,500	3,000
Diphenylchlorarsine	1.50	15,000	4,000
Diphenylcyanarsine	1.00	10,000	4,000
Bromacetone	3.20	32,000	4,000
Chloracetophenone	0.85	8,500	4,000
Benzyl bromide	4.50	45,000	6,000
Xylyl bromide	5.60	56,000	6,000
Brombenzyl cyanide	0.35	3,500	7,500
Chlorine	5.60	56,000	7,500
Hydrocyanic acid	0.20	2,000	1,000–4,000
Carbon monoxide	5.00	50,000	70,000

One of the difficulties is to be found in the form of the observed toxicity curve shown in Chart II. By selecting various times of exposure, finding the corresponding minimum lethal doses from the curve, and multiplying these figures by each other, we obtain the variations in the lethal index for phosgene as shown in the table on page 17.

Thus, by increasing the time of exposure from 2 to 75 minutes, we find that the lethal index increases threefold, whereas, according to Haber's formula, the lethal index should remain constant, irrespective of the time of exposure. The theoretical toxicity curve for phosgene,

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according to Haber's Formula, is shown in dotted lines on Chart II, based on American data (*i.e.*, 0.5 mg. per liter on 10 minutes' exposure). A comparison of the two curves on Chart II shows that, while the observed data follow in general Haber's Formula, there is not a sufficiently close agreement to maintain a constant lethal index.

Time of exposure, minutes	Minimum lethal dose, Mg. per liter	Lethal index
2	2.00	4,000
5	1.10	5,500
10	0.65	6,500
15	0.46	6,900
20	0.37	7,400
25	0.30	7,500
30	0.27	8,100
45	0.20	9,000
60	0.17	10,200
75	0.16	12,000

While the difficulty mentioned in the foregoing paragraphs would account for such differences in the lethal index as are shown for certain agents, such as ethyldichlorarsine, phenylcarbylamine chloride, and methyldichlorarsine, it is altogether inadequate to explain the other large discrepancies shown above, which in many cases are as much as tenfold.

Many chemical-warfare agents are not fatal in concentrations encountered in the field and their combat value is due to their irritant action on the body. One group of irritant substances act primarily on the eyes and are commonly known as *lacrimators;* others attack the nose and throat and are generally termed *respiratory irritants*, or *sternutators:* a few have special selective effects against other organs such as the ears (termed *labyrinthic agents* by the French). Also many lethal agents have an irritant effect far below their lethal concentrations.

All irritant agents, regardless of their special physiological action, have an *intolerable limit*, which means the maximum concentration that an *unprotected* man can endure without physical incapacitation, for the period of time considered. Usually this period is 1 minute.

The intolerable limits for the majority of irritant agents as determined by investigators in different countries are in much closer agreement than toxicity determinations, most of the differences being well within experimental error.

The following tabulation shows the intolerable limits of the principal irritant agents and agents of other classes having an irritant effect:

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LIMITS OF HUMAN TOLERANCE FOR IRRITANTS

Agent	CWS symbol	Mg. per liter
Diphenylcyanarsine	CDA	0.00025
Diphenylaminechlorarsine	DM	0.0004
Lewisite	MI	0.0008
Mustard gas	HS	0.0010
Diphenylchlorarsine	DA	0.0012
Chloracetophenone	CN	0.0045
Bromacetone	BA	0.0100
Ethyldichlorarsine	ED	0.0100
Ethyliodoacetate	.....	0.0150
Xylyl bromide	.....	0.0150
Phosgene	CG	0.0200
Methyldichlorarsine	MD	0.0250
Phenylcarbylamine chloride	.....	0.0250
Brombenzyl cyanide	CA	0.0300
Benzyl iodide	.....	0.0300
Ethylbromacetate	.....	0.0400
Methylsulfuryl chloride	.....	0.0400
Dichlormethyl ether	.....	0.0400
Diphosgene	.....	0.0400
Ethylsulfuryl chloride	.....	0.0500
Chlorpicrin	PS	0.0500
Acrolein	.....	0.0500
Dibrommethyl ether	.....	0.0500
Benzyl bromide	.....	0.0600

Cyanogen bromide	.....	0.0600
Cyanogen chloride	...	0.0610
Perchlormethylmercaptan	.....	0.0700
Chlorine	Cl	0.1000
Chloracetone	.....	0.1000

Of these compounds, diphenylcyanarsine appears to exert the greatest irritant effect, since only 0.00025 mg. of this gas per liter of air is intolerable after 1 minute, and 0.00000001 *gram per liter of air* proves decidedly disagreeable.

From what has been said above, it is evident that high toxicity, while an important factor, does not solely determine the utility of warfare gases. An irritant agent of even low intrinsic toxicity becomes extremely effective when not countered by the protection of the gas mask, so that some sacrifice of toxicity value is clearly warranted if this serves to circumvent or increase the burden of protection. Thus, forcing the enemy to mask frequently becomes an end in itself, which is attained positively and most efficiently by the irritant nonlethal gases.

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PERSISTENCY

Persistence is, in general, an expression for the length of time during which a chemical agent remains and exerts its effect on the place where it has been released. The physical properties of a substance are nearly always the determining factors in its persistence.

In considering persistence, we distinguish two groups of chemical agents:

1. Pure *gases*, *e.g.*, Cl and CG and toxic smokes (DA and DM).
2. *Liquids* and *solids*, *e.g.*, HS and M-1.

In the case of substances of the *first* group, the entire amount of the combat chemical is distributed over the target area and there is none on the ground in liquid or solid form. If it is later deposited on the ground, as is sometimes the case with toxic smokes, it plays no important role. Since these true gases are completely distributed in and float with the air, they have about the same persistency as the air with which they are mixed. They follow completely every current of air and, if a layer of air which has been over the target area moves away, the chemical agents of this group follow its course. There are, however, always small differences in the persistence of these substances.

The pure gases (Cl, CG) are heavier than the air, and so they have a tendency to sink into depressions in the ground and remain for a time in the form of gas pockets in the deep spots where the air currents cannot easily penetrate and carry them further away. But, even in a complete calm, they diffuse from these sheltered places and gradually become harmless through dilution with air.

The toxic smokes (DA, DM) sink finally to the ground, as does every smoke, with a speed which is proportionate to the size of the smoke particles. Once on the ground, they can no longer rise and, like ordinary dust, they are carried away by the atmospheric precipitations.

But both the diffusion of the pure gases and the fall of the smoke particles proceed so comparatively slowly that these factors play no essential part as compared with the diffusing and dividing effect of the vertical and horizontal air currents. The persistence of the chemical agent of this group depends, therefore, chiefly on the conditions of wind and, so far as the wind is affected by the lay of the land and its covering, on these factors also. It is thus easily seen that deep depressions in the ground or thick high-standing forests may considerably increase the persistence of the materials.

In the case of the materials of the *second* group (HS, M-1), the persistence is considerably greater than it is with the first group, yet it varies greatly according to the specific properties of each substance. Most of the materials of this kind are liquids, which on the explosion

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of the shell in which they are placed are sprayed out over the terrain in large or small drops, whence they evaporate into the air layers above the ground. As long as there is liquid chemical material on the ground, it is a constant source of replacement for the evaporated portion of the material, which has been thinned down or carried away by the air currents. The air is constantly contaminated anew with toxic or irritant gases. Similar to the liquid chemical agents are some agents which in the open air evaporate without first becoming liquid (*e.g.*, CA).

For tactical considerations, it is of decisive importance to know how long this process continues on a target area that has been covered with gas. If we leave out of consideration, at first, the ordinary external influences, then it appears that, above all else, the air temperature is the determining factor.

Chemical agents volatilize with a rapidity proportional to the temperature of the air, but in this they show great differences among themselves. For example, HS volatilizes in the cold so slowly that the air above the contaminated ground often does not contain enough of the vapor to endanger respiration. In summer it always vaporizes fast enough, yet so economically that it may persist on the contaminated ground under favorable conditions for three weeks or longer. On the other hand, CG volatilizes so quickly that an open country treated with it may be entered without danger a quarter of an hour to half an hour later.

The physical reasons for the great differences in the persistence of chemical agents are to be found in the fact that these substances have very different vapor pressures and in the degree to which these pressures vary on change of temperature. The higher the vapor pressure at a given temperature of the air, the less persistence at that temperature. But the rapidity of volatilization of a chemical, which alone gives an objective measure for its persistence, is not simply proportionate to the vapor pressure, but has a complicated dependence on other decisive factors.

A more satisfactory basis for gauging the persistence of the combat materials is a table of the reciprocal values of rapidity of volatilization which serves as a table of the relative persistence of the chemical agents. For purposes of comparison, the rapidity of volatilization of water at 15°C., is assumed to be 1.

The reciprocal values of the rapidity of volatilization are taken because the persistency of a combat material is greater in proportion as its rapidity of volatilization is small; water was selected as the material for comparison because the rapidity of its volatilization, by observation, has come within the experience of everyone. Computing the rapidity of the volatilization from the vapor pressure was accomplished by the

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inversion of a process which, in principle, was first applied by the American physicist Langmuir (*Phys. J.*, vol. 14, p. 1273) in the formula

$$S = \frac{c_1}{c} = \frac{p_1}{p}\sqrt{\frac{M_1 T}{M T_1}}$$

In this formula S signifies the persistency of the chemical agent, c_1 the rapidity of volatilization of water at 15°C., c the rapidity of volatilization of the chemical at the absolute temperature T, p_1 the vapor pressure of water at 15°C., p the vapor pressure of the substance at the temperature T, M_1 the molecular weight of the water, M that of the substance, T the absolute temperature of the air, T_1 the absolute temperature corresponding to the Celcius temperature of 15°.

PERSISTENCY OF SOME TYPICAL CHEMICAL AGENTS
(That of Water at 15° Assumed as 1)

Chemical agent	Physical state	Temperature, °C.								
		−10	−5	0	5	10	15	20	25	30
CA	Solid	6,930	4,110	2,490	1,530	960	610	395	260	173
	Liquid	(2,720)	(1,830)	(1,250)	(860)	(600)	(427)	(307)	(222)	(163)
HS	Solid	2,400	1,210	630	333	181	Melts at 13.9°C.			
	Liquid	(1,162)	(690)	(418)	(258)	(162)	103	67	44	29
M-1	Liquid	96.0	63.1	42.1	28.5	19.6	13.6	9.6	6.9	5.0
Diphosgene	Liquid	2.7	1.9	1.4	1.0	0.7	0.5	0.4	0.3	0.2
PS	Liquid	1.36	0.98	0.72	0.54	0.4	0.3	0.23	0.18	0.14
CG	Liquid	0.014	0.012	0.010	0.008	Boils at 8.02°C.				

In the case of CA and HS, under the normal melting point, are given in brackets the persistency of the liquid phases. These materials, especially the first, are obstinately inclined to remain liquid when cooled below the freezing point. Moreover, the freezing point of the commercial product, on account of the unavoidable impurities contained therein, is

of itself lower than that of the chemically pure compound.

The use of the table is shown by the following examples. Liquid HS has, at 15°C., a persistence of 103; liquid CA has a persistence of 427. This means that the first material under otherwise similar conditions (similar average size of drops, similar wind conditions, etc.), takes 103 times as long to disappear from the ground by evaporation as an equal mass of water, and CA is $^{427}/_{103}$, or about four times, as persistent as HS.

Diphosgene and phosgene are also two materials which are chemically closely related. But the difference in persistence between them is an important factor in their tactical use. This can be compared directly, as a rule, only under 8°C. (the boiling point of phosgene). Above this

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temperature, phosgene no longer exists as a liquid under atmospheric pressure, but changes into a heavy gas which seeks a way through uneven lands, partly following its own weight, partly the air currents. In level country, it moves only with the wind. Under 8°, phosgene can exist as a liquid in the open, but even at 10° the persistence of diphosgene is 100 times greater than that of phosgene.

HS and M-1 are likewise two materials of very similar physiological effect, distinguished by the vesicant effect on the skin which they produce, especially when they are in liquid condition. But their persistence is quite different. In summer HS has a persistence seven to eight times greater than that of M-1. This is a well-known disadvantage of M-1 in most of the tactical uses for these materials, and it is still further emphasized by the fact that M-1 easily undergoes chemical decomposition in warm weather if moisture is present, which is often the case at this season. But in winter M-1 is superior to HS, as we shall see. The difference of the persistence of the two materials is greater then than it is in summer, for HS freezes; as a solid body, it does not moisten the uniforms, clings to them less, and cannot work through them to the skin. M-1, however, remains fluid even in winter and, moreover, its persistence increases to the degree possessed by HS in summer. So HS may be called a summer gas and M-1 a winter gas.

CA, a lacrimator, is, so far as concerns persistence, the king of all the combat materials. The great persistence which it attains in low temperatures has a limited value, however, as its rapidity of evaporation is then so small that the air, in movement, does not become sufficiently charged with the vapor of the material and so cannot exert a satisfactory physiological effect. Even in summer, the persistence of CA is so great that it is frequently too long for most of the tactical uses of an irritant agent. For this reason, the Americans prefer CN, another irritant that has other advantages also, such as simple preparation and compounding with explosive materials. On the explosion of the shell, it vaporizes. The vapor exercises intense physiological irritation, but it disappears quickly from the air of the combat terrain for, on its further attenuation (on account of the negative specific heat of the saturated vapor), it precipitates and falls to the ground where, owing to very slow evaporation, it exercises no effect worthy of note.

In the above tabulation all data are based on the rapidity of evaporation of water at 15°C., without making any assumption as to the absolute time of evaporation. Different influences play a weighty role on the length of time that passes before a chemical agent, placed on a terrain, is completely volatilized.

First, the average size of the surface of the drops of the chemical, which are sprinkled over the terrain, is of some significance. The

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greater this surface is, the quicker, as a rule, volatilization will take place. But in this regard it appears that the difference between most of the liquid chemical agents is not considerable. This is due to the fact that their surface tensions, as measured in the laboratory, are about equal. But the chemical agents can be scattered in very different sized drops by varying the amount of explosive material in the shells. Very large drops will be divided up into very small drops in their flight through the air and when they strike the ground. On the other hand, small drops unite and form large ones through constant contacts which take place among their great number. So there results a fairly constant average size for the drops, which makes it possible to disregard the influence exerted by the size of the drops in rough estimates.

But it is different with the influence of the weather, of the ground formation, and of the covering. These factors can naturally affect greatly the rapidity of volatilization. We can estimate their effect approximately only by empirical rules.

If we compare the data that may be deduced from war experience, which in general agree fairly well with the figures in the above tabulation, the following conclusion may be drawn:

The persistence of a chemical agent in dry weather and on open even ground, for the duration of 1 hour, is taken as the unit of persistence in the figures of the above tabulation. In greatly cut up land, double value is to be assigned; in heavy forest, three times the value.

It must be noticed that heavy or continuous rain brings a premature end of the persistence of the chemical agents that are clinging to the ground, by washing them away; a heavy snow fall makes them ineffective by covering them over with a thick layer of snow. Where precipitation is frequent, persistencies of more than two or three weeks are seldom realized, if we except house ruins and similar places which are protected from the weather.

Summary.—The method developed above for determining the persistence of chemical agents makes it possible:

1. To form a dependable judgment in regard to the persistence of even those chemicals, concerning which no war or other practical experiences are available;
2. To take into consideration, as accurately as desired, the temperature of the air, which, next to air currents, exerts the most important tactical influence of the day on the persistence of the chemical agents.

EFFECT OF WEATHER ON CHEMICAL WARFARE

While chemical agents are influenced by weather conditions more than any other weapons, this does not mean that the occasions on which chemicals may be used in battle are limited to favorable weather. Cloud gas released from cylinders is the only form of chemical attack that cannot

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be launched with some degree of effectiveness in almost any weather in which combat takes place. However, weather conditions do largely influence the form and technique of chemical attack and are frequently the deciding factor in the success or failure of the undertaking. Hence, a thorough understanding of the effect of weather conditions on the employment of chemicals is essential to a successful use of chemicals in war.

The Six Weather Elements.—The weather at any particular time and place is completely determined by the following:

Wind.
Precipitation.
Temperature.
Pressure.
Clouds.
Humidity.

Since weather is the condition of the atmosphere at any time and place, it is best described by giving numerical values for its elements. These six elements will be taken up and considered separately. Chemical-warfare operations are more or less concerned with all of them. For example, the factors influencing gas or smoke clouds are, in order of importance: (1) wind, under which should be considered the direction, steadiness, and velocity of the wind, and eddy currents due to the proximity of woods, uneven terrain, etc.; (2) precipitation; (3) temperature; (4) pressure; (5) clouds; (6) humidity. The effectiveness of all smokes is greatly increased by high humidity; on the other hand, high humidity tends to destroy some of the irritant agents by hydrolysis. Cloudiness has a very marked effect on the rise of smoke clouds. The persistency of agents is largely dependent upon temperature and wind velocity. So it will be seen that no chemical-warfare operation can be considered without reference to the weather elements.

The numerical values of the weather elements are by no means constant, but are always undergoing change or variations.

Wind

Air in motion near the earth's surface and nearly parallel to it is called *wind*. All other motions of masses of air should be spoken of as air currents. In connection with wind there are three things to be

determined or measured, *viz.*, the direction, the velocity, and the gustiness.

Direction.—The wind is named for the direction from which it comes; thus, if the air moves from the north toward the south, it is called a *north* wind.

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In noting wind direction, eight points of the compass are used, *viz.*, the cardinal points, north, south, east, and west, and the four intermediary points, northwest, southwest, northeast, and southeast. The magnetic azimuth of winds is sometimes used in chemical-warfare operations.

Wind direction can be determined in the field by measuring with a compass the direction of drift of smoke or of dust thrown into the air and adding 180 degrees. It can also be determined by means of a portable wind vane previously oriented by compass, or by taking the magnetic azimuth from the wind vane to a point indicated by its arrow.

Velocity.—Wind velocity can be estimated by using the following *table:*

Titles	Description	Meters per second	Miles per hour
Calm	Calm, smoke rises vertically	Less than 0.3	Less than 1
Light air	Direction of wind shown by smoke drift but not by wind vanes	0.3–1.5	1–3
Slight breeze	Wind felt on face; leaves rustle; ordinary vane moved by wind	1.6–3.3	4–7
Gentle breeze	Leaves and small twigs in constant motion; wind extends light flag	3.4–5.4	8–12
Moderate breeze	Sways branches of trees, blows up dust from the ground, and drives leaves and paper rapidly before it	5.5–9.8	12–22
Fresh breeze	This sways whole trees, blows twigs and small branches along the ground, raises clouds of dust, and hinders walking somewhat	9.9–14.3	23–32
High wind	This breaks branches, loosens bricks from chimneys, etc., litters the ground with twigs and branches of trees, and hinders walking decidedly	14.4–32.2	33–72
Hurricane	Complete destruction of almost everything in its path	32.2 on	72 on

Wind velocity can be measured by means of an anemometer and a watch. The anemometer measures the distance in meters traveled by the wind in the space of time measured by the watch. Thus, if in 1 minute the anemometer registers 606 meters, the wind has traveled 606 meters in 60 seconds or

$$606 \div 60 = 10.1 \text{ meters per second}$$
$$\text{Meters per second} \times 2.237 = \text{miles per hour}$$
$$\text{Miles per hour} \times 0.447 = \text{meters per second}$$

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Wind velocity increases markedly with altitude. This will often be noted in observing the travel of smoke clouds. The higher velocity above the ground sometimes causes a rolling movement of the top of the cloud and the top is carried forward faster than the body of the cloud. The increase in velocity with altitude is very rapid in the first 100 to 200 ft., particularly over land.

The effects of surroundings on wind should be carefully considered in any local observation of direction and velocity.

Gustiness.—Wind, both as regards direction and velocity, is probably more affected by the immediate surroundings of the place at which observations are made than any other of the meteorological elements. There are four things to be especially considered: valleys, buildings, nature of the surface, and altitude. Valleys influence wind direction markedly and velocity to a slight extent. Valleys have a tendency to cause the wind to blow along their length. Buildings increase the wind velocity near them and also make the wind gusty. In fact, one result of all unevennesses in the surface over which air passes is to cause gusts. The nature of the surface also has a marked influence on wind velocity. On land the wind velocity is very much reduced near the earth's surface. This is brought about not only by friction but also by the intermingling of air masses and by the formation of eddies that result from the uneven surface. *Turbulence* may be defined as the sum of all the local air currents. It causes a complete mixing of the atmosphere and consequently the dilution of a gas or smoke cloud. *Steadiness* is the opposite of gustiness.

Effect of Wind on Chemical Warfare.—*Persistent agents* are used to saturate the surface of the ground and the vegetation and hence are not easily blown away. Winds have little effect on their use. Evaporation will be slightly increased by high winds, but the high winds blow the vapors away so rapidly that their effectiveness is not greatly increased.

Nonpersistent Agents.—With this class of agents the wind is of primary importance, especially if the method of propagation is by the use of cylinders. The three characteristics of the wind which are especially important are the *direction*, the *velocity*, and the *steadiness*.

1. *Direction.*—When cylinders or irritant candles are used, the direction of the wind must be such that it will carry the agent from our emplacement to the enemy's position without carrying it into any portion of our own position. When our own lines and the target for projectors or mortars are in close proximity, the wind direction is similarly of importance. When we are using chemicals from artillery shells, bombs, or airplanes, the direction may not be so important unless the action is long sustained with a wind toward our own troops. Then the fumes may be carried to our position and cause trouble.

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2. *Velocity.*—When cylinders and irritant candles are used, the velocity should not be less than 3 miles per hour because winds having a lower velocity than this are likely to be gusty and variable. They may die down or even reverse and blow the agent back on our own troops. However, when the agent is delivered by artillery, mortars, projectors, or bombs, this lower limit of wind velocity need not be considered.

The velocity should not be over 12 miles per hour because winds having higher velocities than this tear the cloud apart and, immediately after the agent is released, mix it with large quantities of air (through turbulence) and cause the concentration to be lowered.

The higher the wind velocity, the faster a given wave or cloud will pass over the enemy's position, the shorter the time he will be exposed to it, and the less effective it will be. If a certain result is desired and if a high wind is blowing, more agent must be used.

It is clear from the foregoing that, in general, a low rather than a high wind velocity is to be desired in order that the cloud may stay over the enemy as long as possible and in order that economy in the use of agents may be practiced.

The higher wind velocities also tend to cause turbulence and eddies over trenches and valleys, causing the agent to rise and preventing it from penetrating into trenches and dugouts.

With high wind velocities the cloud may also be so torn apart that groups of the enemy will be left in gas-free "islands" and so escape its effect.

The upper limit of 12 miles per hour is just as important with artillery and projector shoots as it is with cylinder attacks, owing to the tendency of high winds to tear the clouds apart and disperse them before they have existed long enough to be effective.

The technical limit of 12 miles per hour is sufficiently high to prevent the enemy from running out of the cloud to safety. This becomes evident when we consider that a man at a brisk walk covers only 4 miles per hour, that a horse at a trot covers 8 miles per hour and at a gallop 12 miles per hour.

3. *Steadiness* is important both as to direction and velocity. The wind should maintain its direction and velocity over a wide front for at least as long as the chemical attack is to last. Otherwise, conditions will be gusty and squally and the gas cloud will be broken, whirled up into the air, and rarefied. For obvious reasons, the nearer the cloud approaches any portion of our own trenches, the steadier the wind should be.

Irritant Smoke Clouds and Screening Smokes.—Irritant smoke clouds may be generated from candles or from shells or bombs. In the first case, the same principles apply as were discussed under nonpersistent

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clouds. Again in the two latter cases, only the upper wind-velocity limit need be considered, when the cloud might be dispersed or blown over the enemy too rapidly for sufficient effect.

Screening smokes may also be generated from candles, shells, bombs, or airplanes. When a smoke screen is generated from candles, the wind must be in the proper direction to accomplish the desired result. It must usually blow toward the enemy. Here again, and for the same reasons as stated above, the upper velocity limit should not be exceeded. The lower limit is not so important since, even if the wind did reverse itself, the screening smokes are harmless to personnel. Steadiness of the wind is important with screening smokes so the smoke cloud or screen will not be torn asunder, leaving gaps through which the enemy may see. Generally, variations in wind velocity are accompanied by variations in the wind direction, even as much as 180 degrees. Large wind-direction changes, occurring at rapid intervals, often produce turbulent conditions, especially if accompanied by large velocity changes.

The effect of varying winds makes successful screening difficult because of the breaks in the screen and the rapid dissipation of the smoke.

Convection currents, due to bright sunshine, lift the cloud high in the air and often prevent satisfactory screening.

Convection currents are not so strong in presence of high winds as in the cases of light winds because high winds rapidly mix the warm surface-heated air with the superimposed and surrounding cooler air and tend to prevent their development.

Wind and Safety Limits.—Since the successful use of nonpersistent agents is largely dependent on wind conditions, it is essential to establish rules governing the relation of the wind direction and velocity to the use of nonpersistent agents. Wind-direction limits are prescribed primarily in the interest of safety to friendly troops, while wind-velocity limits insure a reasonable chance of success in the operation. Safety precautions require wind limits for the portable cylinder, the irritant candle, the Livens projector, and the 4-in. chemical mortar.
They are not required for artillery weapons or for the 4.2-in. chemical mortar unless the range is less than 1,200 yd.

A general rule for the use of mustard gas and other highly persistent vesicants is as follows:
Let X = safe distance from our lines to near edge of target area,
A = depth of target area in direction of fire,
B = width of target area.
Then

$$X = \frac{A + B}{2} \text{ (but never less than 1,000 yd.)}$$

Temperature and Clouds

Effect of Temperature on Chemical Warfare.—*Persistent agents* are much more effective when used in hot weather. Under these conditions there is sufficient vapor generated to cause skin and lung casualties. Hot weather without rising air currents gives the ideal temperature condition. Under cold-weather conditions the blister effect from the vapor is not obtained, although the agents will still cause casualties if personnel comes in actual contact with the chemical, as by walking through vegetation on which the agent has been sprayed.

Nonpersistent Agents.—In contrast to the effect on the persistent agents, high temperatures are a serious handicap to the use of nonpersistent agents. High temperatures cause the atmosphere near the ground to become heated, and thus lighter than the overlying and surrounding air. It then has a tendency to rise or be displaced by the cooler, heavier air, and rising or convection currents may be set up. These will cause the cloud or agent to rise rapidly over the heads of the enemy and to mix with large quantities of air, thus lowering both the persistency and the concentration. Convection currents are especially prevalent in the afternoon over dry or plowed ground or ground free from vegetation. On the other hand, on days when the temperature is low, the lower layers of the air will remain cool and there will be no tendency for an overturning of the atmosphere. The length of time that a definite amount of agent will give an effective cloud of a desired persistency and concentration is thus increased.

It may be said, then, that high temperatures which usually occur on bright sunny days usually produce conditions unfavorable to the success of nonpersistent gas attacks, and that the cooler parts of the day, such as from midnight to dawn, are the most favorable periods for gas attacks. Normally, the coldest part of the 24 hours occurs at approximately sunrise.

Irritant Smokes and Screening Smokes.—The smokes are comparatively free from the influence of atmospheric temperature insofar as the formation of the original cloud is concerned. The cloud once formed is affected in the same way as clouds of nonpersistent agents.

Temperature Effects at Night.—During the daytime the temperature over a limited area, say a square mile, is about the same unless there are marked changes in topography or soil. On days with much sunshine and a low wind velocity, the lower points, particularly those in narrow valleys, may be a few tenths of a degree warmer than the upper parts of the area. At night, the layer of air next to the ground grows colder and denser and drains like water into the valleys and places of low elevation. If the wind is unable to remove these pockets of cold air, a

marked variation in temperature over a limited area will be found. For every limited area, there will be a critical value of wind velocity, which for most areas is probably not far from 3 miles per hour. As long as the wind velocity remains higher than 3 miles per hour, these pockets of air will be removed and mixed with air at other points and no variation in temperature will be found. Since the question of variation in temperature depends upon the interplay between the drainage of colder air and the ability of the wind to remove these pockets of cold air, the variation will depend not only upon the elevation but also upon the openness of the valleys, their direction, the roughness of the surface, and the direction from which the wind comes.

Because of the tendency of surface air to cool and drain into valleys and depressions, such places in the vicinity of gassed areas will, on calm nights particularly, be likely to contain dangerous concentrations of toxic agents. This is a matter which should receive careful consideration in the disposition of troops near a gassed area.

Effects of Clouds on Chemical Warfare.—Clouds as meteorological formations have no direct effect on any chemical agent. It is through their effects upon other meteorological elements that they become important to the chemical-warfare officer. Clouds attain their effects through their control over temperature. They shut off the sun's rays and thus shield the surface of the earth from some of the heat of the sun. A clear hot sunshiny day has been described as one favorable to convection currents and to a rapid rise of the agent from the ground. An overcast or cloudy day is less favorable for the development of rising air currents, and hence the agent will stay near the surface of the earth for a longer period of time. A sunshiny day, then, is unfavorable to the success of chemical attacks and a cloudy day is favorable.

Precipitation

Effects of Precipitation on Chemical Warfare. *Persistent Agents.*—Heavy rain is unfavorable to the successful use of any chemical agent. Under this weather condition the cloud of any agent will be washed from the air and beaten to the ground. Even the liquid agent, such as mustard, will be washed away, hydrolized, and destroyed.

Nonpersistent Agents.—The concentration of clouds of other agents such as phosgene and chlorine is immediately lowered by rain. Snow and hail, to a lesser extent, act in the same way.

Irritant Smokes.—These agents not being hydrolized, light rains and mists are not especially unfavorable and may even be of assistance in hiding the characteristic color of the cloud. Heavy precipitation, however, is unfavorable in the case of irritant smokes. Heavy rains wash the agent from the air in the same way that they clear the air of

other dust particles. Heavy snow will also remove toxic smokes from the air by coming in contact with the smoke particles and carrying them to the ground.

Screening Smokes.—For the same reasons that a high humidity is favorable for the use of the screening smokes, so also are light precipitation, fogs, and mists. These furnish the necessary water for the hydrolysis reaction. Also under conditions of fog, light rain, or mist, visibility will be very much restricted and hence the amount of screening smokes necessary to obtain a desired end will be reduced. This is due both to the obscuring power of the mist and to the increased efficiency of the smoke in the damp air. On the other hand, here again heavy precipitation tends to beat the smoke cloud down and wash it from the atmosphere.

Humidity

Humidity is defined as the state of the atmosphere as regards moisture. If the air were absolutely dry, its humidity would be spoken of as zero. It is the humidity, as much as the temperature, which makes one uncomfortable on a hot sultry day. A moist hot day in summer is much more oppressive than a dry hot day because the moisture in the atmosphere prevents that free evaporation of the perspiration from the human body which cools it. The cold is also more penetrating on a damp day than on a dry day. The reason is that the moisture makes the clothing a better conductor of heat and hence the body is cooled faster. *Absolute humidity* is defined as the actual quantity of moisture present in a given quantity of air. It may be expressed in grains per cubic foot or grams per cubic meter. By *relative humidity* is meant the ratio of the actual amount of water vapor present in the atmosphere to the maximum quantity it could hold without precipitation. Relative humidity is always expressed in percentage.

Effect of Humidity on Chemical Warfare. *Persistent Agents.*—The humidity of the air will have no appreciable effect on the persistent agents regardless of how they may be released.

Nonpersistent Agents.—The nonpersistent agents are very slightly hydrolized by water vapor in the air. Phosgene shows the greatest effect in this, but even it is not greatly attacked. Thus the first part of a phosgene cloud moving through an extremely damp atmosphere will have a slightly lower content of phosgene than the following portions of the cloud, but still the cloud as a whole will be effective.

Irritant Smokes.—These agents are not affected by the amount of water vapor in the air, since the agents hydrolize very slowly.

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Screening Smokes.—These agents are made much more effective by a high absolute humidity in the surrounding air. Since the initial chemical reaction generally produces a compound which is readily hydrolized and which in being hydrolized is broken into still smaller particles, the cloud becomes more effective on damp days. It is not necessary in the field, however, to make measurements of the humidity because the other weather conditions favorable to smoke screens are usually accompanied by a sufficiently high humidity. If humidity is low and other conditions are favorable, a satisfactory screen may be maintained by firing a somewhat greater quantity of agent.

Atmospheric Pressure

The pressure of the atmosphere is simply the weight of the column of air above the station in question, extending to the limits of the atmosphere. Atmospheric pressure thus diminishes with elevation above the earth's surface because there is a smaller quantity of air to exert a downward pressure. We are probably less conscious of atmospheric pressure and its changes than of any of the other weather elements. In meteorological work the pressure of the atmosphere is usually expressed in terms of inches of mercury. Thus a pressure of 30 in. means that the pressure of the atmosphere is the same as the pressure exerted by a column of mercury 30 in. long.

Effects of Pressure on Chemical Warfare.—Pressure has no appreciable effect upon any of the chemical agents except insofar as it controls vertical air currents and winds. The winds tend to move from highs toward lows, and the greater the change in pressure, the stronger the winds which may be expected.

Rising air currents are unfavorable since they cause the cloud of agent to be carried upward, in spite of its weight, and to rise over the heads of the enemy and be carried away. Rising air currents are often formed when the pressure is low, and they tend to follow the center of the low area.

Descending air currents are to be desired. These are often found when the pressure is high, and they tend to accompany high areas in their movements. In the presence of these currents the air tends to carry the agent downward and thus holds the cloud close to the surface of the earth where it is most effective.

MILITARY APPLICATION

Now that the basic principles of chemical action have been broadly outlined, there remains to be considered the manner in which chemical agents are employed in battle.

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Viewing the typical modern battlefield in panoramic plan, each military arm may be regarded as responsible for definite areas which are largely delimited by the ranges of the weapons of that arm. Infantry, for example, is directly concerned to a distance of say 1,000 yd. to its front, which is about as far as infantry rifles are practically effective. Chemical troops operate in the next zone out to about 2,500 yd. from the front lines. Light artillery can reach well beyond this limit and therefore is concerned with areas up to about 8,500 yd. beyond its own front lines. Beyond this zone the longer ranges of corps and army artillery come into play, extending the depth of attack to 15,000 yd. Attack aircraft employing chemicals usually cover the enemy's combat zone to a depth of about 15 miles. Bombardment aircraft are seldom utilized within the effective range limits of artillery, but beyond this may be employed so far as cruising radii permit (about 1,150 miles). Flanks are usually given over to mechanized cavalry, which may be expected to penetrate for considerable distances within enemy territory (see Diagram I, Chap. III). Weapons appropriate for the dispersion of chemical agents are characteristically employed in each of these distinct areas of military action.

Within their range (2,500 yd.), the special weapons of the chemical troops afford most effective and efficient means of laying down chemical concentrations. For this reason, chemical troops are attached to the front-line infantry units in the attack and render close support by accompanying them in the advance and treating the vital zone directly in front of the attack with concentrations of gas and smoke upon targets most threatening to the advancing infantry.

The zone next beyond that covered by chemical troops' weapons is treated by the divisional artillery with chemicals as well as high explosives. Medium and heavy artillery of the corps and army are then called upon to disperse gas and incendiary agents at longer ranges; aircraft utilize the same agents in operations which in most cases may be termed *self-completing*, *i.e.*, they are not dependent upon ground force for consolidation and exploitation. To support and supplement the action of mechanized cavalry, special chemical troops are attached and act as components of these units, dispersing smoke and both persistent and nonpersistent gases.

Means for employing of chemical agents in military operations are therefore characterized by considerable flexibility, and properly so, because the successful use of the chemicals in battle often hinges on natural and tactical circumstances not predictable long in advance. The infantry and cavalry are thus not encumbered by chemical weapons, but are supported within their immediate zones by the attachment of chemical units from higher tactical reserves when the need for them

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arises; the supporting arms—artillery, air and chemical—are habitually provided with suitable chemical munitions which permit the establishment of appropriate concentrations of chemical agents in the areas with which they are particularly concerned.

So the chemical arm has been assimilated into the organic structure of modern armies without necessitating material changes in their basic organization. But the use of chemicals in combat has brought about the extension of military action into the fourth dimension, thus completing a cycle of evolution that has witnessed battles successively waged with fists, clubs, arrows, bullets, and molecules.

By means of molecular "bullets," man has finally learned the secret of waging war in such manner as to temper the blows of battle with something of the nicety of a skilled anesthetist. For, among chemical agents, it is actually practicable to select those that vary in effect all the way from simple lacrimation to quick death; it is thus within the range of possibility to conduct a virtually deathless war with chemicals—a result entirely beyond the scope of explosive munitions or any other military agents heretofore devised.

As to those gases that are potentially lethal, we know with certainty what the expectancy of fatalities per hundred casualties will be under any given conditions, while complete recoveries from nonfatal gas casualties are surprisingly high. In fact, the military value of chemicals derives not from their deadliness per se, but from their direct influence upon tactical situations, from their effect upon military units rather than on

individuals.

The gradations with which this effect may be exerted are wide, thus affording a flexibility never previously attainable in weapons of warfare. The laws of diffusion and dilution of gases, and of the travel of gas clouds in the field, have been carefully determined and have been found to be as definite and exact as the laws of ballistics, so that, while effective concentrations of gases may be extended over wide areas, such concentrations may also be carefully delimited so as never to extend beyond the areas intended to be gassed. Moreover, within a specific area concentrations may be strengthened or reduced according to the nature of the task at hand. *Controlled effect*, resulting from technically correct application, is therefore a novel and outstanding characteristic of chemical warfare.

From this it follows as an underlying principle of chemical action that any sizable gas attack, delivered with due regard to tactical and technical considerations, may be depended upon to produce predictable military results. In subsequent chapters is to be found an elucidation of the corollary principle that the number of outright casualties so inflicted upon an opponent will be increasingly high in proportion to his deficiencies in gas discipline.

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CHAPTER II

TECHNICAL AND TACTICAL REQUIREMENTS OF CHEMICAL AGENTS

The total number of compounds known to chemical science has been variously estimated at from 300,000 to 500,000. Of these, some 200,000 have been studied to the extent that their principal properties are of record (8). As nearly all chemical compounds exert some toxic effects (either local or general) upon the body, it is not possible to estimate with accuracy the total number of toxic substances. However, several thousands of compounds have such pronounced toxic properties as to bring them distinctly within the field of toxicology, and their toxic powers are well known.

From this vast field, over 3,000 chemical compounds were selected and investigated for use as chemical agents during the World War, but only about 30 were found suitable for actual use in the field. From this group, about a dozen were finally adopted and used extensively as war agents, and of these not more than half were notably successful. This may seem remarkable when it is recalled that the combined efforts of the world's leading chemists were intensively concentrated for nearly four years on the problem of finding and producing the most effective chemical agents. The reason for this apparent meager return for the effort expended is found in the many exacting requirements which a chemical substance must meet before it can qualify as a successful chemical-warfare agent.

These requirements may be logically considered in two groups—(1) technical and (2) tactical. The technical requirements are those concerned with the problems of quantity production and utilization in the various forms of chemical munitions; the tactical requirements are those involved in the effects produced on the field of battle.

TECHNICAL REQUIREMENTS

Since the technical requirements for chemical agents are common to all the classes, *i.e.*, gases, smokes, and incendiaries, these requirements will be considered without distinction as to class of agent.

Raw Materials.—To be effective in war, chemical agents must be used in enormous quantities, and hence the raw materials from which these agents are made must receive first consideration. It is obvious

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that before a chemical substance is adopted for use in war, the raw materials from which it is manufactured must be available in the quantities required for, no matter how militarily effective a substance may be, it should not be adopted as a chemical agent unless it can be made in sufficient quantities from materials that are available under war conditions. Thus, if a chemical compound requires for its manufacture one or more ingredients which *cannot* be produced in quantities from domestic materials, dependence must be placed on importation from some foreign country. Such a source of supply may be cut off in war, for even neutral sources of supply will be unavailable if control of the sea or intervening land areas is lost.

For certain critical materials which are not required in prohibitive quantities and are stable in long storage, it is possible for a government to acquire in time of peace a sufficient stock to last through the duration of a war. Such cases will be exceptional, and we may therefore lay down as a first requirement that the raw materials for a chemical agent should be available from domestic sources. This requirement at once rules out a vast field of possible compounds depending upon the extent of the domestic resources of a country.

Ease of Manufacture.—Of hardly less importance than availability of raw materials is the next general consideration—ease of manufacture. No matter how effective a compound may be on the field of battle, if it is difficult to make, there is always the serious threat of failure of supply under war conditions. Complicated chemical processes require highly skilled personnel to carry them put successfully, and such personnel is difficult to make available when the whole industrial machinery is in high gear to meet mobilization demands. Moreover, special apparatus and equipment are frequently needed in the more complex chemical processes, often limiting production.

A classic example of the difficulties and delays, encountered in attempting to produce a chemical agent that involves a complicated process of manufacture, is mustard gas. Notwithstanding that a process of making mustard gas had been worked out by Victor Meyer years before the war, France was unable to manufacture mustard and use it in retaliation against the Germans for nearly a year while England did not use it until after 15 months of intensive effort. Even when the Allies did produce mustard gas they had to make it by a much simpler process than that used by the Germans.

Simplicity in production not only makes far less demands on the chemical industry but immensely simplifies the supply problem in war. Simple processes can easily be completely performed in one plant, thus avoiding unnecessary transfer of intermediates from one plant to another with the attendant confusion and difficulty of coordinating production.

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Chemical Stability.—The next most important general requirement is perhaps chemical stability under all conditions of storage. Many compounds otherwise suitable for chemical warfare react with iron and therefore cannot be stored either in bulk in steel tanks, or in ordinary shells, bombs and other projectiles. This seriously detracts from the value of the compound for war purposes since it necessitates special linings of lead, porcelain, etc., in all containers and munitions into which the chemical is filled.

The most effective lacrimators used in the war were bromine compounds, and these were not stable in contact with iron and steel containers. Much time and effort was therefore expended in developing and producing special linings for all receptacles for these gases.

The production of satisfactory linings in this country proved to be such a formidable task that immediately after the war the United States Army developed a new tear gas (CN) which did not contain bromine and was stable in long storage under all conditions.

Hydrolysis.—Closely associated with chemical stability is the matter of hydrolysis. If a compound hydrolyzes in contact with water it not only greatly reduces its effectiveness in the field but seriously complicates its storage and loading into munitions. Since water vapor is always present in the atmosphere, compounds that hydrolize must be completely protected from contact with the air in storage and also special precautions must be taken in loading such chemicals into shells and other projectiles.

Thus, phosgene slowly hydrolyzes in contact with water; hence, when filling phosgene into shell, great care must be exercised that the cavity of the shell is absolutely dry before filling. Even water vapor from the air condensing on the inside walls of the shell may be sufficient to hydrolize the phosgene and break it down into hydrochloric acid which at once attacks the steel walls of the shell body.

Polymerization.—Another form of chemical instability which is frequently fatal to the use of a compound as a chemical agent is polymerization. When a chemical compound polymerizes, it usually changes into a substance which has radically different physical and physiological properties. Thus a chemical compound may be a very active lacrimator in

one form while its polymer will have no lacrimatory power at all, so that, if polymerization occurs after filling into munitions, such a compound will be useless in the field. This was the difficulty with the French tear gas "Papite" used in the war. Chemically, "Papite" is acrolein (CH_2:-CHCHO) and is a rather powerful lacrimator in its primary form. In storage, however, it polymerizes into a secondary form which has little or no lacrimatory power. Hence this substance was subsequently abandoned as a chemical agent.

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Dissociation.—An important requirement of a chemical agent, when used in projectiles, is capacity to withstand the heat and pressure of dispersion from strong thick-walled containers (such as artillery shell) without decomposition or dissociation.

In order properly to open an artillery shell and effectively release its chemical contents, a high-explosive charge is used. Upon explosion, temperatures as high as 3,000°C. are created while pressures as great as 80,000 lb. per square inch are generated in the shell. Many compounds that are perfectly stable at ordinary temperatures and pressures will break down and decompose under the high temperatures and pressures generated upon explosion of the bursting charge.

In some cases, the decomposition upon explosion may be complete, as when chlorpicrin is used with a large bursting charge. Here the loss is complete, and such compounds cannot be employed in projectiles which require heavy bursting charges to open them.

In other cases, only a partial destruction of the chemical filling results, as when too large a bursting charge is used with volatile gases, such as phosgene. But to the extent of the decomposition involved, the efficiency of the shell is lowered. To avoid such losses, a shell of lower tensile strength and a low-temperature type of explosive charge may be used. Such shell of cast iron and semisteel were employed by the British and French during the war. But the capacity of these shell was much less than that of the steel shell so that the net gain was not great. Another solution was the thin-walled steel shell which could be opened with a smaller explosive charge. In any case, however, compounds which tend to break down at elevated temperatures and pressures involve limitations and technical difficulties that make it very desirable to find substances that are unaffected by such conditions.

Another form of decomposition is inflammability. If a chemical filling ignites upon explosion and is consumed in flames, its physiological effect is lost; so it is obvious that a prime requisite of a chemical agent for use in bursting munitions is capacity to withstand the temperatures and pressures of explosion without dissociation through burning.

Physical State.—Chemical compounds may be either solids, liquids, or gases at ordinary temperatures. If gaseous at ordinary temperatures, it is essential that the compound be capable of being held in a liquid state under moderate pressures, since the quantity of a *gaseous* substance that can be contained in an ordinary projectile is negligible. Chlorine and phosgene are examples of substances that are gaseous at ordinary temperatures under atmospheric pressure, but these gases may be held in the liquid state under moderate pressures which can be maintained in ordinary projectiles. On the other hand, such compounds as hydrocyanic acid and carbon monoxide, while extremely toxic, cannot be liquefied

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at ordinary temperatures with moderate pressures, and hence these gases cannot be used successfully in projectiles. Accordingly, we may lay it down as a basic requirement that chemical agents must either be solids or liquids at ordinary temperatures and under moderate pressures.

As between solid and liquid chemical agents, the solids are generally to be preferred as shell fillers since solids have many advantages over liquids in projectiles. If the chemical agent is a solid, the cavity in the projectile may be completely filled, as in the case of high-explosive filling, and there is then no difference in ballistic behavior between such chemical shell and H.E. shell. On the other hand, if the chemical agent is a liquid, the shell cavity cannot be completely filled but a certain percentage of empty space must be left in the shell to permit expansion of the liquid with rise in temperature. The void thus left in the shell affects its ballistic characteristics, and the general experience in the war showed that liquid-filled shell had to be fired with special range tables. But whether or not special range tables are required for liquid-filled shell, it is certain that the behavior in flight of liquid-filled shell differs from solid-filled shell. This difference is bound to be reflected in the dispersion of shots and the impact patterns obtained. This problem will be further considered in a later chapter on artillery shell.

Liquids have one possible advantage over solids as chemical fillings for projectiles in that they are generally more easily dispersed on the opening of the shell. As a rule, solids require a greater bursting charge to disperse them effectively, and the solid particles resulting do not disseminate into the surrounding air so readily as the vapors generated by liquid fillings.

Boiling Point.—Among the liquid chemical agents those with the higher boiling points and lower vapor pressures are preferred. In general, the higher the boiling point, the lower the vapor pressure at ordinary temperatures and the less the pressure generated in the container in storage. Hence, generally, a smaller void may be employed in filling the shell and less leakage is apt to occur in storage and handling. On the other hand, the higher the boiling point, the greater the explosive charge required effectively to disperse the substance, and the less chemical will be contained in the shell.

Another factor of great importance in connection with the boiling point is the difficulty of filling the shell. A chemical whose boiling point is below ordinary summer temperatures, *e.g.*, phosgene (b.p. 47°F.), must be artificially cooled and held below its boiling point during the filling operation. This requires refrigeration facilities for precooling the empty shell and bulk phosgene and greatly complicates the process of filling.

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Melting Point.—While not so important as boiling point, the melting point of a chemical agent is often of considerable importance if this point occurs within the range of ordinary atmospheric temperatures. Thus, the melting point of pure mustard gas is about 57°F., so that mustard is a liquid in summer when the temperatures are above 57° and a solid in winter when the temperatures are below that point. In order to secure uniformity in ballistic effects and dispersion, it is necessary to keep the chemical filler in one physical state and, since it is impracticable to keep it as a solid above its melting point, it is necessary to keep it as a liquid at ordinary temperatures below its boiling point by the use of solvents. Concerning this use of solvents, Fries, gives the following interesting data from the World War:

> In order that the product (mustard gas) in the shell might be liquid at all temperatures, winter as well as summer, the Germans added from 10 to 30 per cent of chlorbenzene, later using a mixture of chlorbenzene and nitrobenzene and still later pure nitrobenzene. Carbon tetrachloride has also been used as a means of lowering the melting point. Many other mixtures, such as chlorpicrin, hydrocyanic acid, bromacetone, etc., were tested, but were not used. The effect on the melting point of mustard gas is shown in the following table:

MELTING POINT OF MUSTARD-GAS MIXTURES

Per cent added	Chlorpicrin		Chlorbenzene		Carbon tetrachloride	
	°C.	°F.	°C.	°F.	°C.	°F.
0	13.9	57	13.9	57	13.9	57
10	10.0	50	8.3	47	10.0	50
20	6.1	43	6.1	43	6.7	44
30	2.8	37	−1.1	30	3.3	38

While the difficulties of melting points in the range of ordinary temperatures can be solved by the use of solvents, all these additional steps greatly complicate production and reduce the efficiency of chemical agents.

Specific Gravity.—Substances used as chemical agents during the war varied greatly in specific gravity. Some were lighter than water while others were nearly twice as heavy as water. This large variation in weight creates filling difficulties. On the other hand, all the high explosives ordinarily used as shell fillers closely approximate a specific gravity of 1.5 so that different kinds of explosive charges introduce little variation in the weight of loaded H.E. shell. As it is desirable that all shell be brought to the standard weights, for which range tables are calculated, the nearer a chemical filler approaches the mean H.E., specific gravity 1.5, the less variation there is between the chemical and H.E. shell; also the difficulties of filling chemical shell are fewer.

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Vapor Density.—Regardless of whether the chemical agent is a gas or a smoke, it must have a vapor density greater than that of air for otherwise, as soon as the agent is released from its container, it will immediately rise from the surface of the ground and thus lose its physiological or obscuring effect.

All the principal chemical agents used in the war met this requirement except hydrocyanic acid, the vapor of which was only 0.93 times as heavy as air. In consequence of its light vapor, this substance proved very disappointing in battle, although it is physiologically one of the most deadly gases known to chemists. Carbon monoxide is another very toxic gas which cannot be used in battle chiefly because its vapor density is less than air. Although the various substances used as chemical agents in the war varied only about twofold in specific gravity in their solid or liquid forms, they varied nearly tenfold in vapor density. Thus, the lightest gas used was HCN with a vapor density of 0.93, while one of the heaviest gases used, DA, has a vapor density of 9.0. The average vapor density of the more important agents was about 5.0.

In general, the heavier the vapor, the better it will cling to the ground and roll into depressions, dugouts, and trenches thus exerting a more intensive and lasting effect upon men taking shelter in such places.

As regards vapor density of a substance, we may say that it must at least be heavier than air and the heavier it is, the better its substance is suited for use as a chemical agent.

TACTICAL REQUIREMENTS

Under the heading of Technical Requirements, we have reviewed the essential qualities which chemical agents must possess in order that they may be manufactured and loaded into projectiles in sufficient quantities to meet the vast requirements of modern war. We now come to a consideration of those properties which chemical agents must possess in order to exert the effects required in battle. These we call *tactical requirements*. As the tactical effects of gases are markedly different from smokes and incendiaries, it will be more convenient to consider the tactical requirements of each of these three classes of agents separately.

Gases

We shall begin with the gases and note first those requirements which apply particularly to the gases used on the tactical offensive, as these are the most exacting requirements.

Toxicity.—In general, it may be said that, for the lethal and casualty-producing gases, toxicity is probably the most important requisite. Since the casualty effects of most gases are in direct proportion to their toxicities, it follows that the more toxic the gas, the more effective and

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efficient it is as a chemical agent. Or, stated in another way, the same casualty results can be produced with decreasing quantities of the agent and with shorter periods of exposure, in proportion as its toxicity increases. This follows from Haber's generalization that toxic effect is proportional to toxicity times exposure time (see page 12). Perhaps the only exception to this toxicity requirement is in the case of the lacrimators, where toxic effects are not desired but where temporary incapacitation over the widest area with the minimum expenditure of chemicals is the prime consideration. Such a result, however, is hardly a war requirement but belongs more properly to the class of agents suitable for quelling domestic disturbances. Indeed, with far more effective agents available for general harassment of troops in war, it is difficult to foresee the future use of lacrimators in battle, although they undoubtedly will continue to be widely used in war for the training of troops behind the lines.

With the exception of lacrimators, we may say that toxicity is a fundamental requirement of all battle gases. High toxicity alone, however, does not necessarily make an effective casualty agent on the field of battle, as many other factors enter into the final effect. This fact was not sufficiently appreciable in the early years of the war and many very costly mistakes were made. Thus, the French were deceived into adopting HCN as a toxic shell filler by the extremely high toxicity of this gas in laboratory tests. However, owing to the fact that it is extremely volatile in the open air and that its vapor is lighter than air, it proved to be almost impossible to set up effective concentrations in artillery shoots with these shell. Another peculiarity of HCN is that, unless its concentration exceeds a certain critical figure, it is almost harmless. These two peculiarities made the French Vincennite (HCN) shells one of the most outstanding failures in chemical warfare during the war.

Multiple Effects.—Next to toxicity, the manner in which a gas exerts its action upon the body is the most important tactical consideration. Many gases have more than one mode of action. Thus, chlorpicrin is both a lacrimator and a lung-injurant gas so that both the eyes and lungs must be protected from this agent. Dimethyl sulfate (German D-Stoff) is both a lacrimator and a vesicant, and the eyes as well as the body must be protected; mustard gas has a triple effect, being a vesicant, lung injurant, and lacrimator combined. Hence mustard is the most difficult gas to protect against and for this reason it is one of the most valuable tactical agents.

In general, the more extensive the mode of action of a gas, *i.e.*, the greater the number of physiological effects it produces, the more valuable it is from a tactical viewpoint.

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Persistency.—Since the toxic effect of a gas is a product of its toxicity and time of exposure, the next most important requirement for a casualty-producing gas is its persistency. By persistency is meant the duration of time an agent will remain around its point of release in an effective concentration. It is obvious that, no matter how toxic a gas may be, if it is so volatile that it lasts only a few seconds after being released, it cannot produce worth while casualty effects. Persistency is a function of the boiling point of a substance. That is, the higher the boiling point, the slower the liquid will evaporate and the longer it will persist in the field. Also, since volatility is a measure of the rate at which a liquid evaporates, persistency is an inverse function of volatility, and the more volatile a liquid is, the less persistent it will be.

Duration of Effects.—Assuming that the primary object of battle is to defeat the enemy by inflicting upon him, not fatalities, but rather non-fatal casualties of as long duration as possible, those chemical agents which produce the most lasting casualty effects are the most efficient. In this requirement, mustard is the most efficient chemical agent that was used in the war, as it produced slow-healing wounds but was fatal in only a small percentage of casualties.

Speed of Action.—The next most important tactical requirement is rapidity of action. Some substances act with remarkable speed in producing effects upon the body while others act very slowly, and their effects are not noticeable until many hours after exposure. Thus, HCN acts with almost lightning rapidity when present in lethal concentrations. One or two full breaths of this gas are sufficient to cause instant collapse and death within a few minutes. On the other hand, mustard gas is very slow acting and, in usual field concentrations, does not produce noticeable symptoms until several hours after exposure.

Regardless of the type of gas, it is obvious that the quicker it produces its effects, the sooner it secures the desired tactical results. Gases that are intended for casualty effects on the offensive must obviously be quick-acting and bring about incapacitation during the attack which may last only a few minutes. For this reason, mustard gas, which does not incapacitate for several hours after exposure, is unsuitable as an offensive gas and would be of more general value as a war gas if its speed of effect were greater.

Insidiousness.—If a gas produces uncomfortable or painful physiological effects upon first exposure to it, men will at once be aware of its presence and take measures to protect themselves and thus render ineffective the power of the gas. On the other hand, if a gas is insidious in action and produces no warning discomfort during the necessary period of exposure, it will exert its full casualty effect before countermeasures can be taken. Obviously, therefore, the more insidious the action of a

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gas, the greater its surprise effect and tactical value. Moreover, the slower the action of a gas in producing its physiological effects, the greater the need for insidiousness in action. Thus, mustard-gas vapor is effective in low concentrations only after several hours' exposure, so that, if it were not insidious in its action and difficult to detect in low concentrations, troops would not remain exposed to it for a sufficient time to become casualties. But because mustard-gas vapor is both insidious in action and almost impossible to detect in low concentrations,

it has a high casualty power, although it is slow in action and although its effects do not manifest themselves for several hours after exposure.

Volatility is also an important property of a casualty gas since it determines the maximum concentration which can exist in the open air at any given temperature. In general, liquids of low boiling points and high vapor pressures build up much heavier concentrations in a given volume of air than liquids with high boiling points and low vapor pressures. In fact the maximum concentration that can be held in the air (saturation point) is a direct function of the volatility of a substance (see definition on page 8). The mathematical relations between persistency, volatility, and vapor pressure are shown by the formulas in Appendix A.

The foregoing remarks concerning volatility apply particularly to the lethal or casualty-producing gases. With the neutralizing gases, such as mustard, and the harassing gases, such as DA, where immediate casualty effects are not primarily sought, the best tactical results are secured by maintaining a low concentration on the target area for a maximum period of time, and persistency then becomes of paramount importance. The principal requirements for the neutralizing and harassing gases are, first, great persistency and, second, effectiveness in low concentrations over long periods of time.

Penetrability.—Other things being equal, the greater the power of a gas to penetrate the enemy's masks, protective clothing, and other means of chemical defense, the greater will be the offensive power and tactical value of the gas. It has been estimated that the mere wearing of a mask (even of the latest improved type) reduces the physical vigor of troops about one-fourth. The addition of protective clothing still further reduces the physical activity and stamina of troops and thus greatly impairs their fighting ability. The greater the penetrating power of a gas, the more elaborate must be the protective equipment of the enemy with a corresponding reduction in this combat power. Hence, the penetrability of a gas is an important factor in its tactical value.

Invisibility.—Regardless of the type or kind of gas, it is generally agreed that it is most effective in the field when used as a surprise. The more difficult a gas is to detect by the senses, the more readily men are taken unawares—hence the importance of invisibility, which prevents

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troops from seeing the approach of a gas cloud and perceiving the extent and limits of its concentration.

Odorlessness.—Next to visibility, gas concentrations are most usually detected in the field, especially at night, by the characteristic odor of the agent. The more nearly odorless the substance is, the more deadly is its surprise effect.

Smokes*

* The smokes here considered are the nontoxic screening smokes. Toxic smokes are tactically the same as casualty gases except with regard to visibility.

***Total* Obscuring Power.**—Passing now to a consideration of the second class of chemical agents—the smokes—we find quite different tactical requirements. Since the purpose of a smoke is to obscure vision, conceal terrain, and not to cause casualties, there is no necessity for a smoke to be odorless, while visibility or rather obscuring power is a fundamental requirement. Smokes are generally rated on the basis of their total obscuring power (T.O.P.). Total obscuring power is a function of the opacity of the smoke particle and its density per cubic foot of air. More specifically, the total obscuring power of a smoke is the product of the volume of smoke produced per unit weight of material and the density of the smoke. Chemical agents vary greatly in obscuring power and only those with high total obscuring powers are suitable as screening smokes.

Persistency.—Next to total obscuring power, persistency is the most important requirement for a smoke agent. The more persistent a smoke is, the less material is required to maintain a screen for a given time, and hence the more effective and economical the agent is.

Capacity.—The third requirement for a smoke agent is its smoke-producing capacity per pound of agent. Smoke-producing chemical compounds vary greatly in their output per unit of material and the compound which produces the greatest quantity of smoke per pound of material is the most efficient.

Density.—The next most desirable property for a smoke is density, or specific weight relative to air. It is obvious that the heavier the smoke is, the less it will rise from the ground and the better it will cling to and cover the areas to be screened, so that density or heaviness is an important requirement.

Harmlessness.—Another important requirement for a screening smoke is that it should exert no deleterious effect upon personnel, since smoke is frequently used to envelop friendly troops for their protection. If a smoke is irritating, the time during which troops can be blanketed is reduced and the effect upon the morale of the troops is adverse, even if no undesirable physiological effects are produced.

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Temperature.—Other things being equal, a cold smoke is preferable to a hot one, for the hotter a smoke is, the more it will tend to ascend in the air, and the less its screening value will be. For this reason, smokes which are the products of chemical action, such as hydrolysis (*e.g.*, FM) possess certain advantages over smokes which are the result of combustion, as burning-oil smoke.

Color.—White smoke in most terrains blends better with the horizon line and is preferred to black or colored smokes for general concealment.

Incendiaries

The purpose of incendiary agents is to destroy enemy material by conflagration. Accordingly, the fundamental requirement of an incendiary agent is that it have the capacity to set fire, under the most adverse conditions encountered in the field, to whatever targets it is employed against.

Temperature.—The first tactical requirement of an incendiary agent is that it generate within its own substance an extremely hot fire, preferably one emitting flames. The higher the temperature generated by the incendiary substance, the greater its capacity to set fire to target material of low inflammability.

Time of Burning.—The next requirement is one of time of burning. The longer an incendiary agent burns, per pound of material, the longer it will sustain initiating fires and the greater will be the chances of igniting the material against which it is employed.

Unquenchability.—A military incendiary agent should also preferably be unquenchable by water, as water is generally the only means available in the field for putting out fires.

Spontaneous Combustion.—From a tactical viewpoint, spontaneous combustion is a distinct advantage in an incendiary material, since all that is necessary to use this material for initiating fires is to spread it over the target area and spontaneous combustion will create the desired results. From a technical viewpoint, spontaneous combustion is advantageous in that such a material does not require a fuse and special igniting charge with the resulting complications that these elements involve. On the other hand, technical difficulties in storage, handling, and filling into projectiles are created when an incendiary agent is spontaneously combustible, and these must be carefully weighed against the above advantages.

Extinguishment in Flight.—If an incendiary agent is to be used in a scatter-type projectile, *i.e.*, where the incendiary charge is to be scattered over a large target area, an additional requirement is demanded of the incendiary material, *viz.*, the burning particles must not be extinguished in flight after burst of the projectile. This is a very difficult requirement

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to meet unless the incendiary material is spontaneously combustible for the reason that there is always a critical velocity above which a burning particle cannot be projected through the air without extinguishing its flames. This was the principal reason for the failure of the early types of incendiary bombs which were dropped from the German Zeppelins on London and Paris. These bombs were made of nonspontaneously combustible materials and were ignited, either on release from the bomb rack or by a time fuse after a short period of flight. The bombs would then burst into flames while high in the air. The increasing velocity acquired during the remainder of their fall would exceed the critical flame velocity and extinguish the flames from the bombs before they reached the ground.

The same difficulty occurred with the early types of incendiary artillery shell which were constructed on the shrapnel principle. It was found that when these shell burst they expelled their contents (as lumps

of burning incendiary materials) at such high velocities as to extinguish the flames from the lumps. Consequently, if an incendiary material is not spontaneously combustible, it must be able to maintain its fire when expelled from the projectile by the bursting charge so that the incendiary particles will be brought in contact with the target material in a burning condition.

REQUIREMENTS FOR IDEAL AGENTS

Since we have now reviewed the requirements for chemical agents at some length, we may summarize this subject by stating the qualities and characteristics of an ideal chemical agent of each type.

Offensive Gas.—The ideal combat gas for use on the tactical *offensive* should meet the following requirements:

Tactical	Technical
1. High toxicity.	1. Availability of raw materials.
2. Multiple effectiveness.	2. Ease of manufacture.
3. Nonpersistency.	3. Chemical stability.
4. Effects of maximum duration.	4. Nonhydrolyzable.
5. Immediate effectiveness.	5. Withstands explosion without decomposition.
6. Insidiousness in action.	6. A solid at ordinary temperature.
7. Volatility (maximum field concentration).	7. Melting point above maximum atmospheric temperature.
8. Penetrability.	8. Boiling point as low as possible.
9. Invisibility.	9. High vapor pressure.
10. Odorlessness.	10. Specific gravity approximately 1.5.
	11. Vapor density greater than air (the heavier the better).

Phosgene, which is described in detail in Chap. VII, came closer to meeting the above requirements than any other substance. It fell short

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of the ideal requirements chiefly in respect to the following: it lacked multiple effectiveness, being a lung injurant only; except in high concentrations, it was not immediately effective; it was not odorless and, in contact with water vapor in the air, it formed a white steamlike cloud and was thus not invisible; it hydrolyzed slowly with water and hence was not effective on very wet days; being a gas at ordinary temperatures, it had to be artificially cooled to be filled into projectiles. But even with these limitations, phosgene was the best all-round *offensive* gas used in the war.

Defensive Gas.—The ideal combat gas for use on the tactical *defensive* should also meet the above requirements except that it should be persistent rather than nonpersistent and it should be effective in low concentrations.

Mustard gas came close to the ideal defensive gas, being deficient only in the following particulars: it was not immediately effective; it had a faint odor; it was not easy to manufacture; it slowly hydrolyzed in contact with water vapor in the air and with water on the ground; it was a liquid at summer temperatures and a solid at winter temperatures; it had a rather low vapor pressure. But, even with these limitations, mustard gas proved to be not only the best defensive gas but the best all-round casualty agent used in the war.

Harassing Gas.—The ideal harassing gas should have the same requirements as defensive gas but should also be effective in very much lower concentrations in order that it may cover a large area with minimum expenditure of ammunition, and thus justify its use despite low toxicity.

DA was the most effective harassing gas used in the war and fell short of ideal requirements only as to the following: it had only one physiological effect—sternutatory; it was not very persistent; its effects were of short duration, generally a few hours; it was not volatile; it had a detectable odor; it was extremely difficult to make; it had high melting and boiling points and low vapor pressure; it was difficult to disperse in an effective form. Notwithstanding these deficiencies, however, this compound is a very effective harassing agent when used under proper conditions.

The ideal smoke agent should meet the following requirements:

Tactical	Technical
1. High total obscuring power.	Same as for gases.
2. High persistency.	
3. Large smoke-producing capacity.	
4. High specific weight relative to air.	
5. Low temperature of generation.	
6. No harmful physiological effect.	

White phosphorus was the most successful smoke agent used during the war, although it failed to meet the ideal requirements in the following

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particulars: unless used on the progressive burning principle, it was low in persistency; the smoke generated, being lighter than air, tended to rise rapidly from the ground and, also being a product of combustion, the smoke was hotter than the surrounding air, which still further accelerated its upward movement. While the smoke itself was relatively harmless, the vapors generated by the burning particles of phosphorus were very poisonous, although the effects were not manifest until long after exposure. Also the burning particles of phosphorus caused painful wounds when brought in contact with the body so that phosphorus had a very decided casualty power in addition to its obscuring power.

As to technical requirements for smoke shell, phosphorus was very satisfactory, the only difficulties involved with its use in projectiles being those encountered in any spontaneously combustible material. It had to be stored and loaded under water so as to exclude all contact with air, and any leakage in storage and handling immediately caused fires.

However, notwithstanding its limitations, phosphorus was the best World War smoke agent and in many respects remains among the best smoke producers today although many new cold smokes, generated by noncombustible chemical reaction, have been developed since the war to compete with phosphorus as a smoke agent and are better adapted for erecting smoke screens from airplanes.

The ideal incendiary agent should meet the following requirements:

Tactical	Technical
1. High combustibility.	Same as for gases.
2. High temperature of combustion.	
3. Fire unquenchable with water.	
4. Fire not extinguishable in flight.	
5. Spontaneously combustible.	
6. Sustained fire generation.	
7. Combustion with flames.	

The incendiaries used during the war were chiefly of two kinds: (1) the *scatter type* consisting mainly of mixtures of inflammable oils, resins, tar, etc., primed with phosphorus, sodium, and the like; and (2) the *intensive type*, consisting chiefly of thermite and similar metallic chemically reactive mixtures producing intense though highly concentrated fires.

None of the World War incendiaries proved to be outstandingly successful, and much room for improvement remained in this field at the close of the war.

Although primarily a smoke producer, white phosphorus was about as satisfactory an incendiary agent as any material used in the war, although it lacked many desirable qualities.

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In the light of what has been said above as to the many exacting requirements which chemical compounds must meet in order to qualify as chemical agents, it is not difficult to understand why, with many thousands of compounds from which to choose, so few met with success in the World War and why so many of the early chemical agents were failures.

This does not mean, however, that there will not be greatly superior chemical agents in the future. On the contrary, the progress that has been made in chemical-warfare research and development during the few years since the war completely negatives such an idea. Future developments will undoubtedly be along two general lines of effort (1) to find more effective ways and means of using known chemical agents and (2) to find more powerful compounds.

The progress since the war has been mainly in the first field, *i.e.*, improving the ways and means of using known chemical agents. The reason for this is that the full power of successful World War chemical agents was by no means developed by the military technique under which they were employed. There is consequently little advantage in finding more powerful agents while the full possibilities of those already known remain unexploited. For example, it has been determined that 20 mg. (about two-thirds of a teaspoonful) of mustard vapor quickly absorbed into the lungs of a man will cause his death. At this rate, there is enough potential poison in 1 ton of mustard gas to kill 45,000,000

men. Yet, during the last war 12,000 tons of mustard caused only 400,000 casualties, or an average of 33 casualties to every ton of mustard used in battle With this great discrepancy between the potential and actual casualty-producing power of mustard gas, there is little reason to look for still more powerful compounds. On the contrary, if sufficient effort is expended in finding more efficient ways of using it, mustard will undoubtedly yield far greater results. Already two means of using mustard gas have been developed which greatly increase its effectiveness in the field, *viz.*, sprinkling from ground vehicles and spraying from airplanes, of which more will be said in a later chapter.

However, while military effort is being principally devoted to improving field technique in the use of chemical agents, industrial research is constantly discovering and studying new compounds, some of which will undoubtedly prove more powerful than any chemical agents heretofore employed. In fact, so vast is the field of chemistry and so far-reaching are its potential powers that no man will presume to predict its ultimate possibilities in either peace or war. The only certainty in the future is that of *progress;* no government worthy of the name will risk the security of its people by failure to take military advantage of the unremitting progress that has been and will continue to be made in the ever-widening fields of science.

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CHAPTER III

DISSEMINATION OF CHEMICAL AGENTS

To be effective in battle, chemical agents must be properly disseminated over a suitable target area. Dissemination comprises two processes—the delivering of the chemicals to the target (accomplished by *projection*), and the spreading of the chemicals over the target in an effective state (accomplished by *dispersion*). Dissemination of chemicals, therefore, consists broadly of their projection and dispersion.

The various methods and processes of dissemination are considered in this chapter, while the weapons and material utilized for this purpose are treated in Chaps. XIV to XVIII, in connection with the arms to which they pertain.

MEANS OF PROJECTION

During the World War, chemicals were disseminated by every military arm, although the air corps did not use toxic gases. When chemical warfare made its appearance in 1915, there was already a large variety of high-explosive weapons in use. As chemical warfare was born during the war and there was no prewar development of its matériel, the first chemical munitions were hasty adaptations of high-explosive weapons, although subsequent experience showed that some of these weapons were not suitable for chemical dissemination and were every inefficient for this purpose.

The first use of gas in the World War was from hand grenades, which could be thrown about 25 or 30 yd. Owing to their limited range, they could be used only in hand-to-hand combat and frequently exposed the using troops to the chemicals employed almost to the same extent as the enemy. They were, therefore, of advantage only when employed by masked troops against an unmasked enemy. When masks were available to both sides, their general combat effectiveness largely disappeared.

The next step was to put chemicals into rifle grenades which could be projected from 200 to 250 yd. This was still too close to permit the troops using them to employ them without masks and, as masks furnished complete protection against the gases in these grenades, they were not much more effective than the hand grenades. However, when used with smoke fillings, especially white phosphorus, they did afford

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considerable protection to small bodies of infantry in the attack and continued to be used for this purpose throughout the war.

Although chronologically the next use of gas was in artillery shell (in January, 1915, by the Germans on the Russian Front), these shell were a failure and the successful use of gas in artillery shell was not accomplished until the summer of 1915 after the great cloud-gas attacks from cylinders in the spring of 1915. We may, therefore, say that the next development in chemical warfare was the cylinder method of dispersion. The effective range of gas released from cylinders varied greatly with the weather and other local conditions and the numbers of cylinders employed. As a general rule, it may be said that gas clouds were effective to a depth approximately equal to the front from which they were projected, although in several notable instances the effective depth was much greater. As the diffusion and dilution of the gas released from cylinders increase roughly as the cube of the distance downwind from the point of release, very large quantities of gas are required to project effective concentrations for distances greater than 2,500 yd., and we may, therefore, delimit the effective zone of cylinder attacks by this range, except for unusually large operations.

Beginning in the summer of 1915, chemicals were loaded into artillery shell, first of the light calibers, and then of heavier calibers, as the war progressed. By 1917, artillery of all calibers were firing chemical shell although many of the heavier shell were unsuitable for chemical dissemination.

Following the artillery shell, the use of chemicals next extended to the trench mortars, though here again the slow rate of fire and immobility of heavier calibers were altogether unsuitable for chemicals; the lighter calibers did not have shells of sufficient capacity for this purpose.

It was soon found that artillery was not adapted to disseminate chemicals within the zone of infantry combat because of the flat trajectory of the guns, the low chemical capacity of the shell, and the difficulty of placing effective concentrations relatively close to our own front lines, without danger to friendly infantry. Since existing types of trench mortars which normally covered this zone with high-explosive fires were unsuitable for establishing and maintaining gas and smoke concentrations, and since cylinder operations were too limited by adverse winds and weather conditions, the problem of how to cover the infantry combat zone with effective chemical concentrations at all times became very acute.

This problem was finally solved by the British, who first devised special (Livens) projectors which were adapted to fire in one salvo a large number of high-capacity bombs for a maximum distance of 1,800 yd., and thus create extremely heavy gas concentrations within the enemy's

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defensive positions. The chemicals released from Livens bombs were already on the target area and hence did not have to travel across unoccupied terrain with resulting loss of strength, as in the case of gas released from cylinders. The Livens projector was a very effective means of chemical projection and was extensively employed on both sides during the remainder of the war. However, it required much labor and time to install and was adapted for use only in very stabilized situations.

To supplement the Livens projector and to provide a more mobile device which could be used in open warfare, the British also developed a special chemical (4-in. Stokes) mortar, which was a compromise in mobility and capacity between the 3-in. and the 6-in. H.E. mortars. The 4-in. chemical mortar had the same range and rate of fire (20 rounds per minute) and almost the same mobility as the 3-in. mortar and, at the same time, a shell holding nearly three times the amount of chemical. The 4-in. chemical mortar thus had a gas-projecting capacity nearly three times that of the 3-in. mortar and proved to be one of the most valuable means of projecting chemicals devised in the war. Because of its mobility and the fact that it could be used in small and large groups equally well, it was a very flexible weapon well adapted for a wide variety of tactical situations.

The cylinder, projector, and chemical mortar were all used to lay down chemical concentrations in the infantry combat zone. Each was necessary to supplement the other in order to fully cover this important field with chemicals in all tactical situations, and these devices were, therefore, grouped together as special chemical weapons. Because of the skill and special training required to place effective concentrations of gas and smoke in the infantry combat zone, close to friendly troops, it was early found necessary to organize special troops to man these special chemical weapons. These troops were particularly trained in the use of these special weapons and thoroughly understood the capabilities and limitations of each. They were known in the war as *special gas troops* and, while originally organized as engineer units, they devoted their full time to chemical operations and were in fact chemical troops.

Although gas was not disseminated from airplanes during the late war, incendiary and smoke agents were employed in drop bombs early in the war. Since the war, many nations have developed means for employing chemicals from airplanes.

Numerous special chemical devices such as land mines, toxic smoke candles, smoke generators on tanks, etc., have also been developed during the postwar period by many of the principal world powers.

We may summarize the possible means for projecting chemical agents by operating arms as follows:

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Munition	Operating Arm
Smoke generators on tanks Hand and rifle grenades Smoke candles	Infantry and cavalry
Smoke generators, portable Accompanying mortar (81-mm.) smoke	Infantry
Toxic gas cylinders Livens projectors Chemical mortars Chemical sprinklers (mechanized) Toxic smoke candles Flame projectors	Special chemical troops
Artillery shell (Light and medium calibers)	Field artillery
Drop bombs Chemical sprinklers and sprayers	Air corps

With the addition of the postwar chemical armament, there now exists means for disseminating chemicals, not only to all parts of the battlefield, but even to the areas behind the front and as far into the interior of the enemy's country as the cruising radius of bombardment planes will permit.

In order to coordinate all the various means for disseminating chemicals and to insure that each is used to supplement the others in the most efficient manner, the Theater of Operations is divided into zones progressively increasing in depth from the battle front. Diagram I (page 55) shows in schematic form such a zoning of the Theater of Operations.

METHODS OF PROJECTION

Regardless of the technical means employed, there are but three basic methods of placing chemicals on a target area. First, by releasing the chemical from containers installed in one's own front lines, and depending upon the wind to carry it to and over the target area. This may be called the method of release *at origin*. Second, by releasing from containers projected *on the target area* by some physical means, such as firing from a gun (chemical shell), dropping from an airplane (chemical bomb), or placing in position by retreating troops (chemical mines). This is the method of release *on target*. Third, by releasing the chemical from containers carried by airplanes over the target area and depending upon gravity to carry it down to the target area. This is the method of release *over target*.

From what has been said above, we may now summarize the possible methods of projecting chemicals as shown on page 56.

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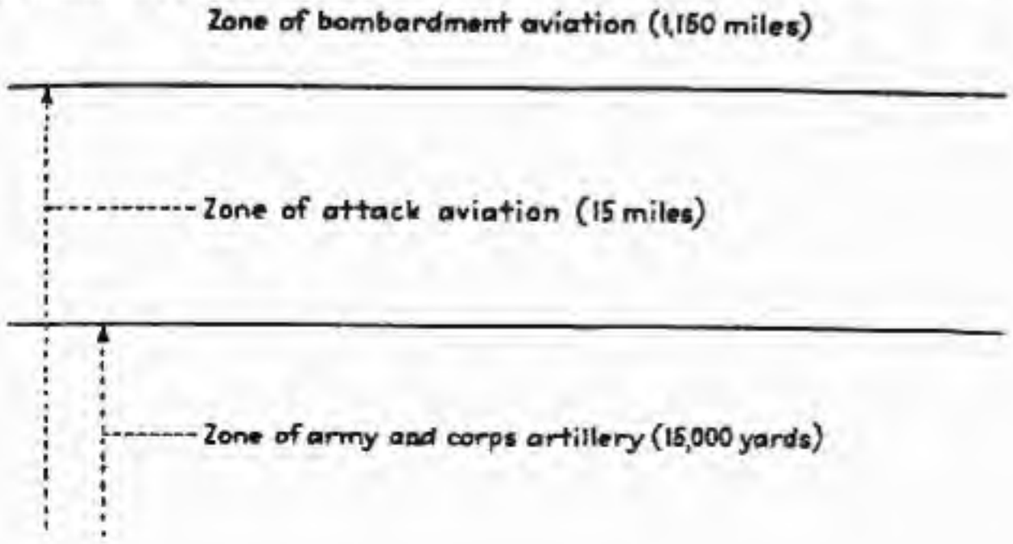
A discussion of the technical means and matériel used for projecting chemicals will be found in subsequent chapters pertaining to the several arms which employ chemicals.



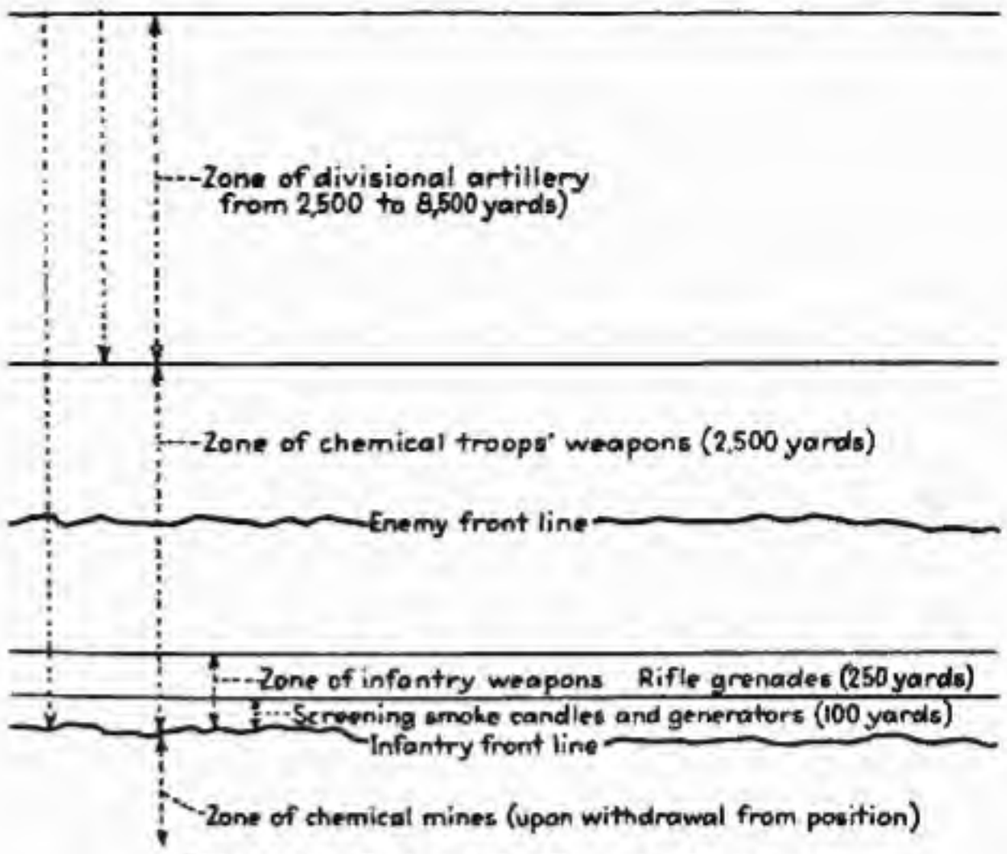


DIAGRAM I.—Zoning of the Theater of Operations.

METHODS OF DISPERSION

In previous chapters we have seen that chemicals to be tactically effective must be brought into contact with the body or the body must be surrounded by a toxic atmosphere in which the concentration of the

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METHODS OF PROJECTING CHEMICALS

Basic method of projection	Technical means utilized	Operating arm of service	Type of chemicals employed	Depth of normal zone covered
Release at origin	Toxic gas cylinders	Chemical troops	Nonpersistent toxic gases	2,500 yd.
	Toxic smoke candles	Chemical troops	Respiratory irritant gases	1,500 yd.
	Screening smoke Candles and generators	Infantry and cavalry	Screening smokes	100 yd.
Release on target	Artillery shell	Artillery	All kinds of toxic gases, screening smokes, and incendiaries	2,500 to 15,000 yd.
	Chemical mortar shell	Chemical troops	All kinds of toxic gases, screening smokes, and incendiaries	2,500 yd
	Chemical sprinklers (mechanized)			
	Livens projectors	Chemical troops	Toxic gas and incendiaries	1,800 yd.
	81-mm. mortar shell	Infantry	Smoke	3,000 yd.
	Hand and rifle grenades	Infantry and cavalry	Toxic gas, smoke, and incendiaries	25 to 250 yd.
	Chemical mines	Chemical troops	Toxic gas	Area evacuated
Release over target	Drop bombs	Air corps	Toxic gas, smoke, and incendiaries	1,150 miles
	Airplane sprinklers	Air corps	Persistent gases	15 miles
	Airplane sprayers	Air corps	Persistent gases	15 miles

In previous chapters we have seen that chemicals to be tactically effective must be brought into contact with the body or the body must be surrounded by a toxic atmosphere in which the concentration of the chemical is at least equal to the minimum effective strength for a given time of exposure. Since troops in battle normally take advantage of all available sheltering cover, it is not ordinarily possible to bring a combat chemical (in its original physical state) directly in contact with the body. This being the case, it is necessary to distribute the chemical as uniformly as possible, in a finely divided form, throughout the atmosphere covering the target area, so as to create a toxic concentration which envelops the unprotected body and penetrates it through the lungs or skin. This is the problem of dispersion.

Physical States.—Under ordinary field conditions, combat chemicals may originally be either solids, liquids, or gases; only a very few (Cl and CG) are true gases; a few (DA, DM, and CN) are solids; the majority are liquids.

Dispersion as a Gas.—If the chemical is a gas at ordinary temperatures [say +20°C. (68°F.)] and atmospheric pressure, its dispersion is easily accomplished. It has only to be released from its container, when it will escape into the air and rapidly permeate it by expansion and diffusion, until a fairly homogeneous mixture is obtained. The problem of dispersion of a gaseous chemical is, therefore, very simple; it being necessary only to release a sufficient amount of the chemical to insure an effective concentration by the time the toxic cloud covers the target area.

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Dispersion as an Aerosol.—The dispersion of liquid and solid chemicals is much more difficult. All liquids and many solids give off some vapor at ordinary temperatures even though their boiling points are far above maximum atmospheric temperatures. These vapors act like true gases and, from a chemical-warfare viewpoint, may be regarded as such.* But the percentage of vapors given off by most liquid and solid combat chemicals under ordinary field conditions is so small as to be practically negligible unless the substance is heated, in which case the larger part, if not all, of the substance may be vaporized and pass off into the air in vapor form. Excepting the few chemicals that are true gases in the field and those that can be readily vaporized at ordinary field temperatures, chemical agents are usually dispersed in the form of exceedingly small solid or liquid particles.

* In physics, a vapor is a gas at a temperature below the boiling point of the corresponding liquid.

As each molecule in a vapor is free to move according to the gas laws, vapors, *in general*, obey the laws of gases and yield with air *homogeneous* mixtures. In smokes, however, the molecules are not free to move individually, but are clustered together in bunches, so that smokes do not rigidly obey the laws of gases, but yield with the air *heterogeneous* mixtures. Such mixtures are *dispersed systems*, comprising a gaseous phase —the air—and a solid or liquid phase—the toxic substance—in very finely divided particles. The most common forms of dispersed systems are those in which a solid or a liquid is dispersed in a liquid. These are *called colloidal solutions*, or *sols*. If the dispersing medium is water, the system is a hydrosol and, if the dispersing medium is air, the system is an *aerosol*. As a colloidal solution is intermediate between a true solution and a suspension of large particles in a liquid, an aerosol is intermediate between a true gaseous mixture and a suspension of large particles in the air. Accordingly, aerosols, although elastic fluids, do not rigidly obey the laws of gases, but closely approximate the properties of colloidal solutions. As chemical smokes are aerosols, they also in general follow the laws governing colloidal solutions.

Regardless of whether the aerosol is a toxic or simple obscuring smoke, the *method* of dispersion is the same and consists basically of the condensation in the air, by a physical or chemical process, of a substance emitted in the state of molecular dispersion. The structure and stability of the aerosols thus obtained are subsequently modified by secondary phenomena, such as: condensation of water on the surface of the minute solid particles or drops, oxydation on contact with the air, or hydration.

Processes of Dispersion.—The *primary dispersion* of the substance may be effected by either a physical or a chemical process.

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Physical Means of Dispersion.—In the *physical* process, three general means are employed: (1) mechanical force, as when a very fine dust is sprayed from an airplane; (2) heat, as when a substance is distilled in the air (from smoke candles); and (3) a combination of force and heat, as when the contents of a chemical shell are scattered by the explosion of a bursting charge.

When *mechanical force* alone is employed for primary dispersion, the substance must be first reduced to an impalpable powder and must also have, when thus finely divided a sufficient vapor pressure to be vaporized on contact with the air.

When *heat* is the means employed for primary dispersion, the solid or liquid chemical is heated and distills into the atmosphere in a gaseous state and then condenses to a dispersed or aerosol state. Certain smoke producers, such as phosphorus, oleum, and chlorsulfuric acid, for example, are dispersed in this manner. The vapors of these substances act as fog producers, for their anhydrides have a strong affinity for water and by hydration form acids which are themselves very hygroscopic. Thus, the sulfuric anhydride (SO_3) in oleum and chlorsulfuric acid reacts with water to form sulfuric acid (H_2SO_4), which in turn absorbs large quantities of water. A smoke composed of liquid droplets, *i.e.*, fog, is in reality a dispersed solution of acid in water.

When *mechanical force and heat* are both employed for primary dispersion, the former scatters the substance in very finely divided form, while the latter volatilizes it and reduces it to the vapor phase.

Chemical Means of Dispersion.—When the primary dispersion is effected by a *chemical* process, two substances in a gaseous state are simultaneously emitted and, by chemical reaction on each other, yield a liquid or solid compound in the dispersed state. Thus, gaseous hydrochloric acid and ammonia yield ammonium chloride in the form of a dense white fume. Similarly, sulfuric acid fumes formed by the hydration of sulfuric anhydride form, on contact with ammonia, ammonium sulfate, another dense white smoke, thus:

$$H_2SO_4 + 2NH_3 = (NH_4)_2SO_4$$

If the products of decomposition are volatile, as in these cases, the reactions are reversible, and we have the general equation

$$\text{Salt} \rightleftarrows \text{Acid} + \text{Base}.$$

The direction and intensity of all reversible reactions [according to Gibbs' Phase Rule (10)] depends upon the factors of temperature, pressure, and concentration of reacting bodies. Thus the reaction

$$NH_4Cl \rightleftarrows HCl + NH_3$$

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depends for its direction primarily on the amount of moisture present, for gaseous hydrochloric acid and ammonia mixed together in the air form ammonium chloride up to a certain point, when further formation of the same is inhibited by the reverse reaction.

Of all the factors affecting the formation of fogs and smoke, water plays the most important role. It not only converts anhydrides (P_2O_5, SO_3) to corresponding acids and precipitates them in the dispersed state, but also assures the dissociation of hydrolyzable salts and their reprecipitation in colloidal dimensions. The water vapor in the air can also adhere to the surfaces of minute solid particles floating in the air, and convert them to liquid droplets, as is the case when natural fogs form over smoky cities.

In the chemical process of dispersion, salts that are both volatile and easily hydrolyzable produce the best smokes. Hence oxides with feeble bases or feeble acids, because readily hydrolyzable, are most generally employed.

Summary.—Chemicals then are dispersed in two forms, one, in which a vapor (or gas) is mixed with air (gas clouds) and the other, a suspension of solid or liquid particles in the air (smoke clouds). As the behavior in the field of these two forms of chemical dispersion are somewhat different, the principal characteristics of each will be briefly summarized.

Gas Clouds

Density.—As a liquid changing into a gas absorbs heat from the air during vaporization, the air in contact with the vapor is cooled. The magnitude of this cooling effect depends upon the material used and its concentration and, while usually small, it is sufficient to cause an appreciable increase in the density of the air mixed with the vapor. Also, war gases themselves are heavier than air. The result of these two phenomena is to cause gas clouds to hug the ground and flow into all depressions and low places.

Lateral Spread.—When a gas is released in the open air, it immediately expands and diffuses into the atmosphere. This causes the cloud to spread laterally and vertically. Shifting wind and air currents also increase lateral spread as the cloud moves downwind. Under average conditions, the lateral spread is about 20 per cent of the distance traveled, while for favorable conditions it is about 15 per cent, and for unfavorable conditions it will amount to as much as 50 per cent.

Vertical Rise.—The expansion and diffusion of a gas upon its release in the open air also cause the cloud to rise as it travels with the wind, notwithstanding that the gas itself may be heavier than the air and that it cools the air when expanding. The vertical rise of a gas cloud depends

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upon several factors, chief among which are convection currents. These currents are strongest when the ground is dry and warmer than the air and when the sun is shining brightly. On the other hand, at night and in the early morning, the ground surface is usually cooler than the surrounding air, and there are no convection currents, so that gas clouds have much less vertical rise under such conditions. This rise will vary

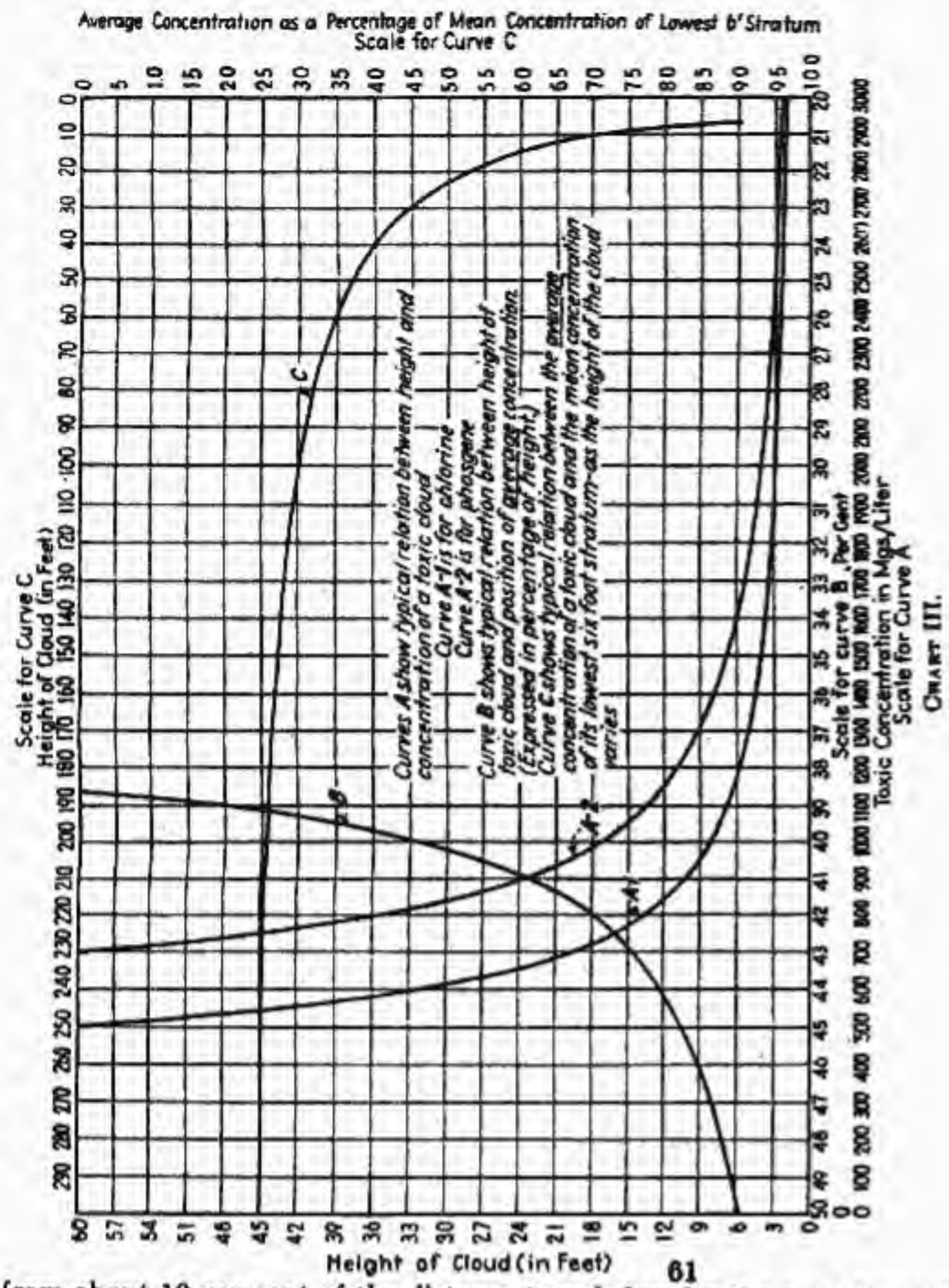

CHART III.

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from about 10 per cent of the distance traveled under the most favorable conditions to as much as 35 per cent under adverse conditions.

Drag Effect.—Since the wind velocity along the ground is practically zero, but increases rapidly upward, gas clouds are carried over the ground with a sort of rolling motion, which causes the cloud to incline forward and stretch out in length more at the top than the bottom. This increase in the length of the cloud is called the *drag effect* and, for clouds released on the ground, amounts to from 10 to 30 per cent of the distance traveled, depending upon the nature of the terrain. For gas released from airplanes, up to 100 ft. above ground, the drag effect is equal to 100 per cent of the distance traveled, owing principally to the high velocity of the airplane.

Variation of Concentration.—The concentration of vapor in a gas cloud varies inversely as the logarithm of the height above ground. Thus, if C_1 is the concentration at a height H_1 and C_2 the concentration at a higher point H_2, then

$$C_2 = C_1 \times \frac{\log H_1}{\log H_2} \qquad (1)$$

This causes the lower layers of the gas cloud to be more dense and more toxic than the upper layers, as is clearly shown in Chart III, in which curve A shows the general relation between heights above ground (ordinates) and the concentrations at these heights (abscissas) and indicates the form of the relation between height and concentration.

Average Concentration.—In a gas cloud, the average concentration is not in the geometrical center of the cloud, but varies therefrom as the height of the cloud increases. In Chart III, curve B shows the change in the position of the *average* concentration, as the height varies.

If the concentration at any height in a toxic cloud is known, the concentration at any other height may be computed from Eq. (1). If the concentration is not known for any given height, then the total height and the average concentration of the toxic cloud may be computed from a given quantity of chemical as shown on pages 64–66. The position of the average concentration is then located from curve B in Chart III. With the average concentration and its position thus determined, the concentration at any other height in the cloud can be computed from Eq. (1). Also the effective concentration in the lowest 6-ft. layer of the cloud may be determined from curve C in Chart III.

Smoke Clouds

Density.—When chemicals create a smoke they either burn or hydrolyze in the air, thus generating heat which warms the air immediately downwind from the source of smoke. Smoke clouds thus rise more than gas clouds, since air containing hot smoke particles, being less dense, tends to rise above the surrounding cooler air. Again, unlike gas clouds, smoke clouds have an *even* concentration at *all* elevations above ground.

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Lateral Spread and Drag Effect.—The *lateral* spread and *drag effect* of smoke clouds are substantially the same as for gas clouds.

Vertical Rise.—The rate of *vertical rise* of smoke is much greater than that of gas because the smoke particles absorb heat waves from the sun and are warmed up thereby. The transfer of heat to and from smoke particles by radiation is also very important, especially in bright sunshine. Since each smoke particle has a diameter of 10^{-3} to 10^{-6} cm. and is surrounded by a tightly held air film about 10^{-3} cm. thick, it acts like a tiny air-filled balloon, rising when heated and falling when cooled below the surrounding air. Thus, while convection currents tend to give the same rise to both gas and smoke, radiation primarily affects the smoke particles only. In addition, smoke particles in the air are heated by radiation from the ground surface as well as from the sun and, when the ground is cooler than the air, the smoke particles actually lose their heat by radiation to the ground. Hence smoke clouds are more influenced by ground temperature and time of day than gas clouds.

RELATION BETWEEN QUANTITY AND RANGE

The amount of chemical required to establish an effective concentration on a target is determined by the general relation between a quantity of chemical and its effective range.

Let W = weight of chemical released from one point, in pounds,
D = density of chemical released (air = 1),
V = original volume of chemical released from one point, at atmospheric temperature and pressure, in cubic feet,
V_s = volume of chemical after it has traveled a distance S, in cubic feet,
S = distance traveled from point of release at any time T, in feet,
T = time of travel, in minutes,
C_a = *average* concentration of the toxic cloud,
C_1 = ground concentration of the toxic cloud (*i.e.*, mean concentration of lowest 6-ft. stratum),
C = minimum effective concentration expressed as a volumetric ratio of chemical to air, in parts per thousand,
H_a = height of C_a above ground, and
H_1 = height of C_1 above ground.

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Experience shows that the dimensions of a chemical cloud generated from one point of emission can be expressed in terms of the distance traveled under various field conditions as follows:

Let S = distance traveled by top of cloud,
F_s = width of cloud at any distance, S,
H_s = height of cloud at any distance, S,
R_s = drag effect of cloud at any distance, S.

The values of F_s, H_s, and R_s, as functions of S, for various field conditions, are shown in the following tabulation:

VALUES OF WIDTH, HEIGHT, AND DRAG OF CHEMICAL CLOUDS*

Field conditions	Sky	Time of day	Terrain	Ground temperature	Winds, m.p.h.	Value of F_s		Value of H_s		Value of R_s	
						Gas	Smoke	Gas	Smoke	Gas	Smoke
Favorable	Heavily overcast	Night or early morning	Level fields or water	Colder than air	Steady 0–4	0.15S	0.15S	0.03S	0.10S	0.10S	0.10S
Average	Partly	Mid-	Moder-		Slightly	0.20S	0.20S	0.10S	0.20S	0.20S	0.20S

	overcast	morning or late afternoon	ately rolling farm lands		shifting 4–9						
Unfavorable	Clear	11 A.M.–4 P.M.	Broken or wooded	Hotter than air	Variable or over 9	0.50S	0.50S	0.35S	0.35S	0.30S	0.30S

* NOTE: The values given for *smoke* in the above table apply only to a *range* smoke, i.e., one blowing directly toward the target area. For data pertaining to *lateral* smoke clouds, see Chap. XIII.

In the above table, it is shown that, under *average* field conditions, a *gas* cloud will have a vertical rise of 10 per cent and a drag and lateral spread of 20 per cent of the distance traveled. After the gas has traveled a distance S, we have a toxic cloud of the following dimensions:

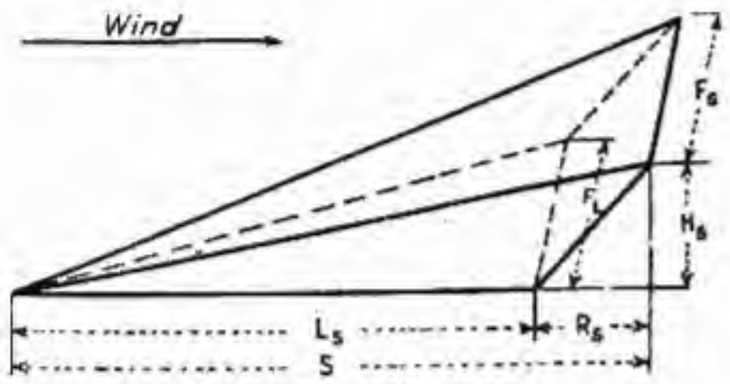

FIG. 1.—Travel of gas clouds.

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Top length of cloud at distance S $= S$
Bottom length of cloud at distance S $= L_s$
Drag of cloud at distance S $= R_s$
Bottom width of cloud at distance S $= F_l$
Height of cloud at distance S $= H_s$

Hence
$$V_s = \frac{L_s F_l H_s}{6} \tag{2}$$

But
$$L_s = S - R_s \tag{3}$$

And, for *average* field conditions,

$$R_s = 0.2S$$

Hence
$$L_s = 0.8S$$
$$F_l = 0.2 \times 0.8S = 0.16S$$
$$H_s = 0.1S$$

Therefore
$$V_s = \frac{0.8S \times 0.16S \times 0.1S}{6} = 0.00213S^3 \tag{4}$$

If we denote the coefficient of S by the symbol K, Eq. (4) takes the form

$$V_s = KS^3 \tag{5}$$

When the toxic cloud reaches a length S,

$$V_s = \frac{V}{C_s} \tag{6}$$

where C_s is the average concentration at the distance, S. Substituting value of V_s from (6) in Eq. (5), we have

$$\frac{V}{C_s} = KS^3 \tag{7}$$

Hence
$$V = KC_sS^3 \tag{8}$$

or
$$S = \sqrt[3]{\frac{V}{KC_s}} \tag{9}$$

Since
$$V = \frac{W}{D}$$

$$W = KC_sDS^3 \tag{10}$$

and
$$S = \sqrt[3]{\frac{W}{KC_sD}} \tag{11}$$

From Eq. (1), page 61, we have

$$C_s = \frac{C_1 \log H_1}{\log H_s} \tag{12}$$

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Since C_1 is the mean concentration of lowest 6-ft. stratum of the toxic cloud,

$$H_1 = 3 \text{ ft. (curve } B\text{, Chart III)}$$

and
$$\log H_1 = 0.4771$$

Also, when the cloud reaches its maximum *effective* length,

$$C_1 = C \tag{13}$$

C is a definite quantity for each gas according to the physiological effect desired and the time of exposure to the gas.

Hence, when the cloud reaches its maximum *effective* length:

$$C_s = \frac{0.4771}{\log H_s} \times C \tag{14}$$

Substituting the value of C_s from Eq. (14) in Eqs. (10) and (11), we have

$$W = \frac{0.4771KCDS^3}{\log H_s} \tag{15}$$

$$S = \sqrt[3]{\frac{W \log H_s}{0.4771CKD}} \tag{16}$$

Since the ground distance, or range, L in any given case is a definite percentage of the distance S [Eq. (3) and table on page 63], we see from Eq. (15) that the quantity of chemical required to set up an effective concentration on a distant target increases as the cube of the distance to the target and, from Eq. (16), the effective range of a given quantity of chemical varies directly as the cube root of the weight of chemical released and inversely with the cube root of its density and effective concentration.

Since the values of K in the foregoing equations depend upon the corresponding values of F_s, H_s, and R_s, which in turn vary with the distance S, as shown in the table on page 63, the values of K for gases and smokes, under varying field conditions, may be summarized as follows:

Field conditions	Values of K	
	Gas	Smoke
Favorable	0.000608	0.002025
Average	0.002133	0.004267
Unfavorable	0.014292	0.014292

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As H_s, the height above ground of the *average* concentration, also varies with the distance S, we might express H_s as a function of S and so convert Eqs. (15) and (16) to functions of S and the quantities K, C, D, which are definite constants for any given case. Such a procedure, however, leads to very complicated formulas for W and S, which would be cumbersome to apply in practice.

A shorter and simpler method is to plot a curve for Eq. (14) from which the value of C_s in terms of C_1 may be read directly for any given case and then inserted in Eqs. (10) and (11). Curve C on Chart III is such a curve and expresses the value of C_s as a percentage of C_1 for any rise up to 300 ft. Above a rise of 300 ft., which corresponds to a gas range of 3,000 ft. under average field conditions, the value of C_s is obtained from Eq. (14).

In order to illustrate the time and space factors involved in dissemination of a gaseous chemical, from a single point of emission, let us take the simplest case of a cylinder discharging chlorine. We shall assume that the cylinder holds 30 lb. of liquid phosgene. A cubic foot of air at 20°C. (68°F.) and atmospheric pressure weighs 0.075 lb. and, as the density of gaseous chlorine is 3.5 times the density of air at this temperature and pressure, it weighs $3.5 \times 0.075 = 0.2625$ lb. per cubic foot. Using Eq. (11) above, and a lethal concentration of 1:10,000, we have for *average field* conditions

$$S = \sqrt[3]{\frac{30}{\frac{0.002133 \times 0.2625}{10{,}000}}} = 812.2 \text{ ft.}$$

for an *average* concentration of 1:10,000. But at this range the ground

concentration equals approximately three times average concentration. Substituting this value for C_a in Eq. (11), we have

$$S = 1{,}172 \text{ ft.}$$
$$L_a = 0.8S = 942 \text{ ft.}$$

Thus, 30 lb. of phosgene under *average* field conditions will have a range of 942 ft., with ground concentration of 1:10,000 (0.434 mg. per liter), which is lethal on 15 minutes' exposure. With *favorable* field conditions, the same amount of chlorine will have an equally effective range of 1,233 ft., while with *unfavorable* field conditions this effective range will be reduced to 430 ft. In this case, favorable conditions increase it to 53 per cent of the range under average conditions.

If the wind is blowing steadily toward the target at a rate of 5.4 miles per hour (475 ft. per minute), the cloud will, under average field con-

ditions, reach its full development (in the form shown in Fig. 1) in $^{942}/_{475} = 1.98$, or approximately 2 minutes. To maintain an average concentration of 1:10,000, our cylinder should be emptied in that time, requiring a discharge rate of approximately 15 lb. per minute. If a slower rate of discharge is used, the gas cloud will be attenuated and its concentration will be correspondingly lowered. Also, if there is an increase in the wind velocity, there should be a corresponding increase in the discharge rate in order to maintain the same concentration.

On the other hand, with a 5.4-mile wind and a discharge rate greater than 15 lb. per minute, the initial concentration of the cloud will be raised above the strength of 1:10,000 (0.434 mg. per liter). After the cloud has traveled the same ground distance (942 ft.), its concentration will fall off, as indicated above, but will still be higher than 1:10,000 by the time the cloud reaches the target. There is, therefore, a theoretical advantage in increasing the discharge rate, but there are practical difficulties involved in so doing. In the first place, much higher pressures are required for greater velocities of discharge, the pressure increasing as the square of the velocity. Also, if the emission is too rapid, there is insufficient time for the ejected liquid to change into vapor and the liquid chemical falls to the ground where part of it is lost by absorption. Moreover, the liquid on the ground produces a very high local concentration immediately adjacent to the operating troops and may endanger them if there is any unsteadiness in the wind.

Size of Target.—Another very important factor in the cloud or wave method of disseminating gas is the size of the target area to be covered.

Width.—The width of the target area should be approximately equal, but should not exceed the width of the gas cloud at the front edge of the target, *i.e.*, the value of F_i as shown in the following table:

Field conditions	Values of F.		Values of F_i		Per cent of range L.	
	Gas	Smoke	Gas	Smoke	Gas	Smoke
Favorable	$0.15S$	$0.15S$	$0.135S$	$0.135S$	0.90	0.90
Average	$0.20S$	$0.20S$	$0.160S$	$0.160S$	0.80	0.80
Unfavorable	$0.50S$	$0.50S$	$0.350S$	$0.350S$	0.70	0.70

For chemicals emitted from a single point, with a range of 1,000 ft., the width of target should be: for favorable conditions, 90 ft.; for average conditions, 80 ft.; and for unfavorable conditions, 70 ft.

Depth.—If the target area is of material depth as compared to its distance from the point of emission of the gas, it should always be *included as a part of the range.* Otherwise, by the time the gas cloud reaches the

rear boundary of the target, its concentration will have fallen below the required effective strength. As an illustration of this point, let us assume that the discharge from the cylinder mentioned above travels over a target 200 ft. deep whose front edge is at the distance $L = 1{,}050$ ft. from the cylinder emplacement. We shall also assume that the cylinder is emptied in 2 minutes, so that, by the time the first chlorine discharged reaches the front edge of the target, the last chlorine will have just been released from the cylinder. Traveling at the rate of 6 miles per hour (528 ft. per minute) it will require 0.40 minute for the cloud to pass over the target area. During this time, the cloud will expand to the larger

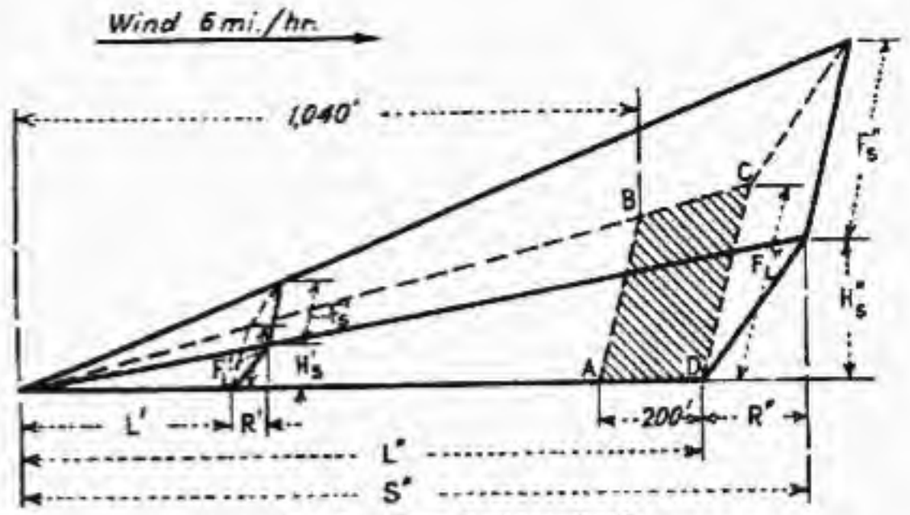

FIG. 2.—Travel of gas clouds.

dimensions indicated by (") letters in Fig. 2. At the same time, the rear part of this volume, following the expiration of the cylinder discharge and indicated by (') letters, will be uncontaminated air.

$ABCD$ = target area: $AD = 200'$

Assuming *average* field conditions,

$$S'' = S' + \frac{200}{0.8} = 1{,}563'$$
$$R'' = 0.2S'' = 312.6'$$
$$L'' = S'' - R'' = 1{,}250'$$
$$F_i'' = 0.16S'' = 250'$$
$$H_s'' = 0.1S'' = 156.3'$$
$$V_s'' = \frac{L'F_i''H_s''}{6} = \frac{1{,}250 \times 250 \times 156.3}{6} = 8{,}140{,}625 \text{ cu. ft.}$$
$$V_s' = \frac{L'F_i'H'}{6} = \frac{200 \times 40 \times 25}{6} = 33{,}300 \text{ cu. ft.}$$

The volume of the expanded toxic cloud is $V_s'' - V_s' = 8{,}107{,}325$ cu. ft., while its *average* concentration is

$$8{,}107{,}325 + \frac{30}{0.1865} = 1{:}50{,}000$$

and its ground concentration is 1:15,000 which is only one-fifteenth of the lethal concentration.

Time of Emission.—Again referring to the example given on page 66, we see that 30 lb. of chlorine will produce a lethal concentration of 1:1,000 over a target area 168 ft. wide at a distance of 1,050 ft. from the point of emission if discharged at the rate of 15 lb. per minute. This concentration is, however, lethal only after 30 minutes' exposure, so that 450 lb. of chlorine would be required to produce *deaths* per 168 ft. of enemy front, or almost 3 lb. per foot of front. Of course, *nonfatal* casualties will be produced over a much wider front, since chlorine causes such casualties in concentrations of 1:10,000, or approximately one-tenth the lethal concentration. In this case, nonfatal casualties could be secured with the same amount of chlorine over a target area 361 ft. wide at a distance of 1,806 ft.

Comparison with Smoke.—If instead of a gas we used the same quantity (30 lb.) of a toxic smoke of the same density, under the same conditions, in a concentration of 1:10,000, we should have

$$S = \sqrt[3]{\frac{30}{\frac{0.004267 \times 0.1865}{10{,}000}}} = 1{,}556 \text{ ft.}$$
$$L_a = 0.8 \times 1{,}556 = 1{,}245 \text{ ft.}$$
$$F_i = 0.2L_a = 249 \text{ ft.}$$

from which we see that our effective range is 1,245 ft. and our width of target 249 ft.

When a gas concentration is increased tenfold and all other factors remain the same, the effective range is increased by the cube root of 10, or 2.154 times. The *smoke* cloud in our example does not realize such an increase over the gas cloud because the vertical rise of smoke is twice as great as that of gas, *i.e.*, K smoke $= 2K$ gas (table, page 63).

Multiple Points of Emission.—In the foregoing discussion concerning the relation between a quantity of chemical and its effective range, we have considered only emissions from a single point. In actual practice,

however, the gas-cloud method of chemical attack is always carried out on a large scale over a considerable portion of the enemy's front. To cover such an area the chemical must be discharged from a sector of one's own front bearing relation to the size of the target to be covered, *i.e.*, the chemical is discharged from a large number of cylinders uniformly distributed along a line substantially parallel to the enemy's front and of a length in proportion to the target area.

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In order to determine the relation between the amount of chemical and its effective range when discharged from multiple points of emission and the optimum arrangement of these points with reference to the target

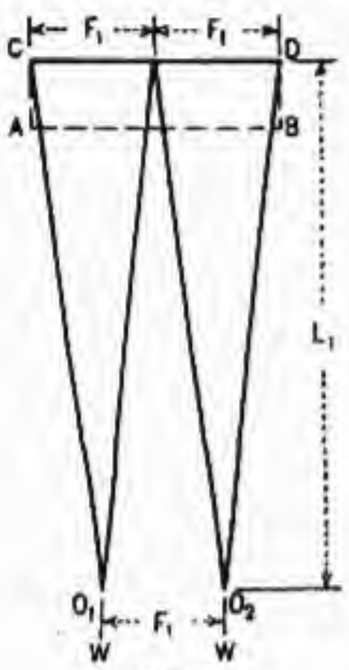

Fig. 3.

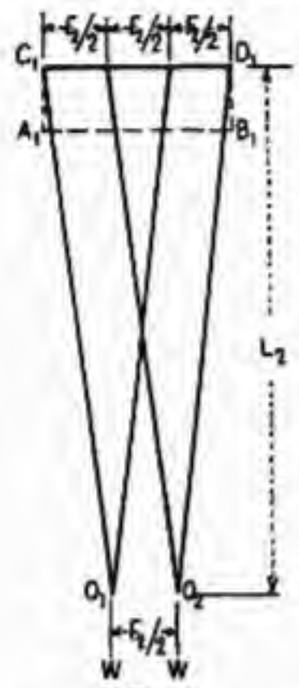

Fig. 4.

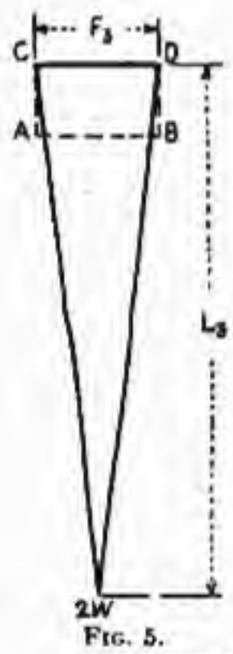

Fig. 5.

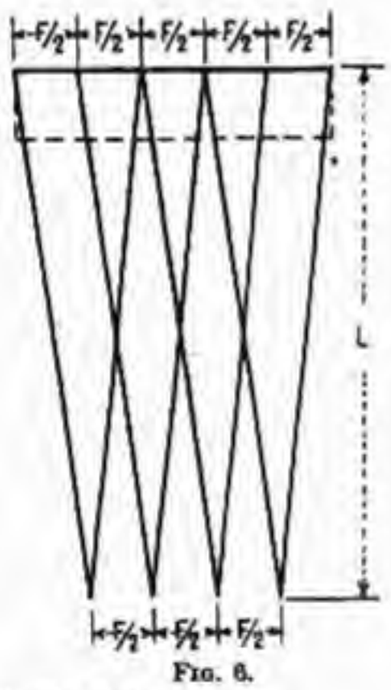

Fig. 6.

Figs. 3–6.—Multiple points of emission.

area, we shall first consider some fundamental elements of the problem As the vertical rise of a gas or smoke cloud bears a constant ratio to its length in any case, it will somewhat simplify our discussion if we confine our attention to the *plan* views of the chemical clouds considered.

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Accordingly, in Figs. 3, 4, and 5 we have plan views of three possible arrangements of *two* cylinders, or points of chemical emission. In Fig. 3, the cylinders, each containing a quantity of chemical W, are placed at points O_1 and O_2, F_1 distance apart, along a line parallel to the front of the target area $ABCD$ and at a distance L_1 = 1,000 ft. therefrom. Thus arranged, the contents of the two cylinders cover a target $2F_1$ in width with a concentration C. In Fig. 4, the same cylinders are placed at points O_1 and O_2, half the distance apart, shown in Fig. 3, $F_1/2$, so that their clouds overlap a distance $F_2/2$ at the target line A_1B_1. Thus arranged, the cylinders cover a target $1.5F_2$ in width with a concentration C.

In Fig. 5, both cylinders are placed at the same point O so that their clouds coincide and cover a target F_3 in width with a concentration C. Our first inquiry is as to the relative ranges obtained by these three arrangements, *i.e.*, the relations of L_2 and L_3 to L_1.

It is apparent from inspection that Figs. 3 and 5 show the extreme cases and Fig. 4 shows the mean case of all the ways in which two cylinders or points of chemical emission could be arranged in practice, and that the range L_1 in Fig. 3, is equal to that of a single cylinder. Considering Fig. 5 next, we see that this is really the case of a single cylinder of $2W$ capacity, so that from Eqs. (3) and (11), page 64.

$$L_3 = \sqrt[3]{2} \times L_1 = 1.26L_1 \qquad \text{and} \qquad F_3 = 1.26F_1$$

Comparing these two extreme arrangements, we find that the range in Fig. 5 is 26 per cent larger than that in Fig. 3, while the front covered is only 63 per cent as large.

Now considering Fig. 4, we see that the ground area covered by the two clouds is

$$2F_2\frac{L_2}{2} - F_2\frac{L_2}{8} = \frac{7}{8}F_2L_2$$

while their volume is

$$\frac{7}{8}F_2L_2 \times \frac{H_2}{3} = \frac{7F_2L_2H_2}{24}$$

Since the ground length of a gas cloud is eight-tenths, the spread two-tenths, and the rise one-tenth, of the distance traveled, S, the volumes of the two clouds in Figs. 3, 4, and 5 are, respectively,

$$V_1 = 2\left(\frac{F_1L_1H_1}{6}\right) = \frac{1}{3}\left(\frac{L_1}{4} \times \frac{L_1}{1} \times \frac{L_1}{8}\right) = \frac{L_1^3}{96}$$

$$V_2 = 7\left(\frac{F_2L_2H_2}{24}\right) = \frac{7}{24}\left(\frac{L_2}{4} \times \frac{L_2}{1} \times \frac{L_2}{8}\right) = \frac{7L_2^3}{768}$$

$$V_3 = \frac{F_3L_3H_3}{6} = \frac{1}{6}\left(\frac{L_3}{4} \times \frac{L_3}{1} \times \frac{L_3}{8}\right) = \frac{L_3^3}{192}$$

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But

$$V_1 = 2\frac{W}{DC}$$

$$V_2 = 2\frac{W}{DC}$$

$$V_3 = 2\frac{W}{DC}$$

where D is the density and C the concentration of the gas.

Hence $$V_1 = V_2 = V_3$$

And

$$\frac{7L_2^3}{768} = \frac{L_1^3}{96}$$

$$L_2 = L_1\sqrt[3]{\frac{768}{672}} = 1.045L_1$$

And

$$\frac{L_3^3}{192} = \frac{L_1^3}{96}$$

$$L_3 = L_1\sqrt[3]{\frac{192}{96}} = 1.260L_1$$

From the foregoing we see that, if the range L_1 in Fig. 3 is 100 per cent, the range in Fig. 4 is 4.5 per cent greater, while the range in Fig. 5 is 26 per cent greater.

From the above we conclude that with a given quantity of chemical the maximum *range* is obtained by discharging the whole quantity from one point, while the maximum *width* of target is obtained by discharging half the quantity from each of two points spaced apart a distance equal to half the target width. If the points of emission are further apart than half the target width, then there will be gaps between the clouds over the target area and, if the points are closer together than half the target width, there will not be a uniform concentration C over the target, but an increase above C where the clouds overlap.

When more than two points of emission are used, optimum results are obtained when the points are spaced a distance apart equal to half the width of target covered by one cylinder. With this arrangement, as indicated in Fig. 6, it may be shown that the distance S traveled by the composite cloud emitted from a number of points, N, varies in accordance with the following general equation:

$$S = \sqrt[3]{\frac{W}{N/(N-1)KC_sD}} \qquad (17)$$

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and since $L = 0.8S$ for *average* field conditions

$$L = 0.8\sqrt[3]{\frac{W}{N/(N-1)KC_sD}} \qquad (18)$$

If the range L for one point of emission is given a value of unity, we have the following relation between the range from one point of emission and the successive ranges from multiple points of emission:

Points of Emission	Range to Target
1	1.000
2	1.045
3	1.063
4	1.072
5	1.077
6	1.081
7	1.084
8	1.086
9	1.087
10	1.089
N	1.100

From the foregoing table, it is seen that the range slowly increases with the number of points of emission and approaches a limit of 1.1 times the range from a single point of emission, as the number of points of emission is indefinitely increased. Also, the optimum arrangement of cylinders, as indicated in Fig. 6, gives a front of emission practically equal to the width of the target to be covered.

From what has been shown above, the number of cylinders needed to cover a given target may be determined as follows: Let the target be 1,000 ft. wide by 500 ft. deep and at a distance of 2,000 ft. from the nearest section of front from which the cylinders can be installed. It is desired to set up and maintain a lethal concentration (1:10,000) of phosgene on the target, under average field conditions and with a range wind of 6 miles per hour. Each cylinder holds 30 lb. of phosgene. Required: the number of cylinders and their distribution.

At 20°C. (68°F.), the density of phosgene is 0.2654 lb. per cubic foot. From Eq. (2):

$$2{,}500 \text{ ft.} = S - 0.2S \quad \text{or} \quad S = 3{,}125 \text{ ft.}$$

$F_s = 500$ ft. $H_s = 312.5$ ft. (table, page 63)

From curve *B*, Chart III,

$$H_e = \frac{312.5}{3} = 104.17 \text{ ft.}$$

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From Eq. (14)

$$C_s = \frac{0.4771}{2.1271} \times \frac{1}{10{,}000} = 0.00002243$$

Since here F_s equals half the target width and the optimum arrangement of cylinders is at intervals of $F_s/2$, four groups of cylinders, spaced 250 ft. apart, are required to cover the target area.

From Eq. (18),

$$2{,}500 \text{ ft.} = 0.8\sqrt[3]{\frac{W}{(4/3)0.002133 \times 0.00002243 \times 0.2654}}$$

from which

$$W = 560 \text{ lb.}$$

and the total phosgene required is $4 \times 560 = 2{,}240$ lb.

As the wind is blowing at the rate of 528 ft. per minute, it will require 5 minutes for the cloud to reach the rear boundary of the target and an equal time to move over the target. As the phosgene concentration of 1:10,000 is lethal only after 10 minutes' exposure, it takes twice 2,240 or 4,480 lb. to maintain this concentration on the target area for the necessary time to produce fatal casualties. This is equivalent to a total of 150 cylinders divided into four groups spaced 250 ft. apart.

In the preceding example, it was shown that 2,240 lb. of phosgene are required to establish a concentration of 1:10,000 on a target 500 by 1,000 ft. at a distance of 2,000 ft. (667 yd.) from the line of emission. If the phosgene could be released *on* the target and dispersed uniformly thereover, it would require only

$$\frac{500 \times 1{,}000 \times 6 \times 0.2654}{10{,}000} = 80 \text{ lb.}$$

to set up a lethal blanket of gas 6 ft. high over the target area. Thus, at a distance of only 2,000 ft. (667 yd.), it takes 28 lb. of chemical to disseminate 1 lb. in an effective form on the target area by the cloud-gas method of projection. Moreover, as the quantity of chemical required to establish an effective concentration varies as the cube of the range, the cloud-gas method of attack becomes very wasteful of chemical agents when the range exceeds 1,000 yd., since so large a portion of the chemical is dissipated before it reaches the target or is disseminated in the upper parts of the cloud where it serves no useful purpose. For this reason various forms of projectiles were early employed to carry the chemicals to the target and to release them *on* the target area. The first projectiles used for this purpose were artillery shell. These were soon supplemented by trench-mortar shell and later by special (Livens) gas-projector bombs which were fired in only one salvo and thus released the entire chemical

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concentration at one instant, thereby greatly increasing the surprise effect and the initial toxic concentration. Finally, special (4-in. Stokes) rapid-fire mortars were developed for projecting chemicals in mobile situations and were used very effectively throughout the war.

DISSEMINATION BY PROJECTILES

While the theoretical economy of releasing chemicals on the target area is very large, as indicated above, the practical advantage is not nearly so great, for several deterrant factors enter into the projection and dispersion of chemicals from projectiles.

In the first place, projectiles are not very efficient as carriers of chemicals, for their walls must be made thick enough to withstand the shock of discharge, and this greatly limits their chemical capacity. The efficiency of a chemical projectile may be defined as the ratio of the weight of chemical filling to the gross weight of the projectile. On this basis, the best artillery shell have an efficiency of about 12 per cent. The short-range trench and chemical mortars, having to withstand far less violent shocks of discharge, may have thinner walled projectiles with correspondingly greater chemical capacity. Thus, chemical-mortar shell have an efficiency of about 30 per cent. Livens projector bombs, having a still shorter range, have 50 per cent chemical capacity. Finally, chemical drop bombs and land mines, which are merely dropped or placed in position and thus have no shock of discharge to sustain, have an efficiency of 60 to 70 per cent.

Another factor which greatly reduces the efficiency of artillery for chemical projection is the large increase in dispersion of the projectiles as the range increases. The standard target unit for artillery fire is a square 100 yd. on a side, generally called the *artillery square*. At 3,000 yd., the dispersion of shots from a 75-mm. gun is so small that approximately 91 per cent of the projectiles fired fall within an artillery square. At 8,000 yd., however, owing to greatly increased dispersion of shots, only 41 per cent of the shell fall within an artillery square. Thus, about 2.2 times as many shell and chemical must be expended to produce an effective concentration on a 75-mm. artillery square at 8,000 yd. as at 3,000 yd. The same is true of all other calibers of artillery and, while a greater percentage of shell will fall within a large target area than a small one, a greater amount of chemical is also required for the larger target, although not quite in the same proportion. It thus arises that the efficiency of the artillery as a means for projecting chemicals falls off very rapidly as the range increases.

A third factor limiting the efficiency of artillery shell as chemical vehicles is the loss of chemical on the burst of the shell. On account of its rugged construction, an artillery shell requires a considerable force

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to open it and, when this force is applied from the bursting charge in the shell, it drives a portion of the chemical charge into the ground; also, it throws a portion into the air above the 6-ft. effective stratum, where it is largely lost insofar as any useful effect is concerned. It is variously estimated that from 25 to 50 per cent of the chemical contents of an artillery shell is thus lost on the burst of the shell if the gas is nonpersistent. For persistent gases this loss is much less. Also, the loss is much less if the shell is burst in the air just above the target, as air-burst chemical shell release from 80 to 90 per cent of their contents in an effective form.

What has been said of artillery shell applies also, but to a far less

extent, to short-range projectiles such as Livens bombs and chemical-mortar shell and, to a still less extent, to aviation drop bombs and land mines. Not only are all these latter projectiles of greater efficiency, but they also have much less dispersion than artillery shell at the longer ranges and do not require such large bursting charges to open them.

Because of the great variation in efficiency of the several classes of chemical projectiles, it is obvious that only the most efficient types should be used in the zones they can reach. Thus, the special chemical-projecting devices, such as gas-cloud cylinders, Livens projectors, and chemical mortars, which cover the vital infantry combat zone out to a distance of 2,500 yd. from the front lines, are far more efficient and effective for chemical projection than artillery with its shells of relatively low capacity and efficiency. For the same reasons, aviation drop bombs are more efficient than long-range artillery for dissemination of chemicals beyond a distance of 10,000 yd. (about 6 miles) from the infantry front lines. It is principally on the basis of the relative efficiencies of the several chemical-projecting means that the normal zones for their employment, indicated on page 54, were arrived at.

Regardless of the type of projectile employed to carry the chemical to the target, the dispersion of the chemical after release from the projectile is essentially the same as when released from cylinders. That is to say, the chemical, when released from projectiles, volatilizes, expands, and diffuses into the air, and thus forms a toxic cloud which then moves with the wind exactly as the clouds formed by cylinder discharges.

The same relation between quantity of chemical and the effective range of the chemical obtains when the chemical is released from projectiles as when it is released from cylinders, except, of course, that there is no loss from expansion and diffusion before the toxic cloud reaches the target area.

In addition to obviating this loss, projectiles have two very important advantages over cylinders as a means for disseminating chemicals. First, all kinds of chemicals may be employed in projectiles regardless of their physical state, whereas only chemicals which are relatively volatile liquids

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may be employed in cylinders. Secondly, chemicals can be used in projectiles regardless of the direction of the wind, whereas cylinders can only be used when the wind is blowing toward the enemy's lines. Even when the wind is blowing directly toward one's own lines, chemicals may be put over in projectiles without danger to friendly troops if the dosage is adjusted to the distance between the target and one's own lines in accordance with the quantity-range relation discussed above.

This relation is thus one of the most important in chemical warfare, for it not only enables one to determine the quantity of chemical required to establish and maintain an effective concentration on a given target at a given range, but, what is equally important, it also enables one to determine how much of a chemical can be safely placed at a given distance from one's own troops under the most adverse conditions. Except for cloud-gas emission from one's own front lines, for which favorable winds are required, it is possible by these determinations to use chemicals at all times and under all conditions with perfect safety to one's own troops. It is at once apparent that, if it requires W pounds of chemical to establish an effective concentration on an enemy position X distance from one's own front lines, any amount of this chemical less than W, released within the enemy position, will not produce an effective concentration on friendly troops, even in an adverse wind, since the relation between a quantity of chemical and its effective range applies alike to both situations

CONTROL OF CHEMICAL WARFARE

Because of this definite relationship between chemical quantities and effective ranges, chemical warfare is susceptible of much closer control than is possible with bullets and H.E. shell. When a bullet or shell once leaves the gun, the gunner cannot tell what its effect will be. It may ricochet or be deflected from its path by striking some intervening obstacle, and its ultimate point of impact may be far removed from the intended target. Even if it strikes within the target area, no one can predict where its fragments will strike or what their ultimate effect will be. On the contrary, a given quantity of chemical will have a definite and predictable effect when intelligently used by properly trained troops who thoroughly understand the behavior of chemical concentrations in the field and know how to employ them, for chemical concentrations follow closely the laws of gases and these laws are just as certain and definite as the law of gravity.

This fact cannot be too strongly emphasized, as there is much misapprehension concerning it, not only on the part of the public in general, but even on the part of military men of high rank and position. One of the main arguments advanced against chemical warfare at peace conferences and in other public discussions in the years immediately following

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the late war was the mistaken notion that chemicals employed in military operations cannot be controlled and confined to the battlefield, but will unavoidably extend their deleterious effects to areas far behind the combat zone and thus kill or injure noncombatants and civilian populations.

A typical illustration of this erroneous idea is contained in General March's book on the World War. He says:

> We had had the use of gas forced on us in the war by the action of Germany, and in self-protection had to organise the Chemical Warfare Service. And no soldier can say that he prefers to be killed by being torn to pieces by a shell rather than to be gassed. But the use of poison gas, carried wherever the wind listeth, kills the birds of the air, and may kill women and children in rear of the firing line. When I first reached France I found in Paris an American organization, headed by Miss Lothrop, which had a hospital in which, when I inspected it, were over 100 French women and children who had been living in their homes in rear of and *near the front*, and who were gassed. The sufferings of these children, particularly, were horrible and produced a profound impression on me. War is cruel at best, but the use of an instrument of death which, once launched, cannot be controlled, and which may decimate noncombatants—women and children—reduces civilization to savagery.

The instances in which women and children were gassed in the war were very few and in every such case they were gassed because they were living (as in this case) in areas so close to the battle front that they might easily have become victims of bullets, shells, or any of the other weapons of war, as were many thousands of others who risked their lives by remaining in the combat zone.

As a matter of fact, the largest gas attacks in the war did not extend beyond 10 or 12 kilometers behind the firing lines. Moreover, the concentrations beyond 2 to 3 kilometers from the front were so weak as to require prolonged exposure to produce even light casualties whereas deaths from such concentrations were unheard of. Since the normal range of medium and heavy artillery is from 12 to 15 kilometers behind the front lines, it is obvious that any civilians remaining in this zone do so at their own risk and are in daily jeopardy of their lives. Yet no one advocates the abolishment of artillery as a weapon of warfare. The case is even worse against high-explosive long-range artillery shell and aviation drop bombs, for these two weapons were extensively used throughout the war on Paris and other cities far behind the combat zone where noncombatant civilians had every right to pursue their peaceful occupations without jeopardy of life and limb. Nothing is said of the thousands of women and children who were killed and maimed by long-range artillery and aviation bombs in areas far behind the battlefields. It is apparently considered legitimate for a combatant to fire H.E. shell at random into a large city some 70 kilometers behind the front, as when the Germans fired long-range guns on Paris and with a single shell killed or maimed 80 people worshiping in a church. Instances of this kind could be cited by the score,

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yet the advocates of humanity in warfare are apparently prepared to accept such wholesale destruction when carried out by means of the older and more familiar methods of warfare.

The record of gas in the World War as affecting noncombatants is singularly free from the charge of indiscriminate and uncontrolled injury, for gas was not used in long-range artillery shell or aviation bombs, or in any way beyond a distance of 10 or 12 kilometers behind the firing lines, which zone is universally regarded as the field of battle in modern warfare.

Whatever objections might be logically advanced against the use of chemicals in war, the lack of control of their effect is not one, for chemicals can be far more accurately controlled and their effects more carefully adjusted to the purpose sought than any other weapon heretofore devised by man.

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CHAPTER V

CLASSIFICATION OF CHEMICAL AGENTS

Chemical agents may be classified in several ways depending upon the point of view and the purpose of the classification. Broadly speaking, we may divide the several classifications into two general groups—theoretical and practical. In the theoretical group are included classifications according to: (1) chemical composition, (2) physical state, and (3) physiological effect, whereas the practical group comprises classifications according to: (1) persistency, (2) degree of action, and (3) tactical employment. In this chapter we shall discuss briefly these several classifications, both during and since the World War, including the system of marking to denote the various classes of chemical agents used by the principal nations, and we shall conclude with some general observations on the subject of classification.

Unfortunately, many of the classifications heretofore in use were based upon classes that were not mutually exclusive but tended in many instances to overlap. This was unavoidable from the properties of the agents themselves, as will be more particularly brought out in discussing the various classes of agents, and there is probably no system that can be devised which is absolutely free from this defect. Nevertheless, classifications serve many useful purposes and, for use in the field, should be made as simple and as clear-cut as possible.

CHEMICAL CLASSIFICATION

Although a vast amount of effort has been expended during and since the late war in an attempt to establish some general laws governing the relation between chemical structure and physiological action on the living body, there is, strictly speaking, today no simple classification of toxic substances in accordance with chemical composition. We have mentioned in Chap. II the tremendous number of chemical compounds among which physiologically active substances may be found. With this vast reservoir from which to draw, it is obvious that much research effort would be saved if the field of search could be delimited by the establishment of the general relation between chemical composition and physiological action. Consequently chemists and toxicologists have worked hand in hand on this complex problem for many years and, while they

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have not yet solved it, they have succeeded in throwing much light upon the subject and enabled investigators to confine their research to certain families of compounds where desired physiological properties are most apt to be found.

We cannot go very deeply into this subject here; to attempt to do so would lead us far into the field of biochemistry and pharmacology and space does not permit; but we shall state briefly certain limited generalizations which have been established and found useful. The clearest simple statement of this complex subject known to the author is that of Hederer and Istin (15), of which the following is a condensed extract.

It has long been known that certain metals and metalloids possess well-defined toxic properties and that they often confer upon the compounds in which they are present marked physiological activity. Such metals are arsenic, antimony, tin, mercury, lead, and bismuth. Other elements, themselves of indifferent toxicological action, are capable of combining to form groups or radicals which, although they do not always have an actual existence, have the power of giving to their compounds special physiological properties. For example: (1) the ions H^+ and OH^- which form, respectively, the acids and the bases; (2) the oxidizing groups $—SO_3$, SO_4, NO_2, and P_2O_5; and (3) the reducing groups—SO_2, SH, P_2O_3, and CO.

These materials being known, we can distinguish, without attempting to formulate a law of general application, three different classes in accordance with the organization of toxic molecules; each of them is characterized by particularities of molecular structure and common physiological properties.

In the *first class*, the atom or the toxic group is combined, according to its valence, either with one or several halogens (F, Cl, Br, I) or with *one or several radicals* (SO_3—, SO_4—, NO_2—, NO_3—, CN—) but never with an atom of carbon. The substances constructed on this model are *mineral compounds*, and their schematic formula can be written

$$X—M—X$$

where the symbol X represents either a halogen or a reducing group, and M, the toxic atom or group.

The substance mercuric chloride ($HgCl_2$), the formula of which may be written

$$Cl—Hg—Cl$$

is an example of compounds of the first class. Other toxic compounds of military importance in this class are:

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Sulfur monochloride ..... S_2Cl_2

Arsenic trichloride ..... $Cl—As(Cl)Cl$

Sulfuric chlorhydrin ..... $O_2S(Cl)Cl$

In the *second class*, the toxic elements (M) are combined with one or several organic radicals (such as CH_3—, C_2H_5—, C_3H_5—, C_6H_5—) and are found linked by carbon, or by one or several atoms of hydrogen—the most simple organic radical. There are thus obtained the *organic compounds*, many of which (to indicate the presence of the characteristic element) merit the name *organo-minerals*. They respond to the general formula

$$R—M—R$$

in which the symbol M is the same as before and in which the R represents an organic radical. The substance cacodyl ($(CH_3)_4.As_2$), the formula of which may be written:

$$(CH_3)_2As—As(CH_3)_2$$

is an example of compounds of the second class. Other toxic compounds of military importance belonging to this class are:

Methylmercaptan ..... $H—S—CH_3$

Methylarsine ..... $CH_3—As=H_2$

Lewisite (III) ..... $As\equiv(CH=CHCl)_3$

Methylformate ..... $O=C(H)OCH_3$

Acrolein ..... $O=C(H)CH=CH_2$

Hydrocyanic acid ..... $H—C—N$

Phenylcarbylamine ..... $C\equiv N—C_6H_5$

In the *third class*, the basic materials can combine, in one or several valences, with halogens or with ionizable mineral radicals, as bodies of the first class and thus, or by the remaining free valences, either with carbon or organic radicals or with hydrogen, as bodies of the second class. In order to realize similar compounds, called *organic* or *organo-mineral halogens*, the primary elements should be at least bivalent. The formula for compounds of this class is

$$R—M—X$$

in which all the symbols are the same as above.

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Ethyl mercuric chloride, the formula of which may be written

$$C_2H_5—Hg—Cl$$

is an example of compounds of the third class. Other important military toxic compounds belonging to this class are

Mustard gas ..... $S(CH_2—CH_2—Cl)_2$

Dichlormethylarsine ..... $CH_3—As=Cl_2$

Lewisite (II) ..... $(ClCH—CH)_2=As$

Phosgene ..... $O=C=Cl_2$

Chloroformate of methyl chloride ..... $O—C(Cl)OCCl_3$

Iodoacetone ..... $O=C(CHI)CH_3$

Cyanogen chloride..... $Cl—C\equiv N$
Phenylcarbylamine chloride..... $Cl_2=C=N—C_6H_5$
Methylchlorsulfate..... $SO_2—H(Cl)(OCH_3)$
Chlorpicrin..... $Cl_3C—NO_2$

While it appears from the foregoing that many of the World War chemical agents may be classified in accordance with the scheme outlined, it does not follow that all such agents are so classifiable, as there are many known exceptions, and undoubtedly many more exceptions will be found as new chemical agents are discovered.

Another chemical classification of combat toxics is indicated by Hederer and Istin as follows:

1. Oxydizers, *e.g.*, chlorine, chlorpicrin, or
2. Reducers, *e.g.*, acrolein, ketones.
3. Ionizable, *e.g.*, hydrocyanic acid, arsines, or
4. Nonionizable, *e.g.*, carbon monoxide.

However, there are not clear-cut lines of demarcation between these classes, nor do they in any way help to associate chemical composition with physiological action so that little seems to be gained by efforts to classify toxic compounds along these lines.

Our conclusion, then, as regards the chemical classification of toxic compounds is that at present only very sketchy approximations can be made. Moreover, among compounds of military importance there are

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so many exceptions to any general chemical classification that the whole subject abounds in technical difficulties. Fortunately, however, chemical classification is not of any great importance in chemical warfare, other than as an aid to research. Perhaps the most important point to be emphasized here is the fact that many of the most formidable toxic agents known today belong to two well-defined families of compounds—the cyanides and the organic arsenicals—and it is from these fields that most of the future chemical agents seem likely to be drawn.

PHYSICAL CLASSIFICATION

The physical classification is very simple and is based upon physical state or form of the substance *under ordinary conditions*, *i.e.*, temperature 68°F. (20°C.) and atmospheric pressure (760 mm. Hg). Thus, an agent is a true *gas*, if its boiling point is below ordinary atmospheric temperature, as is the case with chlorine (b.p. – 28°F.). This classification as a *true gas* is not to be confused with the broad generic term *gas*, used to refer generally to toxic chemical agents, but means that the substance is in a gaseous state under ordinary temperatures and pressures.

CLASSIFICATION OF CHEMICAL AGENTS ACCORDING TO PHYSICAL STATE

Gases	Boiling point, °F.	Liquids	Boiling point, °F.	Solids	Melting point, °F.
Carbon monoxide	–310	Brombenzyl cyanide	+77*	Dichlorethyl sulfide	+57
Chlorine	– 28.3	Hydrocyanic acid	79.7	Brombenzyl cyanide	77
Phosgene	+ 46.7	Acrolein	126.3	Diphenylcyanarsine	91
Hydrocyanic acid	+ 79.7	Monochlormethylchloroformate	228.2	White phosphorus	111
		Chlorpicrin	231.5	Diphenylchlorarsine	113
		Chloracetone	246.2	Ethylcarbazol	134
		Trichlormethylchloroformate	260.6	Diphenylaminechlorarsine	387
		Methylsulfuryl chloride	269.6		
		Brommethylethyl ketone	271.4		
		Bromacetone	275		
		Perchlormethylmercaptan	300.2		
		Ethyldichlorarsine	312.8		
		Ethylbromacetate	318.2		
		Dimethyl sulfate	370.4		
		Lewisite	374		
		Benzyl bromide	393.8		
		Phenylcarbylamine chloride	406.4		
		Xylyl bromide	420.8		
		Dichlorethyl sulfide	57*		
		Phenyldichlorarsine	484.7		

* Melting point.

An agent is a *liquid* if its melting point is below ordinary temperatures and its boiling point is above such temperatures, *i.e.*, when the

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range of atmospheric temperatures lie between the melting and boiling points of an agent, *e.g.*, chlorpicrin (m.p. – 92.4°F., b.p. 235.4°F.).

Similarly, an agent is a *solid* when its melting point is above ordinary atmospheric temperatures, *e.g.*, white phosphorus (m.p. 111°F.).

The tabulation on page 111 shows the principal World War chemical agents classified according to physical state.

PHYSIOLOGICAL CLASSIFICATION

This classification arranges chemical agents according to the effects they produce upon the living body. Both during and since the late war, the physiological classification systems of the principal countries has differed considerably; in order to compare these systems, we shall review briefly the salient points of each.

American Classification (World War) —In this system, the toxic substances are classified according to the predominant effects which they exert, with the understanding, however, that the action of any substance is not limited to a single tissue or group of tissues. Thus, a substance, the vapor of which causes injury to the respiratory passages, may, when applied to the skin, cause blistering. If the sole or chief usefulness of a substance in warfare depends upon its effect on the respiratory tract, it is classed as a *respiratory irritant*. If its power to produce casualties is due to its action on the skin, it is classed as a *skin irritant*. If both actions are useful, it is placed in both groups.

1. *Respiratory Irritants.*—By far the greatest number of substances thus far used injure the respiratory apparatus. Three groups may be differentiated:

a. Those which exert their chief effects on the delicate membranes in the lungs through which oxygen passes from the air into the blood. The main result of this injury is to cause fluid to pass from the blood into the minute air sacs and thus to obstruct the oxygen supplied to the blood. Death from one of these substances may be compared to death by drowning, the water in which the victim drowns being drawn into his lungs from his own blood vessels, *e.g.*, phosgene, chlorine, chlorpicrin, diphosgene.

b. Substances which injure the membranes which line the air passages. During normal life these membranes insure protection to the lungs against mechanical injury by particles which may be taken in with the air and against bacterial infection. As a result of the action of substances of this group, their protective power is lost. Portions of the membrane may become swollen and detached and may plug up the smaller passages leading to the lung tissue, or the damaged tissue may become the seat of bacterial infection, thus setting up bronchitis and pneumonia, *e.g.*, mustard gas, ethyldichlorarsine.

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c. Substances which affect chiefly the upper air passages, *i.e.*, the nose and throat. These substances cause intense pain and discomfort, but are not dangerous to life. They cause sneezing, painful smarting of the nose and throat, intense headache, a feeling of severe constriction of the chest, and vomiting. For varying periods after exposure, they may cause general muscular weakness and dizziness, loss of sensation in parts of the body or any transitory unconsciousness, *e.g.*, diphenylchlorarsine, diphenylcyanarsine.

2. *Tear Producers* (*Lacrimators*).—Certain substances have a powerful effect upon the eyes, causing copious flowing of tears, followed by reddening and swelling of the eyes, producing thereby effective temporary blindness. These effects are often produced by extremely minute quantities of tear-producing substances. Large quantities of the same substances usually act as lung irritants as well, *e.g.*, brombenzyl cyanide, bromacetone, ethyliodoacetate, chlorpicrin.

3. *Skin Blisterers* (*Vesicants*).—Certain substances have a powerful irritating effect upon the skin, very much like that produced by poison ivy. The same effect is produced upon all the surfaces of the body with which the substance may come in contact, such as the eyes and the breathing passages. Accordingly, a substance producing skin blistering will, if inhaled, also act as a powerful irritant of the air passages, *e.g.*, mustard gas.

American Classification (Postwar).—Agents are classified physiologically according to their most pronounced effect. The following are the terms usually employed:

1. *Lung Irritants.**—Agents which, when breathed, cause inflammation and injury to the interior cavity of the bronchial tubes and the lungs, *e.g.*, phosgene, diphosgene, chlorpicrin.

2. *Irritants* (*Sternutators*).—Those substances which produce violent sneezing and coughing followed by temporary physical disability. Sternutators are usually in the form of irritant smokes and the two are regarded as synonymous, *e.g.*, diphenylchlorarsine, diphenylaminechlorarsine, diphenylcyanarsine.

3. *Lacrimators.*—Agents which cause a copious flow of tears and intense, though temporary, eye pains, *e.g.*, bromacetone, brombenzyl cyanide, chloracetophenone.

4. *Vesicants.*—Agents which, when absorbed or dissolved in any part of the human body, produce inflammation and burns with destruction of tissues.

* The author has substituted the term *lung injurants* for this class of gases to distinguish them from the nose and throat irritants (sternutators).

British Classification (World War).—During the early part of the war, the British employed four classes, as follows:

1. Gases of permanent effect, roughly corresponding to our class of vesicants, *e.g.*, dichlorethyl sulfide.

2. Gases of temporary effect, roughly corresponding to our class of lung injurants, *e.g.*, phosgene.

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3. Gases having a nonfatal effect, corresponding to our irritants, *e.g.*, ethyliodoacetate.

4. Gases having a fatal effect, corresponding to our class of systemic poisons, *e.g.*, hydrocyanic acid gas.

Later on in the war, the British reduced their physiological classification to only two classes:

1. Lacrimatory agents (ethyliodoacetate).
2. Lethal agents (phosgene, chlorpicrin, mustard gas).

British Classification (Postwar).—Since the war, the British have adopted the following classification:

a. Vesicants, *e.g.*, mustard gas and lewisite.
b. Lung irritants, *e.g.*, phosgene, chlorine, chlorpicrin.
c. Sensory irritants, *e.g.*, diphenylchlorarsine, diphenylcyanarsine.
d. Lacrimators, *e.g.*, brombenzyl cyanide, xylyl bromide, etc.
e. Direct poisons of the nervous system, or paralysants, *e.g.*, hydrocyanic acid gas.
f. Gases which interfere with the respiratory function of the blood, *e.g.*, carbon monoxide.

"Broadly speaking, the gases in groups (*b*) and (*e*) may be regarded as lethal agents, and those in groups (*c*) and (*d*) as irritants, capable of putting a man out of action immediately, though only temporarily; whilst those of group (*a*), though intensely poisonous, have, when used against troops who are well disciplined in defence against gas, a casualty-producing power enormously in excess of their killing power".

French Classification (World War).—The French classification recognized seven classes as follows:

1. Highly toxic gases, *e.g.*, hydrocyanic acid.
2. Suffocating or asphyxiating gases, *e.g.*, chlorine, phosgene, diphosgene, chlorpicrin.
3. Lacrimators, *e.g.*, chloracetone, acrolein.
4. Vesicants, *e.g.*, mustard gas, dimethyl sulfate.
5. Sternutators, *e.g.*, diphenylchlorarsine, diphenylcyanarsine.
6. Labyrinthic, which affect the ear, *e.g.*, dichlormethyl ether.
7. Carbon monoxide.

French Classification (Postwar).—Since the war, the French have simplified their physiological classification to the following:

1. Irritant toxics comprising:
   a. Lacrimators, *e.g.*, benzyl bromide and xylyl bromide.
   b. Respiratory irritants or sternutators, *e.g.*, diphenylchlorarsine, diphenylcyanarsine.
2. Caustic toxics comprising:
   a. Lung caustics or suffocants, *e.g.*, chlorine and phosgene.
   b. Skin caustics or vesicants, *e.g.*, mustard gas, lewisite.
3. General toxics, *e.g.*, hydrocyanic acid type, comprising no actual well-differentiated subdivisions.

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German Classification (World War).—The early German classification distinguished three classes as follows:

1. Irritant gases (*Reizstoffe*) which cause only temporary injuries, comprising:
   a. Lacrimators, e.g., T-Stoff.
   b. Irritants, e.g., B-Stoff, Bn-Stoff, D-Stoff.
2. *Combat gases* (*Kampfstoff*) which cause more permanent injuries, *e.g.*, C-Stoff and K-Stoff.
3. Toxic gases (*Giftstoff*) which cause death or serious incapacitation, *e.g.*, hydrocyanic acid, diphosgene, chlorpicrin.

Later on in the war the middle-class (2) gases gradually dropped out and the Germans came to recognize only two great classes: (1) the nonfatal irritants, and (2) the fatal toxic gases.

German Classification (Postwar).—Since the war the Germans have adopted the following classification:

1. Lacrimators (*tränenerregende Kampfstoffe*), *e.g.*, bromacetone, xylyl bromide, bromhenzyl cyanide, chloracetophenone.
2. Sternutators (*niesenerregende Kampfstoffe*), *e.g.*, diphenylchlorarsine, diphenylcyanarsine.
3. Lung irritants (*lungenreizende Kampfstoffe*), *e.g.*, chlorine, phosgene, diphosgene, chlorpicrin, lewisite B.
4. Vesicants (*blasenziehende Kampfstoffe*), *e.g.*, chlorovinyldichlorarsine, dichlorethyl sulfide.
5. Nerve poisons (*Nervengifte*), *e.g.*, hydrocyanic acid.

On comparing the several World War physiological classifications with those of the postwar period, we find that there was much greater divergence among the various systems during the war than since then.

Thus it is noted that the German World War classification differed in principle from those of the Allies, the German classification being based solely upon the *degree* of physiological effect, while all the Allies' systems were based upon the *nature* of the effect.

Since the war there has been a gradual rapprochement of viewpoint in the matter of physiological classification so that now we find the principal nations in substantial agreement upon the following physiological classification of chemical agents:

1. *Lung injurants*—compounds which attack the pulmonary passages and lungs and generally prove fatal in a few hours if the gas is present in the usual field concentration.

2. *Irritants* (often called *sternutators*)—compounds which produce a strong local irritation of the nose and throat, causing violent sneezing and coughing. This irritation often extends to the stomach through the swallowing of saliva containing the irritant substance and causes severe headache, nausea, and vomiting. Exposure to strong concentrations of irritant compounds generally results in marked physical debility. How-

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ever, these effects are only temporary and are limited to the period of exposure and a few hours thereafter.

3. *Lacrimators*—compounds which act almost exclusively upon the eyes, producing a copious flow of tears and rendering vision impossible during the period of exposure and for from half an hour to an hour thereafter. Lacrimatory gases seldom have any other physiological effects in the concentrations employed in the field.

4. *Vesicants*—compounds which attack all body surfaces with which they came in contact (both internal and external), producing blisters and a general destruction of tissue similar to burns from fire. In addition to this surface action, most of the vesicants were also toxic if inhaled into the lungs in the form of vapor. Because of their multiple effects upon the body, the vesicants were by long odds the most prolific casualty producers of any military agents used in the late war.

5. *Systemic poisons*—compounds which usually attack the blood (as carbon monoxide) or the nerve centers (as hydrocyanic acid) and produce almost instant death by arresting the vital processes of the body at their motor centers. These agents are the most virulent poisons with respect to the quantity required to produce death but they are not the most fatal gases on the battlefield owing to their extreme volatility, light vapor density, and other peculiar properties which detract from their effectiveness in the field.

In addition to the above classes of gases, there are also the smoke and incendiary agents but, as they produce only slight or incidental physiological effects, they are usually omitted from the physiological classifications.

CLASSIFICATION ACCORDING TO PERSISTENCY

As the persistency of an agent in the field measures the length of

time its effective concentration can be maintained and hence the duration of its action in battle, the classification of chemical agents according to persistency of great practical importance.

For the purpose of comparison, we shall note briefly the practice of the principal nations with regard to this classification during and since the World War.

American Classification (World War).—The classification shown in the table on page 117 was employed by the American Army during the War:

American Classification (Postwar).—Since the World War, the American classification has been reduced to two classes by the elimination of the intermediate (moderately persistent) class, so that now agents which persist for more than 10 minutes in the open field are classed as *persistent*, while agents which persist less than 10 minutes are

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classsed as *nonpersistent*. In accordance with this scheme, only the following important chemical agents are nonpersistent: Cl, CG, HCN, CN, DM, DA, DC, WP, FM. All other agents are persistent.

AMERICAN WORLD WAR CLASSIFICATION ACCORDING TO PERSISTENCY

Class	Agents	Persistency		Remarks
		In open	In woods	
I. Nonpersistent....	VN Cl CG CNL DA DC	10 min.	3 hr.	These gases are very volatile, vaporizing entirely at the moment of explosion. They form a cloud, capable of giving deadly effects, but which loses, more or less rapidly, its effectiveness by dilution and dispersion into the atmosphere.
II. Moderately persistent.	NC PS PG PCC DG	3 hr.	12 hr.	These gases, having moderately high boiling points, are only partially vaporized at the moment of explosion. The cloud formed upon explosion is generally not deadly, but it immediately gives penetrative lacrimatory or irritant effects. The majority of the gas contents of the shell is pulverized and projected in the form of a spray of fog, which slowly settles on the ground and continues to give off vapors that prolong the action of the initial cloud.
III. Highly persistent.	HS CA BA	3 days	7 days	These gases, having a very high boiling point, are but little vaporized at the moment of explosion. A small portion of the contents of the shell is atomized and gives immediate effect, but by far the greater part is projected on the ground in the form of droplets which slowly vaporize and continue the action of the initial cloud.

Other Classifications.—The British, French, and Germans, neither during nor since the war, adopted any sharply defined classification of

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chemical agents in accordance with persistency. On the contrary, all three, while recognizing generally the two main classes—nonpersistent and persistent—failed to specify any definite time units to distinguish these classes.

Thus, from the British point of view,

> . . . gases are generally divided into two main categories:
>
> Nonpersistent.
> Persistent.
>
> Nonpersistent substances when liberated are rapidly converted into gas or smoke; clouds of gas so produced continue to be effective until dissipated by the wind and the sun.
>
> Persistent substances used in gas warfare are generally liquids, which contaminate the area on which they are released and continue to give off vapor for a considerable period. Mustard gas and most tear gases are typical examples. Whilst evaporation is going on the immediate neighborhood to leeward of the contamination is dangerous. In the case of gases such as mustard gas, which attack the skin, actual contact with contaminated ground or objects must be avoided".

The French view of this subject is clearly expressed by Hederer and Istin as follows:

> The military employment of the chemical arm leads to the distinction, on the basis of total particular toxic effect, between two categories of aggressive substances; the volatile substances and the persistent substances. The volatile substances are either gases, such as chlorine, or liquids of low boiling point and high vapor pressure, such as phosgene and hydrocyanic acid, which boil, respectively, at 46°F. and 79°F., or solids dispersed as ultramicroscopic particles, such as the chloride or cyanide of diphenylarsine.
>
> The first constitute the gaseous "clouds" and the second smokes which diffuse and rapidly vanish in open country.
>
> The persistent substances are, on the contrary, liquids of high boiling point and low vapor pressure, such as chlorpicrin and mustard gas, which boil, respectively, at 224°F. and 423°F. Their clouds condense upon the soil in the form of minute liquid droplets and evaporate slowly. These substances are generally endowed with great stability. They do not oxydize readily in contact with air and they hydrolyze only with difficulty.

As to German practice, Hanslian says:

> By persistence we understand the period of time during which a combat substance remains on the spot where it was liberated for tactical purposes, and exerts its effects there. This persistence is dependent first of all upon the volatility of the substance in question; it is greater the lower the volatility, and vice versa.
>
> . . . . . .
>
> From a tactical viewpoint, persistency is a matter of vital importance since it is this property which mainly determines whether or not a chemical agent is suitable for use on the offensive. Since attacking troops must traverse the ground between their

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> own position and that of the enemy, and, if their attack is successful, they must occupy the enemy's position, it is manifest that chemical agents employed in support of the attack must be of very low persistency so as to leave the terrain treated with such agents safe for occupancy by the attacking troops when they reach the enemy lines. Under normal battle conditions, it has been found that gases which persist for more than ten minutes after release upon open ground are dangerous to attacking troops when they traverse or occupy such treated areas and hence only nonpersistent gases are suitable for offensive operations, except when the attack is made on such a broad front that certain strong defensive areas can be avoided in the attack, in which case such areas may be treated with persistent gases.
>
> For general harrassing and for defensive operations, where the ground treated with chemical agents is not to be occupied by friendly troops, persistent agents are more effective and are generally employed for these purposes.
>
> For use of troops in the field, no military classification of chemical agents can ignore persistency and the more clear cut and definite the classification according to persistency, the more useful it is.

He then gives a tabulation of the persistencies of several of the more important chemical agents, calculated according to the Leitner formula (see page 21) and arranged in inverse order of persistence, but no segregation into classes according to persistency is made.

CLASSIFICATION ACCORDING TO DEGREE OF ACTION

By degree of action is meant the seriousness of the casualties inflicted by chemical agents and, as chemical agents vary all the way from simple lacrimation to almost instant death, there is a wide range in their degree of action.

From the viewpoint of military operations in the field, chemical agents are generally divided into three classes:

1. *Light-casualty* agents which produce simple lacrimation or temporary irritation of some part of the body, as the nose and throat, *e.g.*, sternutators.

2. *Moderate-casualty* agents which incapacitate for a period of from a few days to several weeks, but seldom cause permanent injuries or death, *e.g.*, the vesicant agents (mustard gas).

3. *Serious-casualty* agents which cause prolonged or permanent casualties and a high percentage of deaths, *e.g.*, lung injurants such as phosgene.

Closely associated with, and really forming a logical part of, the classification according to degree of action, is the further consideration as to the speed of action of chemical agents, *i.e.*, whether they produce immediate or delayed effects. In general, agents of the light-casualty class (1) and serious-casualty class (3) produce immediate effects, whereas those of the moderate-casualty class (2) produce delayed effects, but this rule is variable and there are notable exceptions both ways.

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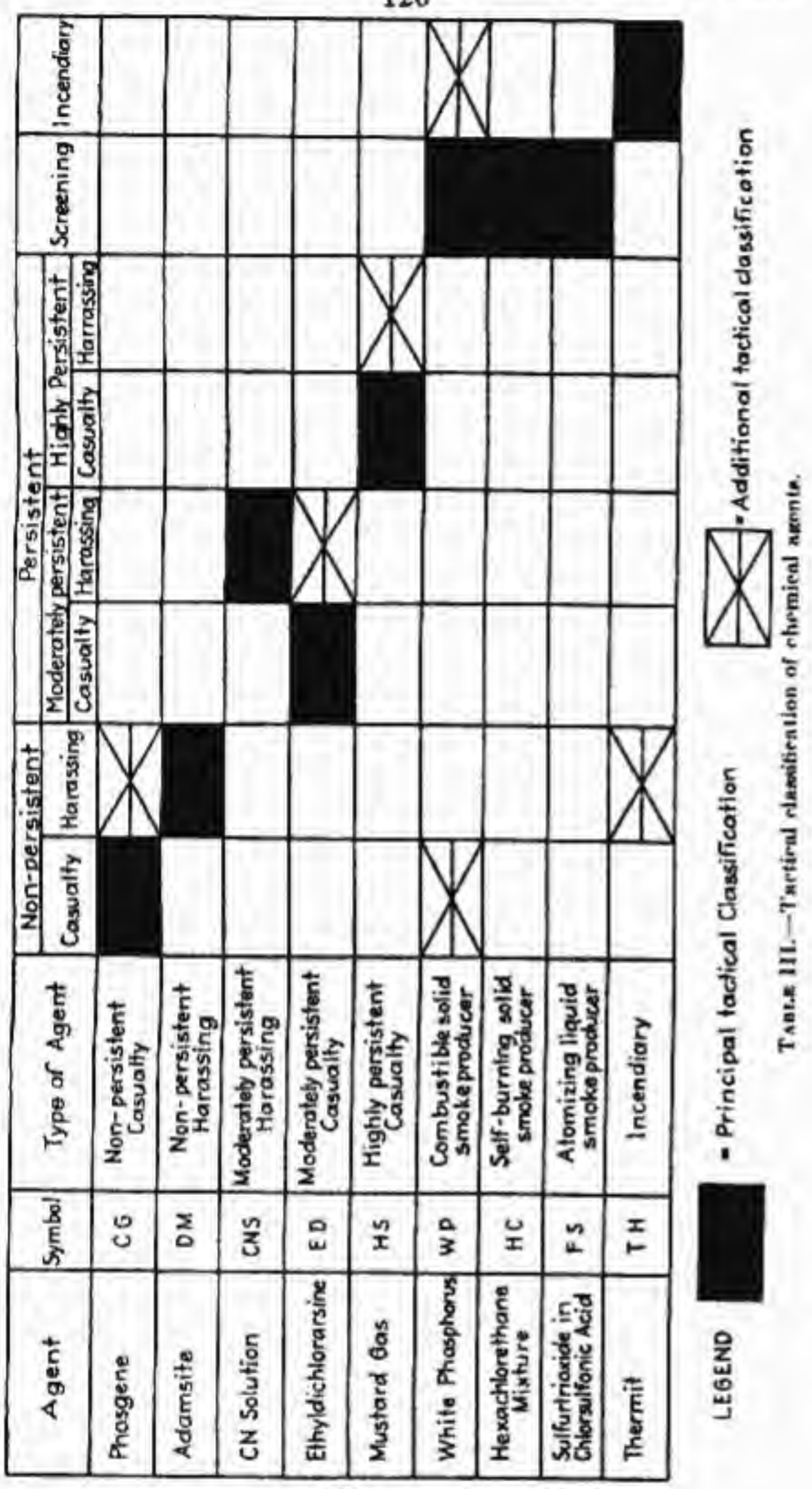

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TABLE III.—Tactical classification of chemical agents.

TACTICAL CLASSIFICATION

This classification is according to tactical use and logically embraces the following classes (see Table III):

1. Casualty agents, which include:
   a. Lung injurants.
   b. Vesicants.
   c. White phosphorus.
2. Harassing agents, which include:
   a. Lacrimators.
   b. Irritants (sternutators and irritant smokes).
3. Screening agents (obscuring smokes).
4. Incendiary agents.

MILITARY CLASSIFICATION

From the six classifications described above may be worked out a single mixed classification which is useful in military operations. This mixed or *military* classification groups all chemical agents into categories most useful to the using troops.

As the two things which are of paramount importance to commanders in the field are (1) *persistency* and (2) *nature of effects* produced upon the enemy, the most logical military classification is as follows:

MILITARY CLASSIFICATION OF COMBAT GASES

I. *Nonpersistent agents*

A. Lung injurants

1. Simple	Chlorine	(Cl_2)
	Methylsulfuryl chloride	($ClSO_2CH_3$)
	Ethylsulfuryl chloride	($ClSO_2C_2H_5$)
	Chlormethylchloroformate	($ClCOOCH_2Cl$)
	Phosgene	($COCl_2$)
	Dimethyl sulfate	($(CH_3)_2SO_4$)
	Perchlormethylmercaptan	($SCCl_4$)
	Trichlormethylchloroformate	($ClCOOCCl_3$)
	Chlorpicrin	(NO_2CCl_3)
	Phenylcarbylamine chloride	($C_6H_5CNCl_2$)
	Dichlormethyl ether	($(CH_2Cl)_2O$)
	Dibrommethyl ether	($(CH_2Br)_2O$)
2. Toxic	Phenyldichlorarsine	($C_6H_5AsCl_2$)
	Ethyldichlorarsine	($C_2H_5AsCl_2$)
	Phenyldibromarsine	($C_6H_5AsBr_2$)

B. Respiratory irritants (sternutators)

1. Simple	Diphenylchlorarsine	($(C_6H_5)_2AsCl$)
	Diphenylcyanarsine	($(C_6H_5)_2AsCN$)
	Ethylcarbazol	($(C_6H_4)_2NC_2H_5$)
	Diphenylaminechlorarsine	($NH(C_6H_4)_2AsCl$)
2. Toxic	Phenyldichlorarsine*	($C_6H_5AsCl_2$)
	Ethyldichlorarsine*	($C_2H_5AsCl_2$)
	Ethyldibromarsine*	($C_2H_5AsBr_2$)

* Primarily toxic lung injurants.

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C. Systemic toxics	Hydrocyanic acid	(HCN)
	Cyanogen bromide	(CNBr)
	Cyanogen chloride	(CNCl)
	Phenylcarbylamine chloride*	($C_6H_5HCCl_2$)

II. *Persistent agents*

A. Immediate effect

1. Pure lacrimators	Ethylbromacetate	($CH_2BrCOOC_2H_5$)
	Xylyl bromide	($CH_3C_6H_4CH_2Br$)
	Benzyl bromide	($C_6H_5CH_2Br$)
	Ethyliodoacetate	($CH_2ICOOC_2H_5$)
	Benzyl iodide	($C_6H_5CH_2I$)
	Brombenzyl cyanide	($C_6H_5CHBrCN$)
	Chloracetophenone	($C_6H_5COCH_2Cl$)
2. Toxic lacrimators	Chloracetone	(CH_3COCH_2Cl)
	Bromacetone	(CH_3COCH_2Br)
	Iodoacetone	(CH_3COCH_2I)
	Acrolein	(CH_2CHCHO)
	Brommethylethyl ketone	($CH_3COCHBrCH_3$)
	Chlorpicrin†	(CCl_3NO_2)
	Phenylcarbylamine chloride†	($C_6H_5CHCl_2$)

B. Delayed effect

1. Pure vesicants	Dimethyl sulfate†	($(CH_3)_2SO_4$)
2. Toxic vesicants	Methyldichlorarsine	(CH_3AsCl_2)
	Dichlorethyl sulfide	($S(C_2H_4Cl)_2$)
	Phenyldichlorarsine†	($C_6H_5AsCl_2$)
	Phenyldibromarsine†	($C_6H_5AsBr_2$)
	Ethyldichlorarsine†	($C_2H_5AsCl_2$)
	Chlorvinyldichlorarsine	($ClCHCHAsCl_2$)

* Primarily toxic lung injurants.
† Primarily lung injurants.

While the above classification is a logical and useful arrangement to combat gases in accordance with properties of primary importance to troops in the field, it is more fortuitous than rigid in its application. Thus, while all vesicant gases heretofore in use have been persistent and have had delayed effects on men and animals, it does not follow that all future vesicants will necessarily have these properties, for there is no known connection between vesication and persistency, or between vesication and delayed effects. On the contrary, it is entirely possible that a nonpersistent vesicant, or one that is immediately effective, will be discovered. There is an urgent tactical demand for such a type of gas and there is no reason why it cannot be found. Similarly, there is no inherent reason why lung-injurant or respiratory-irritant gases should be nonpersistent and it is readily conceivable that persistent gases of these two classes may exist.

Accordingly, all we can say for the military classification indicated above is that it accords with the known facts today and is a logical and useful arrangement. If and when exceptions to this classification appear,

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as is not at all unlikely, we shall then have to amend our arrangement

and formulate a new classification in accordance with the new facts.

MARKING SYSTEMS

In order to indicate to troops in the field essential information concerning the type and character of the fillings contained in chemical projectiles, each nation adopted a special system of marking such projectiles. As the basic theory of the several marking systems used in the war was quite different, the principal features of each will be noted here.

German System.—We have said that the German World War classification of combat gases differed in principle from the classifications of the Allies, in that the German system was based primarily upon the *degree* of effect exerted by the gas, whereas the Allies' systems were predicated upon the *nature* of the effect, *i.e.* whether *lung* injurant or vesicant, etc. Based upon the fundamental idea of degree of effect, the German system grouped all gases into four major classes, with distinguishing marks, as follows:

Class	Physiological action	Marking
1. Harmless gases	Lacrimators (*Augenreizstoff*)	White Cross (*Weisskreuzkampfstoffe*)
T-Stoff	Xylyl bromide	
B-Stoff	Bromacetone	
Bn-Stoff	Brommethylethylketone	
2. Slightly harmful gases	Irritants (*Reizstoffe*)	Blue Cross (*Blaukreuzkampfstoffe*)
Clark I	Diphenylchlorarsine	
Clark II	Diphenylcyanarsine	
Dick	Ethyldichlorarsine	
3. Moderately harmful gases	Vesicants (*blasenziehende Kampfstoffe*)	Yellow Cross (*Gelbkreuzkampfstoffe*)
Lost	Dichlorethyl sulfide	
D-Stoff	Dimethyl sulfate	
	Dichlormethyl ether	
4. Severely harmful	Lung injurants (*lungenreizende Kampfstoffe*)	Green Cross (*Grünkreuzkampfstoffe*)
Chlor	Chlorine	
Phosgen (D-Stoff)	Carbonyl chloride	
Perstoff (diphosgene)	Trichlormethylchloroformate	
Klop (chlorpicrin)	Nitrochloroform	
K-Stoff	Monochlormethylchloroformate	

All projectiles containing gases belonging to any one of the above groups were marked with a corresponding colored cross, as indicated.

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To identify further particular gases within a group, additional marks were used. Thus, if a shell contained diphosgene, it was marked with a green cross; if it contained diphosgene mixed with chlorpicrin, it was marked with a green cross and the figure 1; if it contained phosgene, diphosgene, and diphenylchlorarsine, it was marked with a green cross and the figure 2. Similarly, diphenylchlorarsine was marked with a blue cross and the figure 1, while diphenylcyanarsine was marked with a blue cross and the figure 2. Also ethyldichlorarsine was distinguished from mustard gas (yellow cross) by adding the figure 1 to denote the former filling.

The earlier type shell containing lacrimators and simple irritants were marked with large white letters thus, "B" for B-Stoff, "C" for C-Stoff, and "D" for D-Stoff, etc. There was no uniform body color to denote gas shell as a whole; the earlier types of gas shell were painted gray, whereas the later types were painted blue with a yellow ogive. Smoke shell were painted gray with a black letter "N" (*Nebel*, fog) to distinguish them from gas shell.

Incendiary shell were painted red all over with the word "Brand-Gr" on the side in black letters to distinguish from certain types of HE shell which were also painted red.

The principal defects in the German marking system were: (1) the lack of a distinctive uniform body color to distinguish chemical shell from other types; and (2) the absence of means for indicating the relative persistency of the various chemical fillings, which is of great importance to tactical operations in the field. This second defect was somewhat mitigated by the circumstances that, as a whole, the Green and Blue Cross shell were nonpersistent, while the Yellow Cross were persistent. But this was more fortuitous than deliberate, and the lines of demarcation were not clear cut. Shell containing ethyldichlorarsine were at first marked as Yellow Cross 1, but were later changed to Green Cross 3, when it was found that this gas was sufficiently nonpersistent to be used on the offensive.

French System.—French chemical shell were distinguished from other types by a body color of dark green, and the incendiary shell were distinguished from the gas shell by a red ogive. There were no French smoke shell, distinguished as such. Certain gas shell had a sufficient amount of smoke-producing material to make a visible cloud on burst, but they were regarded as gas shell.

Chemical fillings, regardless of whether they were gas, gas with smoke, or incendiary, were denoted by certain code numbers, sometimes in combination with colored bands or stripes on the shell. The code numbers were purely arbitrary and were not arranged in any way to indicate persistency or even the type of chemical filling. On the contrary, the

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numbers seem to have been chronologically assigned to each filling as it was adopted.

The following table gives the principal French chemical shell with their markings:

Shell	Charge	Markings
75 mm. incendiary	Carbon disulfide; white phosphorus; cylinder of incendiary in celluloid	Green ogive, red body, No. 2 on top of ogive and also on bottom
75 mm. incendiary	White phosphorus; neutral liquid	Green ogive, red body, No. 3 on top and bottom
75 mm. gas	Vincennite quarternaire (V4)	Green, 2 white rings, No. 4 on top and bottom
75 mm. gas	Vitrite; manganite; marsite	White Bands, "4B" on ogive, base and shell case
75 mm. gas and smoke	Collongite, $\frac{3}{5}$; opacite, $\frac{1}{5}$	Green, 1 white ring, No. 5 on top and bottom
75 mm. gas and smoke	Aquinite, $\frac{3}{4}$; opacite, $\frac{1}{4}$	Green, 1 orange-yellow ring, No. 7 on top and bottom
75 mm. gas and smoke	Martonite; opacite	Green, 1 orange-yellow ring, No. 9 on top and bottom
75 mm. gas	Yperite with solvent	2 orange-yellow bands, "20"
75 mm. gas	Camite, 13; aquinite, 100	1 orange-yellow band, "21"
155 mm. gas and smoke	Collongite, $\frac{2}{5}$; opacite, $\frac{3}{5}$	Green body, 1 white ring, No. 5 on top ogive
155 mm. gas	Aquinite, $\frac{3}{4}$; opacite, $\frac{1}{4}$	Green body, 1 white ring, No. 7 on top of the ogive
155 mm. gas	Yperite with solvent	2 orange-yellow bands, "20" on top of ogive
155 mm. F.A. gas	Camite, 13; aquinite, 100	1 orange-yellow band, "21" on top of the ogive
15 mm. F.A. incendiary, Naud.	Carbon disulfide and tar; phosphorus 1; kilogram cylinder of incendiary matter	Green body, red head, and black ring
155 mm. Naud (steel)	Carbon disulfide and tar; white phosphorus; cylinder of incendiary	Green body, red head, and black ring

The French system of marking, being purely arbitrary, had little to recommend it. The information denoted by the code numbers applied only to the filling and, unless troop commanders were very familiar with the properties of these fillings (which was seldom the case), they had little or no guidance in the use of chemical shell in the field. Moreover, the numbers painted on the shell frequently became more or less obliterated, and when they were illegible, the different kinds of gas shell frequently could not be distinguished.

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British System.—The three classes of British chemical shell were distinguished from each other and from all other types of shell by distinctive body colors, as follows: gas shell were painted gray; smoke shell, light green; and incendiary shell, red. In addition, for gas shell, the kind of *gas* filling was indicated by a system of colored stripes encircling the body of the shell as follows:

Filling	Marking bands
SK (ethyliodoacetate)	No bands

KSK	No bands, letters HVV
PS (chlorpicrin)	1 white
PG (50 per cent chlorpicrin)	2 white
NC (80 per cent chlorpicrin; 20 per cent stannic chloride	1 white, 1 red, 1 white
VN (vincennite)	1 white, 1 red
CG (phosgene)	1 red, 1 white, 1 red
CBR	1 red
BB (mustard gas)	4 red

The smoke shell were also distinguished by having a red ring painted around the ogive, close to the nose of the shell, and the letters "PHOS" stenciled in black on the side of the shell to denote phosphorus filling.

The incendiary shell were without distinguishing marks, except all over red color.

From the foregoing, it is apparent that the British system was an improvement of the French, in that each class of chemical shell was distinguished from all other types and the kind of filling was indicated by bands that were more readily identified than the French code numbers. However, the British system also failed to denote the persistency of the gas fillings as a guide to use in the field; in this respect it was open to the same objections as the French system.

American System (World War).—In the war, American chemical shell were distinguished from all other types by a gray body color and black letters reading "Special Gas," "Special Smoke," or "Special Incendiary." The three classes of chemical shell were further distinguished by distinctive color stripes encircling the body of the shell, as follows: gas shell—white and/or red stripes: smoke shell—yellow stripes; incendiary shell—purple stripe.

Among gas shell, those filled with nonpersistent gases were distinguished by white stripes; those with persistent fillings by red stripes; and those with semipersistent fillings with combination white and red stripes. Furthermore, within each group of gases the number of stripes denoted the relative persistency. That is, the least persistent gas of the nonpersistent group was denoted by one white stripe, the next least persistent gas by two white stripes, etc. Similarly, among the persistent

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group, the least persistent gas was denoted by one red stripe, the next least persistent by two red stripes, etc.

The following tabulation shows the chemical fillings used in the war and the markings employed to denote them:

Filling	Marking stripes
Nonpersistent Gases	
DA (diphenylchlorarsine)	1 white
CG (phosgene)	2 white
PD (CG and DA)	3 white
Semipersistent Gases	
PS (chlorpicrin)	1 red, 1 white
NC (chlorpicrin and stannic chloride)	*1 yellow, 1 red, 1 white
PG (PS and CG)	1 white, 1 red, 1 white
Persistent Gases	
BA (bromacetone)	1 red
CA (brombenzyl cyanide)	2 red
HS (mustard gas)	3 red
Smokes	
WP (white phosphorus)	1 yellow
FM (titanium tetrachloride)	2 yellow
Incendiary	
Incendiary mixture	1 purple

*Stannic chloride is a smoke producer, hence the yellow stripe to denote this fact.

From the foregoing, it will be seen that the American marking system was by far the most logical and informative scheme of identifying chemical fillings of any of the marking systems used in the war. It not only distinguished chemical shell from other types, and the three classes of chemical fillings from each other, but it also identified each gas by a mark which indicated to what persistency group the gas belonged and its relative persistency therein. The American system had the further advantage that if a more effective gas of any group were substituted for a less effective gas, no change in the marking of the shell would be necessary. Thus, suppose a more effective lacrimator were substituted for BA. If this new gas were less persistent than CA the shell containing it would continue to be marked with one red stripe. If, however, the new gas were more persistent than CA, but less than HS, the new gas shell would be marked with two red stripes and the shell thereafter filled with CA would be marked with one red stripe to denote the fact that CA was now the least persistent gas of the persistent group.

American System (Post War).—The only disadvantage of the American World War marking system was the number and variety of markings used to denote gas shell, but this was due to the large number of gases which had to be distinguished. Since the war the effort has been to reduce the number of standard chemical fillings to the minimum. To this end, only one chemical filling of each type is now approved as stand-

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ard, *i.e.*, one nonpersistent, one persistent gas, one irritant gas, one smoke and one incendiary filling. When a new filling is developed to a point where it is found to be more effective than any of the existing standard types, it is adopted as the standard for its type and the former standard gas then becomes a substitute standard if it is desired to retain it for possible substitute use, or if not, it is declared obsolete and dropped.

A comparison of the present classification and marking system with the American World War practice shows a marked simplification. While the system of stripes to denote type of chemical agent is retained, these stripes no longer distinguish degree of persistency as between gases of the same type. This is not serious, however, so long as there is but one gas of any one type in use, as is now contemplated.

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CHAPTER VI

LACRIMATORY AGENTS

The first toxic gases employed in the World War were the lacrimators, *i.e.*, substances having a specific action on the eyes and producing a copious flow of tears and temporary blindness. In the concentrations used in battle, neither the eyeball nor the optic nerve was injured and only in rare cases (as when a soldier was so near a shell burst as to have the liquid chemical splashed in his eyes) was any corneal injury experienced. In fact, so transitory was the effect of these early lacrimatory gases that no one, at the time of their introduction, appeared to regard them as *toxic* gases coming within the prohibitions of the Hague Conventions of 1899 and 1907. As a matter of fact, however, most of the World War lacrimators were equally as toxic as many of the lethal gases used. For a comparison of the relative toxicities of the lacrimatory and lethal gases see the tables on pages 14 and 16.

Perhaps the reason why no protest was made over the initial use of lacrimatory gases was that, in the low concentrations ordinarily encountered in the open, temporary lacrimation was the only effect produced, and no one regarded these substances as militarily effective. However, when these gases were employed against enclosed places, such as field fortifications, deep trenches, dugouts, etc., where their vapors could accumulate, toxic concentrations could be built up and serious casualties result. Since toxic concentrations could thus be produced in battle, it is clear that most of the World War lacrimators were in fact *toxic* gases and did come within the prohibitions of the Hague Conventions.

The principal lacrimators employed in the late war, in the order of their introduction are shown in the table on page 130.

As will be noted in the table, the lacrimators fall naturally into two groups: (1) *simple* lacrimators, which in ordinary field concentrations affect the eyes only; and (2) *toxic* lacrimators, which in ordinary field concentrations not only affect the eyes but also exert certain toxic effects against other parts of the body. All the toxic lacrimators, in addition to their lacrimatory action, are also lung injurants. In the cases of chlorpicrin and phenylcarbylamine chloride, their lung-injurant effects are so much more pronounced than their lacrimatory effects that they are usually classed as lung-injurant agents (see Chap. VII).

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Agent	Introduced by	Date
Simple lacrimators		
Ethylbromacetate	French	August, 1914
Xylyl bromide	Germans	January, 1915
Benzyl bromide	Germans	March, 1915

Brommethylethyl ketone	Germans	July, 1915
Ethyliodoacetate	British	September, 1915
Benzyl iodide	French	November, 1915
Brombenzyl cyanide	French	July, 1918
Chloracetophenone	Americans	Postwar

Toxic lacrimators

Chloracetone	French	November, 1914
Bromacetone	Germans	July, 1915
Iodoacetone	French	August, 1915
Acrolein	French	January, 1916
Chlorpicrin*	Russians	August, 1916
Phenylcarbylamine chloride*	Germans	May, 1917

* Primarily lung injurants.

GROUP CHARACTERISTICS

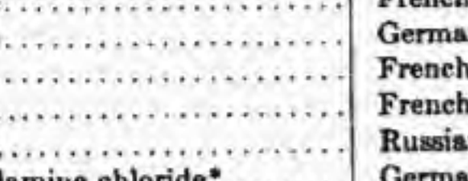
The lacrimators, as a group, have certain well-defined properties in common, the most important of which are the following:

1. They all have the power to irritate certain tissues only, *i.e.*, the eyes, and without producing noticeable lesions; their action is thus both elective and reversible since they affect only one organ, and the irritation produced quickly disappears.

2. Their threshold of action is low, *i.e.*, they are effective in extremely low concentrations, such as a few thousandths of a milligram per liter, and can produce an intolerable atmosphere in concentrations as low as one-thousandth of that required for the most effective lethal agents.

3. They are quick acting, producing almost instantaneous physiological effects (in less than 1 minute) in the form of a muscular reaction of the eyelids, closing the eyes, and a glandular reaction from the lacrimatory glands, producing a copious flow of tears.

4. Chemically they are very closely related, being formed by a central atom of carbon, carrying a halogen and one or several negative groups in which the hydrogen atoms are readily displaced. Hederer and Istin (15), quoting Professor Job, give the following type formulas which explain the chemical relationships of the lacrimators to each other:



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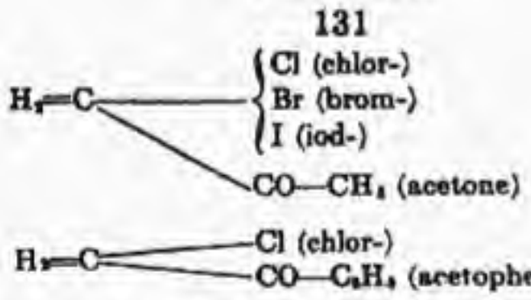

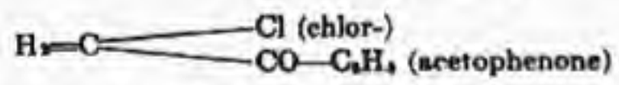

5. Physically, the lacrimators are, in general, liquids of relatively high boiling points and low vapor pressures. They are, therefore, essentially nonvolatile substances that form persistent gases.

Since all the lacrimators are practically insoluble in water, although readily soluble in fats and organic solvents, on coming in contact with the moist surfaces of the eyeball and conjunctiva, they are not diluted by the moisture encountered but are rapidly absorbed by the epithelial surfaces. The effect upon the sensitive nerves at once produces an irritation that passes rapidly from a slight tingling sensation to an intolerable smarting and terminates in a muscular reaction, closure of the eyelids, and a secretion of tears. The reflex action of closing the eyelids and the profuse secretion of tears produces a suspension of vision which, however, usually persists but a few minutes after termination of the exposure to the lacrimatory atmosphere, and rarely produces any pathological lesion or injurious aftereffects.

A marked peculiarity of the lacrimators as a group is their relative ineffectiveness against animals. Thus it was noted early in the war that concentrations which caused profuse lacrimation in men produced no visible effect upon horses and mules. From careful tests, using brombenzyl cyanide as the agent, it was found that it was necessary to use a solution 100 times as strong to lacrimate a dog and 1,000 times as strong to lacrimate a horse to the same degree as a man. The reason for this great difference in the sensitiveness to lacrimation between men and animals has never been satisfactorily explained, though the fact is well established by tests and war experience.

Although lacrimators were used throughout the World War, their employment was more and more limited as other more powerful gases were introduced. During the whole period of the war, about 6,000 tons of lacrimators were used in battle. This was less than 5 per cent of the total tonnage of toxic gases used. However, owing to their effectiveness in extremely low concentrations, forcing troops to mask, with its attendant disadvantages, lacrimators served a useful purpose in the war. Also, owing to their total lack of permanent injury, lacrimators are well adapted for controlling mobs and suppressing domestic disturbances; they have been used in increasing amounts for this purpose since the World War.

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As the later lacrimators are far more powerful than their earlier predecessors, they are of the greatest interest, particularly, as to the future. However, in order to trace the development of the lacrimators as a group and to compare the properties of each with the others, a brief description will be given of each in the chronological order of its introduction.

Ethylbromacetate ($CH_2BrCOOC_2H_5$)

The first combat gas used in the war was *ethylbromacetate*, which was employed by the French in rifle grenades as early as August, 1914. In November, 1914, owing to a shortage of bromine from which brominated compounds could be made, chloracetone was substituted as a filling in the French gas grenades (1).

Ethylbromacetate was first prepared by Perkin and Duppa in 1858 by heating bromacetic acid and alcohol in sealed tubes. The compound was thus known long before the World War and was used in many ways in industry in the manufacture of other chemical substances. Its highly irritant effect upon the eyes was also well known to chemists. This property and the fact that it is easily manufactured and handled were perhaps the reasons for its employment in 1912 as a filling for hand bombs by the Paris police for temporarily disabling criminals and facilitating their arrest. The success attained by the French police in suppressing lawless gangs with this gas undoubtedly led to adoption by the French Army as a filling for 26-mm. rifle grenades.

According to German authors, the French had actually manufactured a quantity of these gas-rifle grenades before the outbreak of the World War, and 30,000 were taken into the field by the French Army in August, 1914, and used during that summer. The French deny this and assert that the hand bombs filled with ethylbromacetate were used for police purposes only. However, regardless of whether or not the French actually manufactured rifle gas grenades *prior to the World War*, they certainly appear to have been employed by the French Army during the first months of the war, and the chemical filling used was ethylbromacetate.

According to Mueller, ethylbromacetate is prepared by the bromination of acetic acid in the presence of red phosphorus and the subsequent esterification with alcohol of the bromacetic acid obtained.

It is a transparent liquid of 1.5 specific gravity, which boils without decomposition at 168°C. (334.4°F.), and does not react with iron. It is almost insoluble in water and is only slowly hydrolyzed thereby.

Ethylbromacetate is very irritating to the eyes and nasal passages, causing lacrimation in concentrations as low as 0.003 mg. per liter. At 0.04 mg. per liter, the concentration becomes intolerable to the eyes, and

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a concentration of 2.30 mg. per liter is lethal on 10 minutes' exposure. Its toxicity is, therefore, over twice that of chlorine. Its volatility is 21.00 mg. per liter at 20°C. (68°F.), so that field concentrations of nearly ten times the lethal dose are practicable.

On account of the scarcity of bromine, ethylbromacetate was displaced by chloracetone in November, 1914, and was not used thereafter. Its use was, therefore, very limited and, aside from the fact that it was the first combat gas used in the World War, this compound was not important.

Chloracetone (CH_3COCH_2Cl)

French: "Tonite"

Chloracetone was introduced by the French in November, 1914, as a substitute for ethylbromacetate in hand and rifle gas grenades. It is obtained by the direct chlorination of acetone and is a clear liquid, of 1.16 specific gravity, which boils at 119°C. (246.2°F.), yielding a vapor 3.7 times heavier than air. Chloracetone is only slightly soluble in water and is not decomposed thereby. It tends, however, to polymerize into a relatively inert form on long storage.

It has a pungent odor like that of hydrochloric acid and lacrimates the eyes (conjunctiva) in concentrations as low as 0.018 mg. per liter. A concentration of 0.10 mg. per liter is intolerable after 1 minute of exposure, and a concentration of 2.30 mg. per liter is lethal on 10 minutes' exposure. It is, therefore, about as toxic as ethylbromacetate. However, it is much more volatile so that its ordinary field concentrations are much higher than those of ethylbromacetate.

Because charcoal readily absorbs chloracetone and therefore even the early gas masks afforded adequate protection against it and because bromacetone proved to be a better tear gas, chloracetone was displaced in 1915 by bromacetone and other more powerful lacrimators then introduced. A relatively small amount of chloracetone was used in the war, and it played but a minor role in the early stages of gas warfare.

Xylyl Bromide ($C_6H_4CH_3CH_2BR$)

German: "T-Stoff"

In the early experiments with various chemical compounds, in an effort to produce more powerful lacrimators, the Germans found that, in general, the bromine derivatives were far more effective than the corresponding chlorine compounds; as there was then no shortage of bromine in Germany (as in France and England), the German chemists proceeded to develop for chemical warfare a series of bromine compounds of which

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xylyl bromide was the first. The first use of this gas in battle was in artillery shells fired against the Russians at Bolimow on Jan. 31, 1915, and its first employment on the Western Front was against the British at Nieuport in March, 1915. The firing of these shells against the Russians not only constituted the first use of gas in artillery shell* but was also the first use of gas in a major operation in the World War, antedating, as it does, the celebrated cloud-gas attack at Ypres in April, 1915, by three months.

* Strictly speaking, the first German gas used in the World War was chlorsulfate of ortho-dianisidin, a powder which was filled between the lead balls of the 10.5-mm. shrapnel. However, only one trial lot of these shell was used on Oct. 27, 1914, at Neuve-Chapelle and, as the success obtained was not sufficient to warrant further use of this material, it was abandoned.

Xylyl bromide is prepared by the direct bromination of xylene and consists of a mixture of the three isomeric substitution products of the ortho-, meta-, and para-xylene present. When pure, the xylyl bromides are light yellow slightly viscous liquids, while the xylylene bromides are solids. Crude xylyl bromide consisted of a mixture of xylyl and xylylene bromides and, as used in gas warfare, was a black liquid, of 1.4 specific gravity, which boils at from 210° to 220°C. (410° to 428°F.), yielding a pungent aromatic vapor, 8.5 times heavier than air, with an odor resembling lilacs. As it corrodes iron and steel very rapidly, xylyl bromide had to be loaded into lead containers which were in turn placed in the shell. Later in the war, lead and enamel linings were developed which successfully protected the shell from corrosion and made the inner lead containers unnecessary.

Xylyl bromide is an extraordinarily powerful irritant to the eyes (conjunctiva). It can be detected by sensitive individuals in concentrations as low as 0.00027 mg. per liter, whereas its lacrimatory concentration is 0.0018 mg. per liter. A concentration of 0.015 mg. per liter is intolerable after 1 minute, and a concentration of 5.60 mg. per liter is lethal on 10 minutes' exposure. Hence while xylyl bromide is a much stronger lacrimator, its toxicity is only half that of ethylbromacetate.

On account of its low volatility (0.60 mg. per liter at 68°F.), xylyl bromide was not very effective at low temperatures, and it was also very readily absorbed by the charcoal in gas-mask canisters, so that masks furnished adequate protection against it. Owing to these facts and its corrosive properties, it was replaced in 1917 by more volatile and powerful substances. However, xylyl bromide played an important role in the history of gas warfare. About 500 tons of T-Stoff were fired by the Germans and, while no serious casualties were produced thereby, this gas first showed the tactical importance of gas shell and paved the way for the more effective gas shell which followed.

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Benzyl Bromide ($C_6H_5CH_2Br$)

German: T-Stoff; French: "Cyclite"

The second bromine compound introduced by the Germans was benzyl bromide. It was first used by them at Verdun in March, 1915, in an effort to obtain a more volatile substance than xylyl bromide, but the improvement was not marked for, while benzyl bromide is somewhat more volatile, it is less irritating than xylyl bromide. The French also later used this compound under the name of "Cyclite."

Benzyl bromide is prepared by the direct bromination of toluene in the same way as xylyl bromide is obtained from xylene. In its pure state, benzyl bromide is a transparent liquid, with a specific gravity of 1.44, which boils at 201°C. (393.8°F.), yielding vapor 6.0 times heavier than air and with a pleasant aromatic odor resembling water cress. It is insoluble in water and is only very slowly decomposed thereby. Its great chemical stability, low vapor pressure, 2.0 mm. Hg at 20°C. (68°F.), and low volatility, 2.4 mg. per liter at 20°C. (68°F.), assures its persistence on the terrain.

While benzyl bromide is a decided eye irritant, its effect is not nearly so great as that of xylyl bromide. Thus, a concentration of 0.004 mg. per liter is required to produce any irritation at all, and the concentration does not become intolerable until it attains 0.06 mg. per liter. In higher concentrations, it also produces much irritation of the nose, throat, and air passages with salivation and nausea. Its lethal concentration for 10 minutes' exposure is 4.50 mg. per liter, as compared to 5.60 mg. per liter for xylyl bromide.

Like other bromide compounds, benzyl bromide corrodes iron and steel and must, therefore, be kept in lead- or enamel-lined containers. It was used in battle in small quantities for a short time because its irritant power was much less than that of other compounds, and its basic component—toluene—was more urgently needed for the manufacture of high explosives. For these reasons, and the fact that charcoal thoroughly absorbs its vapors, it is unlikely that benzyl bromide will ever be used again as a chemical agent.

Bromacetone (CH_3COCH_2Br)

German: "B-Stoff"; French: "Martonite"; British and American: "BA"

Not satisfied with the slight improvement of benzyl bromide over xylyl bromide, the Germans soon brought out a third bromine compound —bromacetone—in an effort to solve the problem of a more easily volatilized irritant. It was also used by the French, mixed with 20 per cent chloracetone, under the name "Martonite," and by the British and Americans under the symbol "BA." This compound was the most

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widely employed of any of the pure lacrimators, more than 1,000 tons being fired in projectiles alone, not to mention use in other weapons such as hand and rifle grenades. Bromacetone is the bromine compound which corresponds to chloracetone and is produced in a similar manner, *i.e.*, by the direct bromination of acetone. It is a colorless liquid, of 1.6 specific gravity, which boils at 135°C. (275°F.), yielding a vapor 4.7 times heavier than air. On long standing, bromacetone decomposes, gradually changing to a black resinous mass, during which process hydrobromic acid is released. Although bromacetone is not soluble in and is not decomposed by water, it is nevertheless a rather unstable compound, as it decomposes even in its purest form, particularly under the influence of heat and light.

Bromacetone was one of the most effective lacrimators used in the war. It produces an irritating effect upon the eyes in concentrations as low as 0.0015 mg. per liter while, a concentration of 0.010 mg. per liter is intolerable, and a concentration of 3.20 mg. per liter is lethal on 10 minutes' exposure. The toxicity of bromacetone is thus intermediate, between that of ethylbromacetate (2.30 mg. per liter) and xylyl bromide

(5.60 mg. per liter).

At 20°C. (68°F.), the vapor pressure of bromacetone is 9 mm. Hg and its volatility 75.0 mg. per liter. Owing to its relatively high volatility, toxic concentrations of bromacetone were often encountered in the field, so that, in addition to its lacrimatory power, this compound is classed as a toxic lacrimator. Moreover, *liquid* bromacetone, on contact with skin, produces blisters which, although they heal rapidly, are extremely painful on the sensitive parts of the body.

In the late war, bromacetone was used by the Germans in artillery (Green T) shells and trench-mortar bombs (B-Minen) for only a short time, owing largely to the ever-increasing demand for acetone for other purposes. The British also used it for a short time until it was replaced by more effective iodine compounds. In the mixture Martonite (80 per cent bromacetone and 20 per cent chloracetone), it was used by the French and Americans throughout the war, although it was rapidly being displaced toward the end of the war by the more powerful compound, brombenzylcyanide, introduced by the French in the summer of 1918.

Brommethylethyl Ketone ($CH_3CO.CH.Br.CH_3$)

German: "Bn-Stoff"; French: "Homomartonite"

By the summer of 1915, the demand for acetone as a solvent for nitrocellulose in the manufacture of powder and dopes for airplane fabrics became so great that both sides began to look for substitutes for bromacetone, with the result that in July, 1915, the Germans introduced brom-

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methylethyl ketone (Bn-Stoff), while the French followed with a mixture of brommethylethyl ketone and chlormethylethyl ketone, under the name "Homomartonite," so called because of its great similarity to Martonite (80 per cent bromacetone and 20 per cent chloracetone) in chemical composition and physiological action.

Methylethyl ketone is present in large quantities in the "acetone oils," which are by-products in the manufacture of acetone from wood, and, if this compound is brominated in a way similar to acetone, brommethylethyl ketone is obtained. When freshly distilled, it is a faintly yellow liquid, insoluble in water, of 1.43 specific gravity, and boils with some decomposition at 145°C. (293°F.), yielding a vapor 5.2 times heavier than air.

The vapor pressure of brommethylethyl ketone is 15.0 mm. Hg at 14°C. (57.2°F.), while its volatility at 20°C. (68°F.) is 34.0 mg. per liter. It is thus less persistent than xylyl bromide. Like all bromine compounds, it corrodes iron and steel and requires lead- or enamel-lined receptacles for storage.

Brommethylethyl ketone is a powerful lacrimator, being more powerful than benzyl bromide and only slightly less powerful than bromacetone, which it resembles to an extraordinary degree in its other properties. Thus, its minimum lacrimatory concentration is 0.0126 mg. per liter, while a concentration of 0.016 mg. per liter is intolerable and a concentration of 2.00 mg. per liter is lethal on 10 minutes' exposure. Owing to its high toxicity and volatility, toxic concentrations of brommethylethyl ketone may readily be produced in the field; for this reason this compound is classed as a toxic lacrimator.

On the whole, brommethylethyl ketone was not so effective a war gas as bromacetone, and its substitution for bromacetone was solely for economic reasons relating to the shortage of acetone.

Iodoacetone ($CH_3CO.CH_2I$)

French: "Bretonite"

The scarcity of bromine caused the French and British to turn to the iodine compounds corresponding to the bromine compounds in use by the Germans, with the result that during the latter part of 1915 three such iodine compounds—iodoacetone, ethyliodoacetate, and benzyl iodide—made their appearance in the war. These substances were, on the whole, somewhat superior in irritant and toxic effects, but less stable than the corresponding bromine compounds.

The first of the iodine compounds to make its appearance was iodoacetone which was introduced by the French in August, 1915, as a filling for artillery shell.

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Iodoacetone is prepared by treating chloracetone with sodium or potassium iodide in alcoholic solution. When first prepared, it is a clear faintly yellow liquid, with a specific gravity of 1.8, which boils at 102°C. (215.6°F.) and turns brown on contact with the air. Iodoacetone decomposes on heating more easily than bromacetone and is converted on standing about one week into symmetrical diiodoacetone. Its vapor possesses a very pronounced pungency and is of about the same lacrimatory strength as brommethylethyl ketone (0.120 mg. per liter), but is more toxic than any of the halogenated ketones.

Iodoacetone was used only a short time by the French, being superseded toward the end of 1915 by benzyl iodide. The British manufactured some iodoacetone but do not appear to have used it in the field, preferring the more powerful ethyliodoacetate.

Ethyliodoacetate ($CH_2ICOOC_2H_5$)

British: "SK"

This compound was introduced by the British at the battle of Loos, Sept. 24, 1915, as a filling for 4.2-in. howitzer shell. It was later also used in 4-in. Stokes-mortar bombs and gas grenades and was the British standard lacrimator throughout the war.

Like iodoacetone, ethyliodoacetate is obtained by the double decomposition of the corresponding chlorine compound (ethylchloracetate) with potassium iodide in alcoholic solution. It is a colorless oily liquid, of specific gravity 1.8, which boils at 180°C. (356°F.) and quickly turns brown in the air, liberating iodine. At 20°C. (68°F.), its vapor pressure is 0.54 mm. Hg, and its volatility is 3.1 mg. per liter. It is somewhat more stable than iodoacetone, but is still quite easily decomposed. Unlike the bromine compounds, it does not attack iron and may, therefore, be loaded into projectiles without any protective lining.

Ethyliodoacetate is extremely irritant and lacrimatory and is moderately toxic as well. Its lowest lacrimatory concentration is 0.0014 mg. per liter; the intolerable concentration is 0.015 mg. per liter; a concentration of 1.5 mg. per liter is toxic on 10 minutes' exposure. It is, therefore, more irritant, lacrimatory, and toxic than any of the lacrimators previously employed in the war. While its toxicity is about one-third that of phosgene, its volatility is very low, and for that reason lethal concentrations were not encountered in the field. To increase its volatility, it was usually diluted with alcohol before filling into projectiles.

While ethyliodoacetate was one of the most powerful lacrimators used in the war, the British were forced to adopt it because of a shortage of bromine and the fact that they then had access to large supplies of iodine from South America. At the present time, the price and scarcity of iodine make the future use of this compound as a chemical agent undesir-

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able, particularly since other even more powerful lacrimators are now available.

Benzyl Iodide ($C_6H_5CH_2I$)

French: "Fraissite"

This substance was the last of the three iodine compounds used as chemical agents in the war. It was introduced by the French in November, 1915, to replace iodoacetone, on account of the shortage of acetone, and was intended to serve the same purpose as benzyl bromide used by the Germans.

Benzyl iodide is obtained by the double decomposition of benzyl chloride with potassium iodide in alcoholic solution. It is a white crystalline solid which melts at 24°C. (75°F.) and boils with complete decomposition at 226°C. (438°F.). Its specific gravity is 1.7; it is insoluble in water and has a marked ability to undergo double decomposition on storage.

As a lacrimator, benzyl iodide has about twice the power of benzyl bromide. Thus, its lowest irritant concentration is 0.002 mg. per liter; its intolerable concentration is 0.03 mg. per liter; its lethal concentration is 3.00 mg. per liter on 10 minutes' exposure. However, its volatility (1.2 mg. per liter at 20°C.) is only half that of benzyl bromide, and for that reason it was usually employed in the field in the form of a 50-50 mixture with benzyl chloride under the name "Fraissite."

While benzyl iodide was an improvement over iodoacetone, it was used for only a short time and was displaced early in 1916 by acrolein. Except for ethyliodoacetate, the iodine compounds were used only in very small quantities and for a short time by the Allies as a temporary measure, owing to the scarcity of bromine, and were soon displaced by other more effective substances.

Acrolein (CH_2CHCHO)

French: "Papite"

Acrolein was introduced by the French in January, 1916, as a filling for gas grenades and artillery shell, in an effort to obtain an effective lacrimator which did not require bromine or acetone for its manufacture. Acrolein is obtained by the dehydration of glycerine, by distilling it in the presence of potassium bisulfate or crystallized magnesium sulfate as a catalyst.

When freshly prepared, acrolein is a clear liquid of greenish yellow color and pungent odor, with a specific gravity of 0.84 at 15°C. It boils at 52°C. (125.6°F.), yielding a light vapor only 1.9 times heavier than air, is very unstable, and is easily oxidized into acrylic acid. Even when

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protected from the air, acrolein gradually polymerizes into disacryl or acrolein gum, an inactive gelatinous substance which has none of the physiological powers of acrolein.

In order to prevent polymerization, the French added about 5 per cent amyl nitrate as a stabilizer. While this tended to prevent polymerization into disacryl, it did not prevent the formation of acrolein gum, so that it was not very effective.

Acrolein is a fairly powerful lacrimator and respiratory irritant, the effects on the eyes and throat occurring simultaneously. In higher concentrations, it is also a lung-injurant toxic gas. In concentrations as low as 0.007 mg. per liter, acrolein lacrimates and greatly irritates the conjunctiva and the mucous membranes of the respiratory organs. At 0.05 mg. per liter, it becomes intolerable, while a concentration of 0.35 mg. per liter is lethal on 10 minutes' exposure. Because of its toxic properties, acrolein is classed as a toxic lacrimator. On account of its great lack of chemical stability, acrolein was not a successful chemical agent in the World War and can never play an important role in chemical warfare.

Chlorpicrin (CCl_3NO_2)

French: "Aquinite"; German: "Klop"; British and American: "PS" and "NC"

Chlorpicrin lacrimates in concentrations as low as 0.002 mg. per liter. A concentration of 0.05 mg. per liter is intolerable, and 2.00 mg. per liter is lethal on 10 minutes' exposure. Chlorpicrin is thus both a lacrimatory and lung-injurant toxic gas, but, as its lung-injurant effects are so much more pronounced than its lacrimatory effects, it is usually considered as a lung-injurant gas and is so regarded here (see Chap. VII).

Phenylcarbylamine Chloride ($C_6H_5CNCl_2$)

This compound is both a lacrimator and a lung injurant. Its minimum lacrimatory concentration is 0.003 mg. per liter, which makes it intermediate between benzyl bromide (0.004 mg. per liter) and benzyl iodide (0.002 mg. per liter). At 0.025 mg. per liter it is intolerable for more than 1 minute, while 0.05 mg. per liter is lethal on 10 minutes' exposure. As its toxic properties are so much more important than its lacrimatory power, it is generally regarded as a lung-injurant agent and is so treated in Chap. VII.

Brombenzyl Cyanide ($C_6H_5CHBrCN$)

French: "Camite"; American: "CA"

Brombenzyl cyanide was the last and most powerful lacrimator used in the World War. It was introduced by the French in July, 1918, as the

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culmination of their efforts to produce more powerful and effective lacrimators. It was also simultaneously adopted by the Americans as their standard lacrimator and manufactured in the United States in the fall of 1918.

Brombenzyl cyanide was first prepared by Riener in 1881 by brominating phenyl cyanide, and its manufacture in industry was commenced in 1914. Industrially, brombenzyl cyanide is prepared in three steps, as follows: (1) chlorination of toluene to form benzyl chloride; (2) the conversion of benzyl chloride to benzyl cyanide by the action of sodium cyanide in alcoholic solution; (3) the bromination of the benzyl cyanide with bromine vapor in the presence of sunlight.

In its pure state, brombenzyl cyanide is a yellow-white crystalline solid which melts at 25°C. (77°F.) into a brownish oily liquid of 1.47 specific gravity, and boils at 225°C. (437°F.). After a slight initial decomposition upon exposure to air, the compound is chemically fairly stable at ordinary temperatures, although it slowly decomposes in storage. When heated above 150°C. (302°F.) it decomposes very rapidly. It is soluble in water, which decomposes it only very gradually. It is also very soluble in phosgene, chlorpicrin, and benzyl cyanide. Its vapor pressure is 0.012 mm. Hg at 20°C. (68°F.), and its volatility is 0.13 mg. per liter at the same temperature. Its persistency in the open is three days; in woods, seven days; and in the ground, from 15 to 30 days. Like most compounds containing bromine, brombenzyl cyanide corrodes iron and steel and can be kept only in glass-, porcelain-, or enamel-lined containers.

This substance has an odor like soured fruit and produces a burning sensation of the mucous membranes and severe irritation and lacrimation of the eyes with acute pain in the forehead. As a lacrimator it is seven times as powerful as bromacetone. Thus, brombenzyl cyanide can be detected in concentrations as low as 1:100,000,000 (0.000087 mg. per liter); it has an irritating effect on the eyes in concentrations of 0.00015 mg. per liter and it produces lacrimation in concentrations of 0.0003 mg. per liter. A concentration of 0.0008 mg. per liter produces an intolerable irritation, and a concentration of 0.90 mg. per liter is lethal on 30 minutes' exposure. It is thus less toxic than phosgene and, owing to its low volatility, toxic concentration cannot be realized in the field.

While brombenzyl cyanide was by far the most powerful lacrimator used in the war, it has three very serious defects: (1) it corrodes iron and steel, requiring specially lined containers; (2), it is not chemically stable, but slowly decomposes in storage; (3), its great sensitiveness to heat makes its use in artillery shell very difficult. If the bursting charge is not kept very small, it causes loss of the chemical filling through decomposition on explosion. An additional disadvantage might also be found in its rather extreme persistency in the soil.

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From a tactical standpoint, therefore, brombenzyl cyanide seems quite limited in its possibilities in the future.

Chloracetophenone ($C_6H_5COCH_2Cl$)

American: "CN"

Because of the difficulties attending the use of brombenzyl cyanide, the Americans toward the end of the war began to investigate the properties of chloracetophenone as a combat gas. This compound was discovered in 1869 by the German chemist, Graebe, who described the powerful effects of its vapors upon the eyes. Owing to the short time it was under study in the war and the difficulty of its manufacture, no chloracetophenone was used in the World War. Shortly after the war, however, American investigators became convinced of its superiority as a tear gas and worked out a satisfactory process of manufacture. This process consists of the following steps:

1. Chlorination of acetic acid to obtain monochloracetic acid, according to the equation

$$CH_3COOH + Cl_2 \rightarrow CH_2ClCOOH + HCl$$

2. The chlorination of this compound with sulfur monochloride and chlorine to obtain chloracetyl chloride according to the equation

$$4CH_2ClCOOH + S_2Cl_2 + 3Cl_2 \rightarrow 4CH_2ClCOCl + 2SO_2 + 4HCl$$

3. Treatment of chloracetyl chloride with benzene in the presence of anhydrous aluminum chloride, according to the equation

$$CH_2ClCOCl + C_6H_6 \rightarrow C_6H_5COCH_2Cl + HCl$$

See Chart VIII.

Unlike the lacrimators used in the late war, chloracetophenone is a solid, and remarkably resistant to heat and moisture. It does not corrode metals, including iron and steel, so it may be loaded direct into shell, either by casting or pressing, without danger to the workmen handling it.

When pure, it consists of colorless crystals, of 1.3 specific gravity, which melt at 59°C. (138°F.) and boil at 247°C. (476°F.), yielding a vapor which in low concentrations has an odor resembling apple blossoms. At 20°C. (68°F.) its vapor pressure is very low (0.013 mm. Hg) and its volatility is 0.106 mg. per liter.

Chloracetophenone is only slightly soluble in water and is not decomposed thereby. It is not decomposed by boiling and may therefore be distilled and poured into shells in the molten state, which greatly facili-

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tates loading into munitions. It is not affected by explosion of high explosives and may even be mixed with same in shell.

In lacrimatory power, chloracetophenone is about equal to brombenzyl cyanide. Thus, it produces lacrimation in concentrations as low as 0.0003 mg. per liter while a concentration of 0.0045 mg. per liter is intolerable and a concentration of 0.85 mg. per liter is lethal on 10 minutes' exposure.

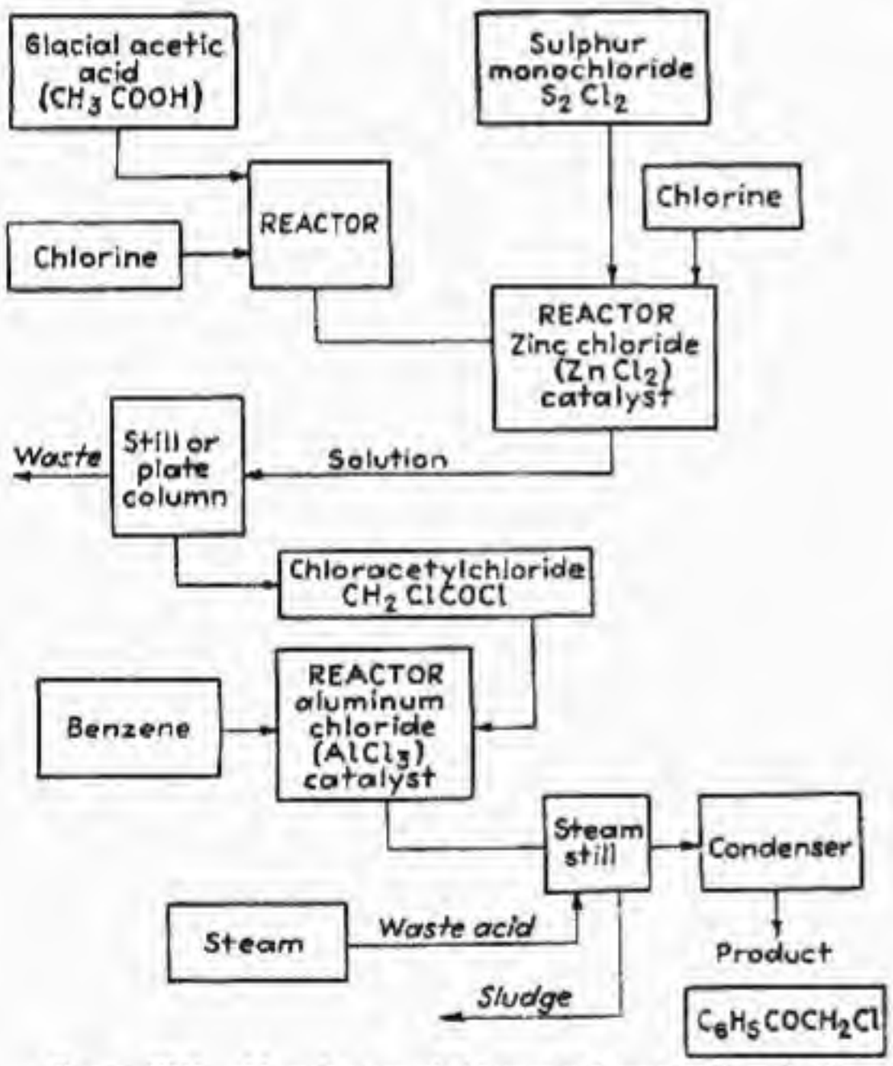

CHART VIII.—Manufacture of chloracetophenone (flow sheet).

In addition to its lacrimatory effect, chloracetophenone is a decided irritant to the upper respiratory passages; in higher concentrations, it is irritating to the skin, producing a burning and itching sensation, especially on moist parts of the body. These effects are very similar to sunburn, are entirely harmless, and disappear in a few hours.

Although chloracetophenone can be effectively dispersed by explosion, it is very much more effective when it is distilled into the air by the heat of a burning composition. A very efficient dispersion results when one part of chloracetophenone is intimately mixed with three parts of small-

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grained smokeless powder and the mixture burned without explosion. Such a progressive burning mixture can be successfully employed in hand and rifle grenades, trench-mortar bombs, and even artillery shell. This mixture is quite stable in storage and has the advantage of being practically inert on exposure to air until actually ignited.

Chloracetophenone is readily soluble in organic solvents and is thus frequently filled into grenades and shells as a liquid solution. Three such solutions have been used as follows: (1) CNB, consisting of CN, benzol, and carbon tetrachloride; (2) CND, consisting of CN and ethylene dichloride; and (3) CNS, consisting of CN, chloroform, and chlorpicrin.

On account of its low volatility, chloracetophenone usually exists in a gaseous form, but in high concentrations at low temperatures it may exist in the form of smoke (solid particules). In this form, it does not react with the charcoal in the gas-mask canister and for that reason canisters must be provided with a mechanical smoke filter in order to insure adequate protection against it.

Aside from its combat use, this substance is excellently suited for use as a training gas for training troops in chemical warfare. It is also of great value in suppressing mobs and internal disorders, as it is safely and easily handled and is not likely to prove injurious to persons who come in contact with it.

COMPARATIVE STRENGTH OF LACRIMATORS

The aggressive power of a lacrimator is a function of its specific lacrimatory power, expressed as the minimum concentration required to produce lacrimation, and its volatility at ordinary temperatures (68°F.). On this basis, the lacrimators described above are arranged below in the descending order of their aggressive powers.

Agent	Minimum lacrimatory concentration (threshold of action), mg. per liter	Volatility, 20°C. (68°F.), mg. per liter
Brombenzyl cyanide	0.00015	0.1300
Chloracetophenone	0.0003	0.1060
Ethyliodoacetate	0.0014	3.1000
Bromacetone	0.0015	75.0000
Xylyl bromide	0.0018	0.6000
Chlorpicrin	0.0020	165.0000
Benzyl iodide	0.0020	0.0012
Ethylbromacetate	0.0030	21.0000
Phenylcarbylamine chloride	0.0030	2.1000
Benzyl bromide	0.0040	0.0024
Acrolein	0.0070	20.0000
Brommethylethyl ketone	0.0126	34.0000
Chloracetone	0.0180	0.1200
Iodacetone	0.0120	0.0031

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TOXICITY OF LACRIMATORS

The toxicity of the World War lacrimators has been previously mentioned in Chap. I. The following table shows their relative toxicity on the basis of 10 minutes' exposure:

Agent	Minimum Lethal Concentration, Mg. per Liter
Acrolein	0.35*
Brombenzyl cyanide	0.35
Phenylcarbylamine chloride	0.50*
Chloracetophenone	0.85
Ethyliodoacetate	1.50*
Iodoacetone	1.90
Chlorpicrin	2.00*
Brommethylethyl ketone	2.00*
Ethylbromacetate	2.30*
Chloracetone	2.30
Benzyl iodide	3.00
Bromacetone	3.20*
Benzyl bromide	4.50
Xylyl bromide	5.60

In the cases of those compounds marked with an asterisk (*), their volatilities at 20°C. (68°F.) exceed their minimum lethal doses, so that fatal concentrations of these compounds may be encountered in the field at ordinary temperatures. Moreover, it must be remembered that, even in the cases of those compounds whose volatilities are below their minimum lethal doses, as shown above (unmarked), a smaller concentration over a correspondingly longer time is equally fatal, so that if these compounds are released in protected places, such as trenches, dugouts, woods, etc., where they may persist for a longer period than 10 minutes, they may also prove fatal.

It is also to be noted that all the above lacrimators are much more toxic than chlorine, and that acrolein and brombenzyl cyanide are more toxic than phosgene, although the volatility of the latter is too low to permit fatal concentrations in the field.

FUTURE OF LACRIMATORS

The future role of the lacrimators in war is uncertain. Their great advantage is the extremely small amounts required to force men to mask with the attendant impairment of their fighting vigor. On the other hand, they produce no real casualties and protection is easily obtained. For these reasons, it seems fairly certain that lacrimators will not be used in any future war between first-class powers, as their armies will be equipped with masks affording adequate protection. At the same time, tear gas is very effective against troops having no protection, and

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for that reason, will probably be used in minor warfare against poorly organized and semicivilized peoples. Also, tear gas will undoubtedly continue to be used to suppress riots and civil disturbances for which purpose it is eminently fitted.

For a summary of the properties of the principal lacrimatory agents, see Table IV.

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CHAPTER VII

LUNG-INJURANT AGENTS

GROUP CHARACTERISTICS

The lung injurants were the second group of agents to make their appearance in the World War. They form a well-defined group, having many properties in common, and for that reason they were designated by the Germans under a single generic class—*Green Cross substances.* In general, they were all liquids of relatively low boiling points and high vapor pressures. They, therefore, were volatile substances that formed nonpersistent gases upon release from their containers. Their principal physiological action was injury of the pulmonary system of the body. The main result of this injury was to cause fluid to pass from the blood into the minute air sacs of the lungs and thus obstruct the supply of oxygen to the blood. Death from one of these substances may be compared to death by drowning, the water in which the victim drowns being drawn into his lungs from his own blood vessels.

As a rule, the lung-injurant agents are lethal (deadly) in concentrations ordinarily employed in battle and have the following properties in common:

1. Their threshold of useful action is relatively high, varying between 1 and 10 mg. per liter of air.
2. They are effective on very short exposure, usually only a few minutes are required to produce death or serious casualties in the concentrations generally employed in battle.
3. They exert a similar physiological action comprising the following factors:
   a. Irritant effect on the mucous membranes of the respiratory system (nose, throat, and trachea).
   b. Special changes (injury) in the lung tissue.
   c. Secondary sequelae of these changes in the lung tissues, chiefly in the circulatory system and in the composition of the blood gases.
4. Their physiological effect is not immediate, but generally produces death or serious casualties in from 1 to 2 hours after exposure.

From both a chemical and physiological viewpoint, the lung-injurant agents may be divided into two distinct groups: (1) the simple lung injurants, derived from chlorine; and (2) the toxic lung injurants, derived from arsenic. The first group acts only locally on the pulmonary system, while the second group exerts an additional systemic poisoning effect by virtue of the arsenic which they contain.

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Chlorine (Cl_2)

French: "Bertholite"

Chlorine was the first gas used on an effective scale in war. It was employed by the Germans against British and French Colonial troops at Ypres, Belgium, on Apr. 22, 1915, when 168 tons of chlorine were released from 5,730 cylinders on the front of 6 kilometers. It was effective to a distance of 5 kilometers downwind and caused 15,000 casualties, of which 5,000 were fatal.

During the war chlorine was the principal gas used for cloud-gas attacks. At first, when the Allies had little or no means of protection, it was a very effective weapon and caused many thousands of casualties.

WORLD WAR LUNG INJURANTS

The principal lung-injurant agents in order of their chronological appearance in the World War, are:

Agent	Introduced by	Date
Simple lung injurants		
Chlorine	Germans	April 22, 1915
Methylsulfuryl chloride	Germans	June, 1915
Ethylsulfuryl chloride	French	June, 1915
Monochlormethylchloroformate	Germans	June 18, 1915
Dimethyl sulfate	Germans	August, 1915
Perchlormethylmercaptan	French	September, 1915
Phosgene	Germans	Dec. 19, 1915
Trichlormethylchloroformate	Germans	May 19, 1916
Chlorpicrin	Russians	August, 1916
Phenylcarbylamine chloride	Germans	May, 1917
Dichlordimethyl ether	Germans	January, 1918
Dibromidimethyl ether	Germans	
Toxic lung injurants		
Phenyldichlorarsine	Germans	September, 1917
Ethyldichlorarsine	Germans	March, 1918
Phenyldibromarsine	Germans	September, 1918

Later in the war, when troops were protected with masks, the effectiveness of chlorine was greatly reduced. However, in mixtures with other gases, such as phosgene and chlorpicrin, it continued to be used throughout the war.

At ordinary temperatures and pressures, chlorine is a greenish yellow volatile gas with a pungent odor and caustic poisonous characteristics.

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It is readily liquefied by moderate pressure (6 atmospheres) at ordinary temperatures (70°F.). When liquid, it has a specific gravity of 1.46 and, when a gas, it is 2.5 times heavier than air, so that when released as a cloud it clings well to the ground as it travels downwind. One liter of liquid chlorine at 25°C. will yield 434 liters of chlorine gas. Since

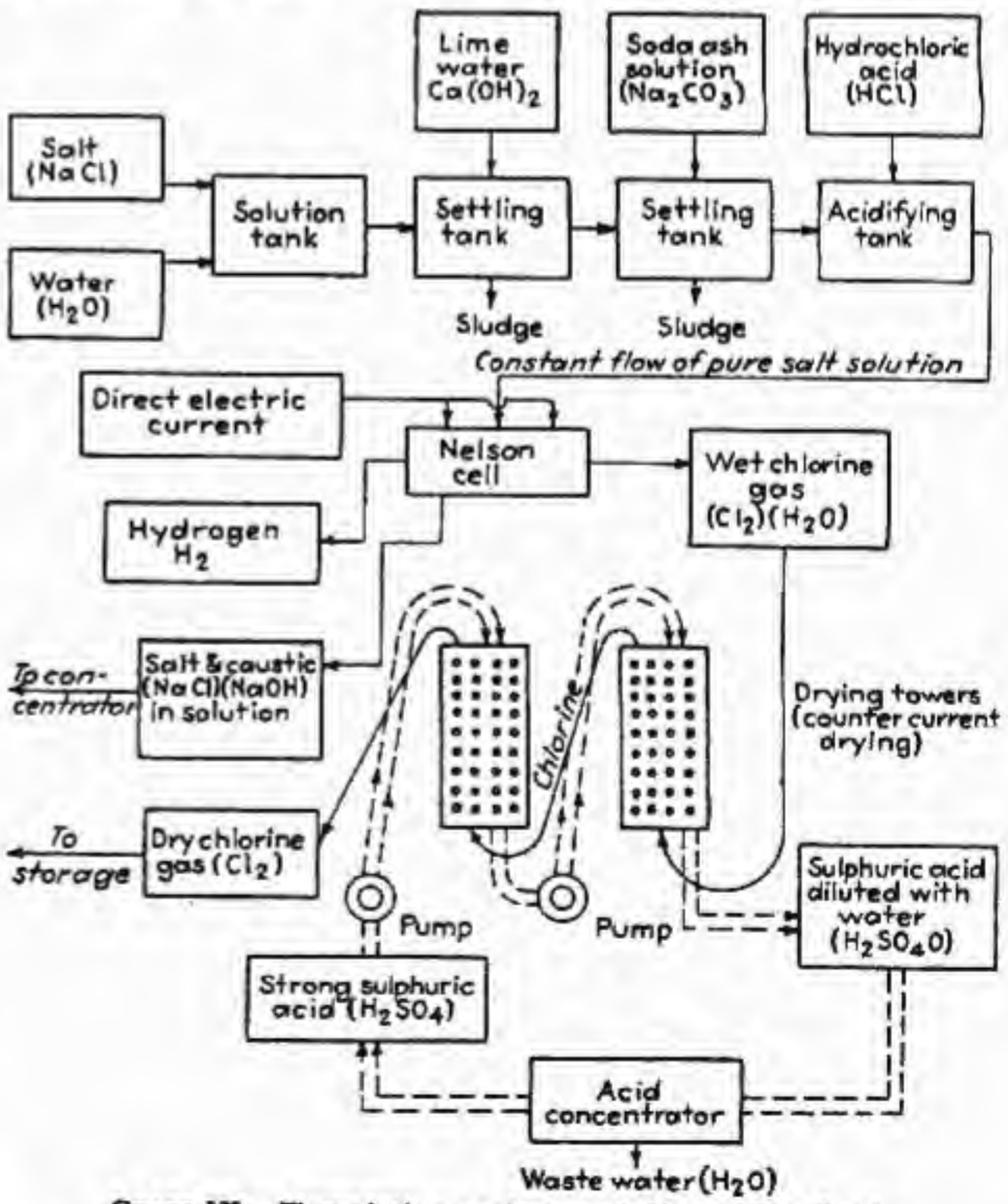

CHART IX.—Electrolytic manufacture of chlorine (flow sheet).

chlorine boils at −33.6°C. (−28.5°F.), it readily vaporizes at ordinary

temperatures and escapes with vigor from its container, so that it is well adapted for cloud-gas operations from cylinders, and this was its principal mode of employment during the war.

Chlorine is manufactured by the electrolysis of common salt (NaCl), as indicated on Chart IX, and is widely used in enormous quantities in industry. In the presence of moisture it is extraordinarily reactive.

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attacking almost all metals and organic substances. This is its principal disadvantage as a chemical agent, as it is very easily neutralized. Although extremely soluble in water, chlorine does not hydrolyze readily and, when strictly anhydrous, it does not attack iron and steel so that it may be kept in such containers indefinitely.

Physiologically, chlorine is classified as a lung-injurant agent. It also causes a marked irritation of the conjunctiva and the mucous membranes of the nose, larynx, and pharynx.

Concerning the physiological effects of chlorine upon the human body, *Gilchrist* says:

> The progressive physiological action of chlorine in man as well as in animals may be summarized as follows:
>
> 1. It stimulates the sensory nerves and produces severe pain and spasm of the muscular walls of the bronchi, thus narrowing their lumen and causing a gasping for breath. The muscular spasm soon relaxes and breathing becomes easier.
> 2. Obstruction of the bronchial tubes by an inflammatory exudate, due to the irritation of the gas.
> 3. A flooding of the pulmonary air sacs by serous effusion, with resulting edema and interference with gaseous exchange of respiration.
> 4. A disruptive emphysema of the lungs and of the subcutaneous tissues, due to continuous coughing, and the rupturing of many of the alveolar cells, resulting in the passage of the air into the tissues of the lungs and into the tissues of the neck. Such a condition interferes with normal respiration and leads to a certain degree of asphyxia.

The lethal concentration of chlorine for 30 minutes' exposure is 2.53 mg. per liter; and for 10 minutes' exposure, 5.6 mg. per liter.

Chlorine possesses many of the tactical and technical requirements of an offensive battle gas, as discussed in Chap. II, page 47. Thus it is:

1. Fairly toxic (5.60 mg. per liter is lethal after 10 minutes).
2. Nonpersistent (5 to 10 minutes in the open).
3. Immediately effective (few minutes of exposure).
4. Extremely volatile (19,369 mg. per liter).
5. Raw materials available in unlimited quantities.
6. Easy to manufacture.
7. Chemically stable (when completely anhydrous).
8. Nonhydrolyzable.
9. Not decomposed under shock of explosion.
10. Of low boiling point (−34.6°C.) (−30.3°F.).
11. Of high vapor pressure.
12. Of specific gravity 1.4.
13. Of high vapor density (2.5).

The chief disadvantage of chlorine is its great chemical activity which makes it easy to protect against.

As chlorine is the basis for the manufacture of nearly all chemical agents and is readily available in enormous quantites in industry, it will always be a potential chemical-warfare threat against any nation whose

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armed forces are not protected against it. However, since present-day gas masks afford complete protection against chlorine and since there are so many more effective combat gases now available, there is little likelihood that chlorine will figure as a chemical agent in any future war between first-class powers.

Methylsulfuryl Chloride ($ClSO_3CH_3$)

Methyl Chlorsulfonate

The great success obtained by the German cloud-gas attacks in April and May, 1915, at once suggested the use of gas in other ways, such as in grenades, trench-mortar bombs, and artillery shell. Since chlorine was too volatile to be loaded into projectiles, a search for a suitable gas for this purpose was begun on both sides.

The first compound to be successfully used in projectiles* was methylsulfuryl chloride, introduced by the Germans in June, 1915. This compound was filled into trench-mortar bombs and hand grenades, but was never employed in artillery shell.

Methylsulfuryl chloride is obtained by the action of sulfuryl chloride on methyl alcohol and is a transparent viscid liquid, of 1.51 specific gravity, which boils at 133°C. (232.4°F.), yielding a vapor 4.5 times as heavy as air, which lacrimates in concentrations as low as 1:750,000 (0.008 mg. per liter). It has a very irritating effect on the conjunctiva and respiratory organs which becomes intolerable when the concentration rises to 0.050 mg. per liter. A concentration of 2.00 mg. per liter is fatal on 10 minutes' exposure, death being caused by lung edema as in the case of chlorine and phosgene poisoning. Its volatility at 20°C. is 60.00 mg. per liter.

Methylsulfuryl chloride was used only a short time, being replaced in the summer of 1915 with K-Stoff.

Ethylsulfuryl Chloride ($ClSO_3C_2H_5$)

French: "Sulvanite"

About the same time that the Germans brought out methylsulfuryl chloride, the French countered with the ethyl compound, as a filling for artillery shell, under the name "Sulvanite."

Ethylsulfuryl chloride is similarly obtained by acting on ethyl alcohol with sulfuryl chloride and is a colorless liquid, of 1.44 specific gravity, which boils with some decomposition at 135°C. (275°F.), yielding a vapor which lacrimates in concentrations as low as 1:1,000,000. A concentration of 0.050 mg. per liter is intolerable and a concentration of 1.00 mg. per liter is toxic.

* The earlier use of xylyl bromide (T-Stoff) in artillery shell on the Russian Front in January, 1915, was unsuccessful.

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Compared to methylsulfuryl chloride, the ethyl compound is more lacrimatory and toxic, but is less volatile, so that the combat values of the two are probably about the same.

Neither of these compounds played a role of any importance in the war; they mark a milestone in the race for a more effective lung-injurant agent and are of historical interest only.

Chlormethylchloroformate ($ClCOOCH_2Cl$)

French: "Palite"; German: "K-Stoff," "C-Stoff"

This substance, known as "K-Stoff" when used in shells and "C-Stoff" when used in trench mortars and projector bombs, was first used by the Germans in June, 1915, in an effort to find a chemical agent more effective than chlorine.

K-Stoff is a mixture of the incompletely chlorinated methyl esters of formic acid (70 per cent $ClCOOCH_2Cl$ and 30 per cent $ClCOOCHCl_2$) and is a clear liquid, of 1.48 specific gravity, which boils at 1.09°C. (228.2°F.), yielding a vapor 4.5 times heavier than air. It has an ethereal odor, is somewhat lacrimatory, and hydrolyzes easily when warm and even when cold in the presence of alkalies, yielding formaldehyde, carbonic acid, and hydrochloric acid. Its vapor pressure at 20°C. (68°F.) is 5.6 mm. Hg.

Chlormethylchloroformate is prepared by first acting on phosgene with methyl alcohol to obtain methylchloroformate as follows:

$$COCl_2 + CH_3(OH) = ClCOOCH_3 + HCl$$

and then chlorinating this ester in the presence of strong light, so that chlorine progressively replaces the hydrogen atoms of the methyl group, yielding monochlormethylchloroformate ($ClCOOCH_2Cl$) and dichlormethylchloroformate ($ClCOOCHCl_2$).

In concentrations of 1:100,000 (0.0528 mg. per liter), K-Stoff causes slight lacrimation, while a concentration of 1.00 mg. per liter is lethal on 30 minutes' exposure.

It is, therefore, about five times more toxic than chlorine, but only about half as toxic as phosgene and diphosgene, so that, while it was a great improvement over chlorine when first used, it was soon displaced by diphosgene and chlorpicrin when these more powerful compounds were introduced.

Dimethyl Sulfate ($(CH_3)_2SO_4$)

German: "D-Stoff"; French: "Rationite"

The question of who first used this compound as a chemical agent in

the late war is somewhat uncertain. Thus, Dr. Hanslian

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says this substance was introduced by the Germans as a filling for artillery shell in August, 1915, under the name of "D-Stoff"; the reports of the Allies' laboratories which analyzed the contents of these early German D shells show that dimethyl sulfate was an ingredient of their chemical contents. On the other hand, Dr. Mueller (21, page 96) emphatically denies the German use of this compound and explains the situation thus:

> The oft-repeated statement to the effect that dimethyl sulfate had been used experimentally by the Germans as early as in 1915 is not true. It is to be explained by the fact that methylsulfuryl chloride used at that time temporarily was slightly polluted with a few per cent of dimethyl sulfate, and the impurities still clung to the commercial product after its manufacture. Under no circumstances was dimethyl sulfate purposely added. Those concerned with such matters would never have agreed to its use.

Whether or not the early German use of dimethyl sulfate was deliberate or accidental, it is clear that no one at that time really realized the true combat value of this substance. Thus, it is not only a good lacrimator and very toxic, but is also a fairly powerful vesicant. These properties were later discovered by the French and dimethyl sulfate was adopted by them as a filling for artillery shell and hand grenades in September, 1918, under the name of "Rationite."

Dimethyl sulfate is produced by acting on fuming sulfuric acid with methyl alcohol and distilling in vacuo. Before the war it was used in industry as a methylating agent for amines and phenols and as a reagent for detecting coal-tar oils.

It is a colorless oily liquid, of 1.35 specific gravity, which boils at 188°C. (370.4°F.), yielding a vapor 4.4 times heavier than air with a faint odor of onions.

At ordinary temperatures (68°F.), its volatility is only 3.3 mg. per liter, which is low for a lung injurant but high for a vesicant. Dimethyl sulfate is very readily decomposed by water so that its vapors quickly combine with moisture in the air to form sulfuric acid. This is one of the chief defects of this substance as a chemical agent.

Dimethyl sulfate is a powerful irritant to the mucous membranes, especially the conjunctiva and respiratory system. Its direct toxic action is exerted against the lungs in a manner very similar to that of chlorine, resulting in bronchitis, pneumonia, and lung edema. A concentration of 0.50 mg. per liter is fatal on 10 minutes' exposure. It is, therefore, about as toxic as phosgene. In lower concentrations it exerts a corrosive action on the skin, resulting in a peculiar analgesia of the skin which is said to last for six months after exposure. For this reason, it may also be regarded as a vesicant agent.

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The limited use of this compound during the war did not definitely establish its combat value. However, the high degree to which it is decomposed by water, and even by the moisture in the air, would require that any tactical effects produced be secured by the vapors directly upon the bursting of the shells before these vapors are decomposed by the moisture in the air. This so greatly limits the combat effectiveness of this substance as to raise a serious question regarding its future value as a chemical agent, particularly since other more toxic and more vesicant compounds have been discovered.

Perchlormethylmercaptan ($SCCl_4$)

Carbon Tetrachlorsulfide

During the summer of 1915, while the Germans were experimenting with halogenated esters, the French conceived the idea of utilizing perchlormethylmercaptan as a chemical-warfare gas, and this substance, which was introduced by the French in the battle of the Champagne in September, 1915, constituted the first use of gas shell by the French Army.

Perchlormethylmercaptan may be obtained by the direct chlorination of methylmercaptan (CH_3SH) or by passing chlorine into carbon disulfide in the presence of a small quantity of iodine as a chlorine carrier. The resulting product is a light yellow liquid, of 1.71 specific gravity, which boils at 149°C. (300.2°F.), yielding a vapor 6.5 times heavier than air. It lacrimates in concentrations as low as 0.010 mg. per liter and is intolerable at 0.070 mg. per liter. A concentration of 3.00 mg. per liter is lethal on 10 minutes' exposure, which makes it about one-sixth as toxic as phosgene.

Perchlormethylmercaptan has the following disadvantages as a chemical agent:

1. Rather low toxicity.
2. Warning odor which betrays its presence before toxic effects are produced.
3. Decomposes in the presence of iron and steel.
4. Charcoal easily fixes its vapors and furnished complete protection against it.

For these reasons, this compound was soon abandoned in favor of other more effective substances and is not likely to be used again as a chemical agent. Commenting on this gas, Izard (23) says, "Its utilization had no other object than to realize a provisional solution."

Phosgene (Carbonyl Chloride) ($COCl_2$)

French: "Collongite"; German: "D-Stoff"; British and American: CG

Phosgene was the second toxic gas to be used in large quantities during the war. It was first employed by the Germans, mixed with

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chlorine, in a cloud-gas attack against the British at Nieltje, in Flanders, on Dec. 19, 1915, when 88 tons of gas were released from 4,000 cylinders and produced 1,069 casualties, of which 120 were fatal.

In February, 1916, phosgene was adopted as an artillery-shell filler by the French in retaliation for the German K-Stoff shell. Throughout the remainder of the war, this gas was the principal offensive battle gas of the Allies, being used in enormous quantities in cylinders, artillery shell, trench mortars, bombs, and projector drums. More than 80 per cent of gas fatalities in the World War were caused by phosgene. Concerning the use of phosgene in the World War, see Table XVII, pages 663 *ff.*

Phosgene was known to chemists for over a hundred years before the World War, being first made by the British chemist John Davy in 1812 by the reaction of carbon monoxide and chlorine in the presence of sunlight. At the beginning of the present century, phosgene was used extensively as an intermediate in the dye industry and had been manufactured on a considerable scale for many years in Germany. With its well-known toxic properties and its ready availability in large quantities, phosgene was a logical choice of the German chemists for a more powerful substitute for chlorine when the Allies had equipped themselves with masks that afforded adequate protection against chlorine.

At ordinary temperatures and pressures, phosgene is a colorless gas which condenses at 46.7°F. to a colorless liquid of 1.38 specific gravity. Above 46.7°F., phosgene immediately evaporates, although at a slower rate than chlorine, and gives off a transparent vapor, 3.5 times heavier than air, with a stifling, but not unpleasant, odor resembling new-mown hay.

Aside from its characteristic odor, phosgene may also be detected in the field by its so-called *tobacco reaction*, by which is meant that men who have breathed only very slight amounts of phosgene experience a peculiar flat metallic taste when smoking tobacco. Certain other gases, such as HCN and sulfur dioxide, however, also have this effect and must be distinguished from phosgene by their very different odors.

Chemically much more inert than chlorine, phosgene is a very stable compound and is not dissociated by explosion of even strong bursting charges. When dry, phosgene does not attack iron and may, therefore, be kept indefinitely in iron and steel containers. It is, however, extremely sensitive to water, in contact with which it quickly breaks down into hydrochloric acid and carbon dioxide, according to the equation

$$COCl_2 + H_2O = CO_2 + 2HCl$$

Hence, even if slight traces of water are present in loading phosgene into shell, the hydrochloric acid formed will attack the shell walls and gen-

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erate dangerous pressure in the shell; if sufficient hydrochloric acid is formed, it will eventually destroy the shell. Because of its rapid hydrolysis in the presence of water, phosgene cannot be efficiently employed in

very wet weather.

While phosgene boils at 46.7°F., which is considerably below ordinary summer temperatures, its rate of evaporation is so slow that it has to be mixed with equal quantities of chlorine in order to set up satisfactory cloud-gas concentrations in the field. This was the manner in which phosgene was employed in cloud-gas attacks throughout the war.

The toxicity of phosgene is over ten times that of chlorine, a concentration of 0.50 mg. per liter being fatal after 10 minutes' exposure. In higher concentrations, which are often met in battle, one or two breaths may be fatal in a few hours.

Phosgene appears to exert its physiological and toxic effects chiefly through the medium of its hydrolysis products—hydrochloric acid and carbon dioxide. Its effects upon the upper air passages of the body, where moisture is relatively small, is therefore comparatively slight. With prolonged breathing, however, sufficient phosgene is decomposed in the bronchi and trachea to produce marked inflammation and corrosion. These effects reach their maximum in the alveoli where the air is saturated with water.

Unlike chlorine, phosgene produces but a slight irritation of the sensory nerves in the upper air passages, so that men exposed to this gas are likely to inhale it more deeply than they would equivalent concentrations of chlorine or other directly irritant vapors. For this reason, phosgene is very insidious in its action and men gassed with it often have little or no warning symptoms until too late to avoid serious poisoning. Generally, the victim first experiences a temporary weak spell, but otherwise feels well and has a good appetite. Suddenly he grows worse, and death frequently follows in a few days.

Concerning the physiological action of phosgene, which is typical of the lung-injurant agents, General Gilchrist says:

> After gassing with phosgene there is irritation of the trachea or bronchi; coughing is not a prominent symptom, and disruptive emphysema is practically never seen. After moderate gassing, a man may feel able to carry on his work for an hour or two with slight symptoms, but he may become suddenly worse, may show evidence of extreme cyanosis, and subsequently may pass into collapse. There are records of men who have undergone a phosgene-gas attack and who seem to have suffered slightly, but have died suddenly some hours later upon attempting physical effort.
>
> Pulmonary edema appears very early. This edema is at first noncellular but, after about five hours, leucocytes are found, and later the exudate is rich in cells. After inhalation of phosgene, red blood cells are seldom found in the exudate; later fibrin appears. Physical examination at this time reveals focal patches of bronchopneumonia. At the height of illness edema is the outstanding condition. After the
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>
> second or third day, if death does not occur, the edema fluid is resorbed and recovery follows, barring complication of the bronchopneumonic process.
>
> The important immediate effects of phosgene are practically limited to the lungs. These changes consist of damage to the capillaries. This damage may be noted a half hour after gassing. The capillaries in the walls of the alveoli are markedly constricted and appear collapsed. Later they become dilated and engorged with blood, and blood stasis is the rule. Frequently thrombi form and block the capillaries for some distance, which increases the blood stasis. This dilation and blood stasis in the capillaries is the main cause of pulmonary edema; the latter progresses rapidly from this time on.
>
> A number of theories have been advanced to explain the production of edema. The preponderance of evidence as to the cause of the edema following phosgene gassing is that it is due to local injury of the endothelial cells which results in an increased capillary permeability; the other changes in the blood and in the circulation are secondary to the trauma sustained by the capillary wall.

The injurious effects of phosgene are materially increased by physical exertion. Frequently those parts of the lungs which have not been damaged by the gas would be sufficient for breathing purposes if the body were at rest, but they are not sufficient while the body is in motion, particularly in view of the excess carbonic acid which is formed in the body by the decomposition of the phosgene.

Phosgene is manufactured in industry by the original process of direct synthesis of chlorine and carbon monoxide, as indicated in Chart X. The only change from the original process of making it is the substitution of a catalyst (animal charcoal) for the action of sunlight.

Compared to chlorine, phosgene has the following advantages as a chemical agent. It is:

1. Far more toxic (0.50 mg. per liter at 10 minutes).
2. A little less volatile and more persistent.
3. Greater vapor density (3.5).
4. More insidious in action.
5. Chemically more inert and, therefore, more difficult to neutralize and protect against.

The principal disadvantages of phosgene are its slower physiological action on the body and its inability to discharge itself from cylinders at a sufficient rate for cloud-gas attacks.

In addition to the foregoing, phosgene is relatively easy to protect against and for that reason would probably be displaced in the future by gases of greater toxicity and more difficult to neutralize.

Trichlormethylchloroformate ($ClCOOCCl_3$)

German: "Perstoff"; French: "Surpalite"; British: "Diphosgene"

This gas was first used in the World War by the Germans at Verdun in May, 1916, in retaliation for the French phosgene shell which were introduced in February, 1916.

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Trichlormethylchloroformate is the completely chlorinated methyl ester of formic acid and is obtained by completing the chlorination of the monochlormethylchloroformate (K-Stoff). In studying the chlorinated methyl esters of formic acid, the German chemists found that their toxic properties increased, while their lacrimatory powers decreased, with

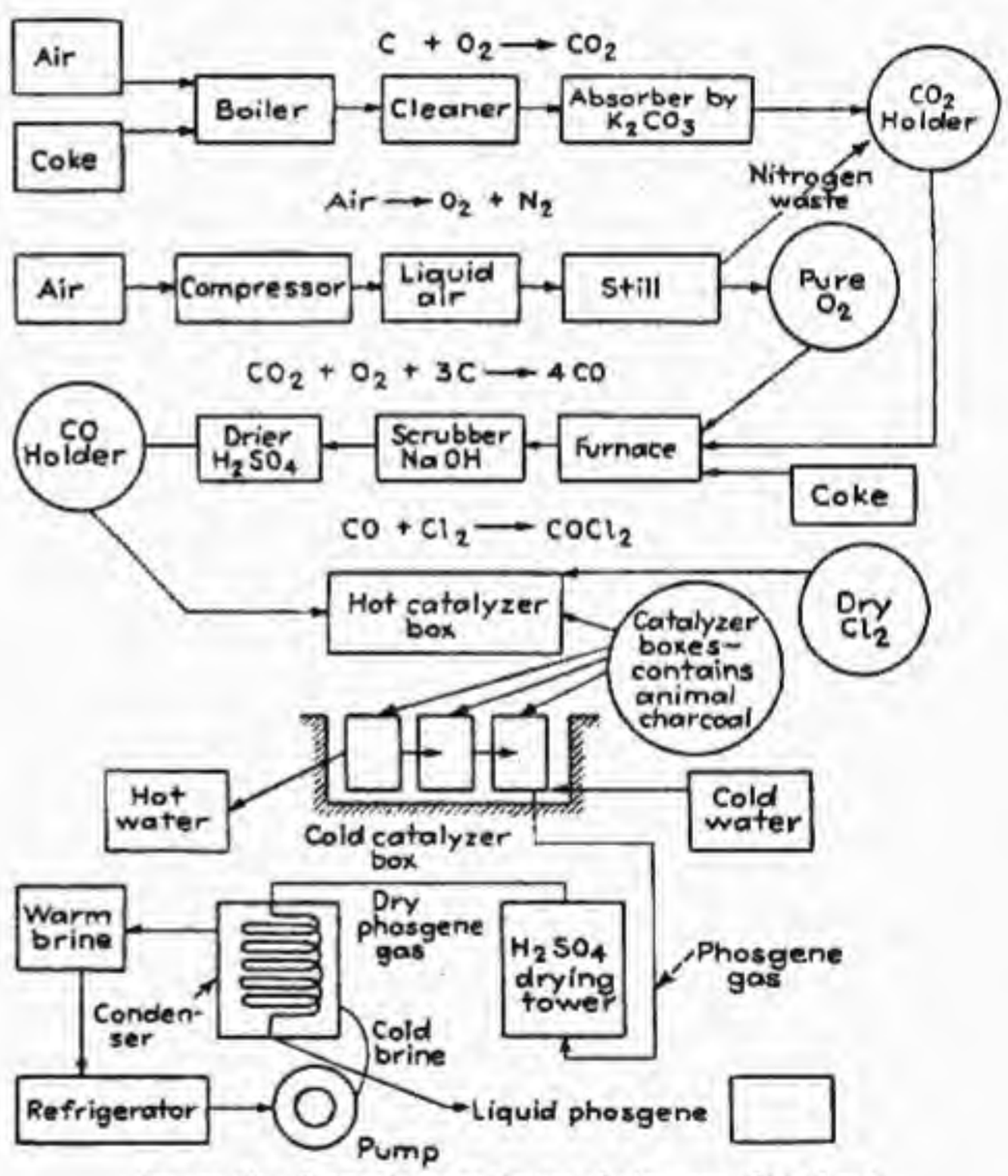

CHART X.—Catalytic manufacture of phosgene (flow sheet).

the addition of chlorine atoms in the methyl group of their molecular structures. Thus, diphosgene, which contains the maximum chlorine atoms, was found to be the least lacrimatory but the most toxic of these compounds and was for that reason substituted for K-Stoff as the standard German nonpersistent lethal gas for shells. An analysis of the gas casualties of the late war indicates that, on the basis of the total

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number of fatalities, diphosgene was the principal *killing* gas used *in shells* during the war.

Trichlormethylchloroformate is an oily liquid of specific gravity 1.65 and a disagreeable suffocating odor. It boils at 127°C. (260.6°F.), giving off a dense whitish vapor 6.9 times heavier than air, which persists on open ground about 30 minutes. At 20°C. (68°F.), its volatility is 26.00 mg. per liter. When heated to about 350°C. (662°F.) or upon contact with moisture, as in the tissues of the body, trichlormethylchloroformate breaks down, yielding two molecules of phosgene, thus: $ClCOOCCl_3 =$

$2COCl_2$, from which it received its English name—diphosgene. Under ordinary conditions of temperature and pressure, it hydrolyzes slowly, ultimately yielding carbonic acid and hydrochloric acid, according to the following equation:

$$ClCOOCCl_3 + 2H_2O = 2CO_2 + 4HCl$$

Because of its high boiling point and the fact that in its primary form it is relatively inactive physiologically, diphosgene is peculiarly adapted for shell filling. Unlike phosgene, which requires artificial refrigeration to keep it below its boiling point during filling operations, diphosgene can be filled into shells in the field, the workmen requiring no other protection than gas masks. This was of great advantage to the Germans during the war as it enabled them to fill shell close behind the front lines, and the filled shell thus required the minimum transportation, handling, and storage. Because of this fact, the Germans were able to use all sorts of H.E. shell for gas by the simple expedient of cementing the joints in the shells, while the Allies, whose shell were filled far from the front and had to withstand much rough handling and long storage, could not successfully use cemented gas shell, because of leakage difficulties.

The toxicity of diphosgene is about the same as that of phosgene. In fact, it is probable that the toxicity of diphosgene is not a specific property of that compound, but is derived from the phosgene molecules into which it decomposes in the tissues of the body.

The German chemist, Haber , quoting the work of Flury, gives the toxicity index of diphosgene as 500, as compared to 450 for phosgene. For a 10-minute exposure, this is equivalent to a concentration of 0.050 mg. per liter of diphosgene and 0.045 mg. per liter of phosgene. American determinations, however, show that the minimum lethal concentrations of phosgene for a 10-minute exposure is 0.50 mg. per liter which is over ten times the German figure. Many reasons have been advanced to account for the large discrepancy in these figures, such as that Flury's determinations were on cats which were subsequently found to be peculiarly sensitive to phosgene and diphosgene concentrations. The cats were also said to be undernourished, which still further increased

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their susceptibility. However, regardless of the differences in *specific* toxicity of phosgene and diphosgene, as between the different nations, all agree that there are no perceptible differences in the physiological effects of these two compounds and that they are substantially equal in toxicity.

As phosgene was the choice of the Allies for a standard nonpersistent lethal gas, while the Germans used diphosgene, it is interesting to compare relative merits of these two compounds as chemical agents.

Both have about the same toxicity and physiological effects on men and animals. Diphosgene is about three times as persistent as phosgene, having an open-ground persistency of 30 minutes against 10 minutes for phosgene, so that diphosgene would not be classed as a nonpersistent gas under our present system of classification, which regards all agents having an open-ground persistency greater than 10 minutes as persistent. However, the present limit of 10 minutes for nonpersistent gases is somewhat arbitrary and, from a tactical standpoint, it is believed that a persistency of 30 minutes is not too great for a nonpersistent gas. The main consideration governing the length of time a nonpersistent gas can be allowed to remain on the target area is the time required for the attacking infantry to traverse the ground between their jump-off lines and the enemy's front line. Under the most favorable conditions, with the jump-off line only 800 yd. from the enemy's front line and maximum rate of advance under fire (100 yd. in 4 minutes), this will not be less than 32 minutes, so that a gas which would not persist for over 30 minutes would be suitable for use in offensive operations.

Within the limits of permissible persistency, the nearer this limit is approached by an agent, the easier it is to maintain effective concentrations in the field; therefore a persistency of 30 minutes is an advantage over a persistency of 10 minutes, so that diphosgene has the advantage in this respect. On the other hand, phosgene is more volatile than diphosgene and higher field concentrations can be effected with phosgene.

The speed and duration of the casualty effects of both phosgene and diphosgene are about the same, but phosgene has the advantage of being more insidious in action, as diphosgene is somewhat lacrimatory and gives a noticeable warning in concentrations of 1:200,000, as compared to 1:100,000 for phosgene. The odor and visibility of phosgene and diphosgene are very similar and almost equal, the latter being somewhat more pungent and visible in cloud formation than the former.

Phosgene is made by the direct synthesis of CO + Cl, whereas diphosgene requires the following additional steps:

1. Formation of methylchloroformate from phosgene and methyl alcohol by reaction with calcium carbonate.
2. Formation of diphosgene from methylchloroformate by the reaction of chlorine by the action of electricity (ultraviolet rays).

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Special title-lined reaction vessels are also required for the manufacture of diphosgene which considerably complicates its production in large quantities. Phosgene is thus far easier to manufacture than diphosgene, and it was primarily on this account that the Allies chose phosgene as their standard lethal agent.

Phosgene is chemically more stable than diphosgene and withstands explosion without decomposition, although diphosgene is first resolved into phosgene by dissociation. Owing to its higher boiling point and relatively inert physiological action in its primary form, diphosgene is far easier to fill into shell, but, on the other hand, it cannot be used for cloud-gas attacks as can phosgene. Finally, diphosgene vapor is more than twice as heavy as phosgene, which gives it greater ground-clinging and searching values in the field.

Chlorpicrin (Nitrochloroform) (CCl_3NO_2)

British: "Vomiting gas"; French: "Aquinite"; German: "Klop"

The next lung-injurant gas to make its appearance in the World War was chlorpicrin. This gas was first used in battle by the Russians in August, 1916, and was subsequently employed by both Germany and the Allies, alone or mixed with other combat substances, in artillery shells, trench-mortar bombs, and in cylinders for cloud-gas attacks. Indeed, chlorpicrin appears to have been the most widely used combat gas in the war, although the total amount used was probably less than that of phosgene and diphosgene.

Like chlorine and phosgene, chlorpicrin was a well-known chemical substance before the World War. It was discovered by the English chemist, Stenhouse, in 1848, and its chemical and physiological properties had been carefully studied many years during the nineteenth century.

Chlorpicrin is a colorless oily liquid, of 1.66 specific gravity, which boils at 112°C. (231.5°F.), giving off a pungent irritating vapor, 5.6 times heavier than air, and having a sweetish odor resembling that of flypaper. Even at ordinary temperatures chlorpicrin evaporates very rapidly, and its vapor pressure is quite high, *e.g.*, at 20°C. (68°F.) it amounts to 18.3 mm. Hg. Its volatility at 20°C. (68°F.) is 165.0 mg. per liter. Chlorpicrin may therefore be used in cylinders for cloud-gas attacks if mixed with chlorine. Mixed with 70 per cent chlorine, chlorpicrin was used in a large number of British gas attacks under the name of "Yellow Star gas."

Chemically, chlorpicrin is quite a stable compound. It is almost insoluble in, and is not decomposed by, water; it does not combine readily with either acids or alkalies. Owing to its chemical inertness, chlorpicrin does not react with any of the chemicals in the gas-mask

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canister and is removed from the air passing through the canister by the charcoal alone. It is therefore one of the most difficult of the war gases to protect against. Owing to this fact, the protection afforded by gas-mask canisters is usually rated in accordance with the number of hours it will protect against ordinary field concentrations of chlorpicrin.

Chlorpicrin is rather easily manufactured by the direct chlorination of picric acid. In practice, the reaction is carried out by injecting live steam into an aqueous solution of bleaching powder and picric acid, as shown on Chart XI. The yield is 114 per cent of the volume of picric acid employed. Since large amounts of picric acid are used in industry and for high explosives and, since bleaching powder is easily obtainable everywhere, the raw materials necessary in the manufacture of chlorpicrin are readily available. This fact and the ease of manufacture undoubtedly

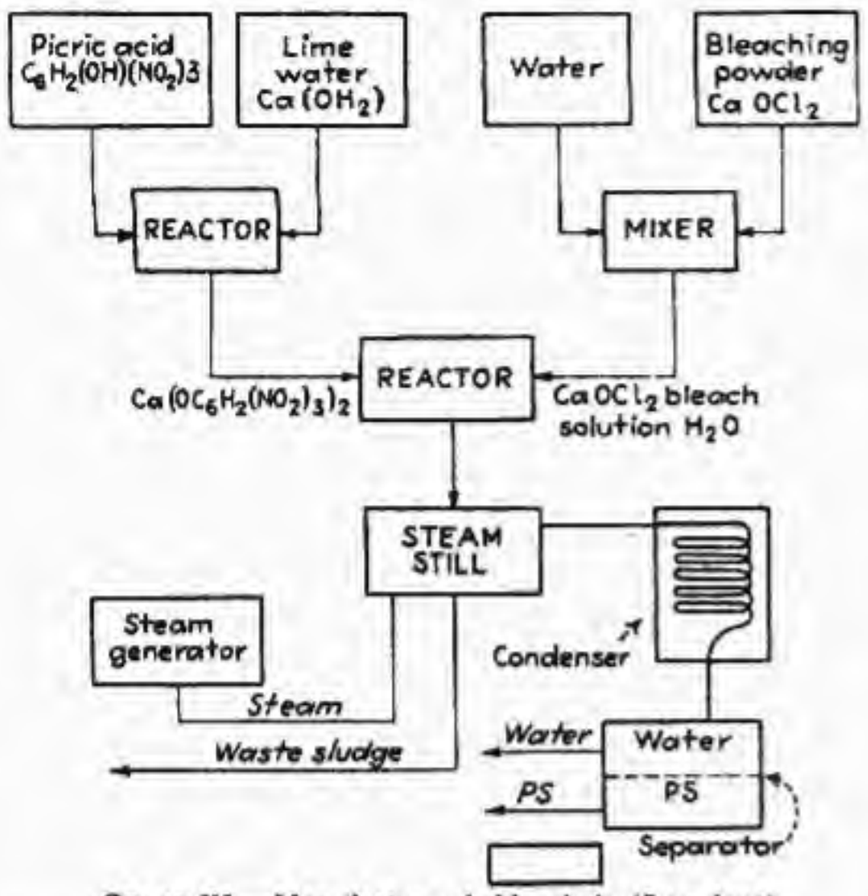

CHART XI.—Manufacture of chlorpicrin (flow sheet).

account for the widespread use of chlorpicrin during the late war.

As a war gas, chlorpicrin has a number of desirable offensive properties. Like chlorine and phosgene, it is a lethal compound which acts primarily as a lung injurant. In toxicity, it is intermediate between chlorine and phosgene, as indicated by the following comparative figures:

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LETHAL CONCENTRATIONS

Exposure, minutes	Chlorine, mg. per liter	Chlorpicrin, mg. per liter	Phosgene, mg. per liter
10	5.60	2.00	0.50
30	2.53	0.80	0.36

In addition to its lethal (lung-injurant) *effects*, chlorpicrin is also a *strong* lacrimator, and has the additional advantage of being capable of penetrating gas-mask canisters that are resistant to ordinary acid gases, such as chlorine and phosgene. The injurious effects of chlorpicrin also extend to the stomach and intestines, causing nausea, vomiting, colic, and diarrhea. These conditions are difficult to combat in the field and often persist for weeks so that even slight cases of chlorpicrin gassing frequently involve large casualty losses.

The main tactical idea in using chlorpicrin, aside from its toxic effect, was to penetrate the mask and produce an intolerable irritation of the eyes, as well as coughing and vomiting from nausea. These effects are sufficient to cause masked troops to remove their masks and thus expose themselves to even more lethal gases, such as phosgene, which would be put over with the chlorpicrin.

The principal disadvantages of chlorpicrin are its relatively low toxicity, as compared to some of the later war gases, and the fact that it decomposes upon heating and when subjected to too high an explosive shock. Notwithstanding this latter peculiarity, the results of the late war showed that chlorpicrin could be successfully used in artillery shells if the bursting charges were properly adjusted to this filling. Another factor limiting the general usefulness of chlorpicrin is its rather high persistency. On open ground chlorpicrin has a persistency of about 3 hours, which would preclude its use on the tactical offensive in ordinary situations.

Owing to the foregoing disadvantages and limitations, the fact that modern gas masks generally furnish adequate protection against chlorpicrin, and the further fact that much more powerful and effective lethal agents were used in the late war and would be in all probability used in any future war, the future role of chlorpicrin as a war gas is at least uncertain, with the probabilities rather against its future use.

Phenylcarbylamine Chloride ($C_6H_5CNCl_2$)
Phenylisocyanide Chloride

This compound, introduced by the Germans in May, 1917, was the last of the simple lung-injurant agents to be employed by them in the

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World War. Two months later they brought out two entirely new and radically different types of agents—the vesicants (Yellow Cross), of which mustard gas was the prototype, and the sternutators (Blue Cross), of which diphenylchlorarsine was the prototype—and thus changed the whole character of gas warfare.

Phenylcarbylamine chloride was the culmination of an attempt to produce a more persistent and enduring lung-injurant agent, *so as to* enable concentrations to be maintained in the field for such a length of time as to exhaust the current types of gas-mask canisters. Later it was used in shoots with mustard gas to mask the presence of the latter.

Phenylcarbylamine chloride is produced by chlorinating phenyl mustard oil (C_6H_5NCS), derived from the action of carbon disulfide on aniline. The product is a transparent liquid, of 1.35 specific gravity, which boils at 210°C. (410°F.), yielding a vapor 6.0 times heavier than air. Its volatility at 20°C. (68°F.) is 2.10 mg. per liter. Its lowest irritant concentration is 0.003 mg. per liter; it lacrimates at 1:1,000,000 (0.0072 mg. per liter); it is intolerable at 0.025 mg. per liter; and a concentration of 0.50 mg. per liter is lethal on 10 minutes' exposure.

Phenylcarbylamine chloride was used chiefly in shells for the 10.5-cm. light field howitzer (without a mark) and 15.0-cm. heavy field howitzer (marked 1 Green Cross – variation). Owing to its low volatility, it was very persistent, and for that reason could not be used on the tactical offensive. Moreover, its low vapor pressure often prevented effective concentrations from being realized in the field. Altogether, about 700 tons of this gas were fired by the Germans from the middle of 1917 to the end of the war and, while this gas was a fair lacrimator and was moderately toxic, it failed to achieve any noteworthy success. It was not considered of much value by the British and the reason for its use by the Germans is not apparent, since they already had far more effective lung-injurant agents (*e.g.*, diphosgene and chlorpicrin).

Dichlordimethyl Ether ($(CH_2Cl)_2O$)
Dibromdimethyl Ether ($(CH_2BR)_2O$)

Dichlormethyl ether is one of the lesser combat substances used by the Germans, usually in mixture with ethyldichlorarsine. It was introduced in January, 1918, and was utilized to increase the volatility of ethyldichlorarsine, which was brought into use about the same time.

Dichlordimethyl ether is a colorless liquid, of 1.37 specific gravity, which boils at 105°C. (221°F.) and has a volatility of 0.180 mg. per liter at 20°C. Its lowest effective concentration is 0.015 mg. per liter; it is intolerable at 0.040 mg. per liter and lethal at 0.470 mg. per liter on 10 minutes' exposure.

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The bromine analogue, dibromdimethyl ether, was also used by the Germans in the same way as dichlordimethyl ether and, as compared to the latter, has the following properties: it has a higher boiling point, 155°C. (311°F.), and a lower volatility (0.022 mg. per liter). It is also less irritant, a concentration of 0.020 mg. per liter being required to produce an irritating effect, while the concentration does not become intolerable until it reaches 0.050 mg. per liter. On the other hand, it is more toxic since a concentration of 0.040 mg. per liter is lethal on 10 minutes' exposure. It is also denser, having a specific gravity of 2.20.

In addition to their typical lung-injurant effects, these two compounds also exert a peculiar selective action on the organs of equilibrium of the body, *i.e.*, the labyrinth of the ear, so that the victim staggers and reels and is unable to maintain his body balance. For this reason the French classified these compounds in a separate class and called them *labyrinthic substances*.

Both dichlormethyl ether and dibrommethyl ether are more toxic than phosgene, and this fact, together with their favorable volatilities and the fact that they are both insidious in action, make them noteworthy combat substances. As they do not appear to have been used to any great extent, except in mixture with ethyldichlorarsine, their individual values as toxic agents were not established in the war. How-

ever, their properties and characteristics are such as to make them of considerable potential value, notwithstanding the fact that they are both rather easily decomposed by water.

Phenyldichlorarsine ($C_6H_5AsCl_2$)

French: "Sternite"

The first of the *toxic* lung-injurant agents to appear in the World War was phenyldichlorarsine. This gas was first used by the Germans in September, 1917, with, and as a solvent for, diphenylcyanarsine (Clark 2) in Blue Cross 1 artillery shell, and later by the French in a mixture with 40 per cent diphenylchlorarsine, known as "Sternite."

Phenyldichlorarsine is a clear somewhat viscid liquid, of 1.64 specific gravity, which boils at 252°C. (485.6°F.) giving off dense vapors 7.75 times heavier than air. It is insoluble in water but dissolves readily in the usual organic solvents. It hydrolyzes readily in contact with water and the oxydants destroy it.

Owing to its high boiling point, phenyldichlorarsine has a very low vapor pressure at ordinary temperatures, being equal to only 0.0146 mm. Hg at 15°C. (59°F.).

While the primary physiological effect of phenyldichlorarsine on men and animals is injury to the lungs and death is usually caused by pulmonary edema, phenyldichlorarsine also has a marked vesicant as well

as a sternutatory effect on the upper respiratory passages. Its toxicity exceeds that of phosgene, a concentration of 0.26 mg. per liter being fatal in 10 minutes; its vesicant action is somewhat slower than that of mustard gas and the resulting wounds as a rule heal more rapidly.

On the whole, phenyldichlorarsine was not used in the war to any great extent. The principal idea underlying its use was as a solvent for diphenylchlorarsine and to assist in the penetration of the gas-mask canister. A mixture of these two compounds in the proportion of 60 per cent phenyldichlorarsine and 40 per cent diphenylchlorarsine was used by the French under the name of "Sternite." It was claimed that this mixture would readily penetrate the masks then in use and, being a liquid, did not present the difficulties in shell filling that attended the filling with a solid diphenylchlorarsine.

The limited use of phenyldichlorarsine in the late war did not clearly demonstrate any marked superiority for this compound over other organic arsenicals simultaneously employed, but it would seem from a consideration of its properties that it is an agent of considerable promise.

Ethyldichlorarsine ($C_2H_5AsCl_2$)

German: "Dick"

This compound was introduced by the Germans in March, 1918, in an attempt to produce a volatile nonpersistent gas that would be quicker acting than diphosgene or mustard gas and would be more lasting in its effects than "Clark" (see Chap. X). Such a gas was particularly desired for use in the immediate preparation for and in support of infantry attacks in the grand offensive operation planned for the spring of 1918, and ethyldichlorarsine was the answer of the German chemists to this demand.

The German process of manufacturing this compound was complicated and comprised the following principal steps: (1) the conversion of ethyl chloride into ethyl sodium arsenate by treatment with sodium arsenate under pressure; (2) reduction to ethyl arsenious oxide by the action of sulfurous acid; (3) conversion of the ethyl arsenious oxide to ethyl dichlorarsine by treatment with hydrochloric acid.

The final product, when pure, is a clear somewhat oily liquid, of 1.7 specific gravity, which boils at 156°C. (312°F.), yielding a vapor 6.5 times denser than air with a piquant fruity odor. At 20°C. (68°F.), its volatility is 100.0 mg. per liter. Although the liquid ethyldichlorarsine is slowly hydrolyzed by water, the vapor seems sufficiently stable to endure for its ordinary period of persistency in the field. The hydrolysis product, ethylarsenious oxide, is also poisonous when swallowed. Although ethyldichlorarsine is but little soluble in water, it is soluble in

alcohol, ether, benzene, or ethyl chloride and is destroyed by oxydants, such as chloride of lime and potassium permanganate. Although ethyldichlorarsine is a fairly powerful sternutator and vesicant agent, its primary action on the body is as a lung injurant. Its first effect in low concentrations is a respiratory irritation which occurs in concentrations as low as 0.001 mg. per liter after 5 minutes' exposure. A concentration of 0.010 mg. per liter is intolerable for more than 1 minute because of the great irritation of the nose and throat. The lethal concentration of ethyldichlorarsine is 0.50 mg. per liter for 10 minutes' exposure and 0.10 mg. per liter for 30 minutes' exposure. Its toxicity is, therefore, the same as phosgene for short exposures (10 minutes), but is over three times the toxicity of phosgene for long exposures (30 minutes). In concentrations as low as 0.005 mg. per liter, this gas causes marked local irritation of the eyes and respiratory tract. The effect upon the eyes and upper respiratory tract is evanescent, while that upon the lower respiratory tract leads to membranous tracheitis and pulmonary congestion, edema, and pneumonia. Arsenic is absorbed rapidly and leads to systemic arsenical poisoning, characterized by lowered temperature, atoxic symptoms, anesthesia, and depression.

On short exposures (*i.e.*, less than 5 minutes), ethyldichlorarsine is not a particularly efficient irritant for the human skin. On exposures greater than 5 minutes, however, positive burns appear which increase in severity with length of exposure. On the basis of rapidity of action, extent of rubefaction, swelling and edema, and time of healing, ethyldichlorarsine is about two-thirds as effective as mustard gas, but for vesication it is only about one-sixth as effective.

Ethyldichlorarsine and its bromic analogue, ethyldibromarsine, were used in mixtures with the equally toxic dichlormethyl ether (21, pages 93 and 95) as fillings for the German Yellow Cross 1 or Green Cross 3 artillery shell. Ethyldibromarsine has the same physiological effects as ethyldichlorarsine, but is less irritant and toxic than the latter and the reason for its use by the Germans is not apparent.

Concerning the use of ethyldichlorarsine in the war, Hanslian says:

> Like the Yellow Cross substance, this combat substance was usually not noticed at all when it was breathed in. It was distinguished from the Yellow Cross substance when used in the field by the fact that in the first place there was no effect on the skin, and in the second place, the injuries to the nose, throat, and chest did not delay for hours but appeared at the end of a few minutes. When small quantities are inhaled, about 5 cc. for 1 minute, the victim is rendered incapable of fighting for as much as 24 hours as the result of dyspnea and pains in the chest, and if large quantities are inhaled the result is fatal. In case small amounts of the substance have already been inhaled before the gas mask is put on, it is impossible to keep the mask on because of the irritation. The substance of the Yellow Cross 1 shell was not nearly

> so persistent on the terrain as that of the regular Yellow Cross. These shells were therefore suitable for gassing operations to be followed by infantry assaults. In summer, terrain could be entered 1 hour after the gas cloud had disappeared, and, in winter, 2 hours after. The Yellow Cross substance No. 1 behaved, accordingly, almost in all respects like the Green Cross substance and not like the Yellow Cross substance.

There is no record of the casualties produced by ethyldichlorarsine, nor any reliable record by which its battle efficacy may be judged. However, it possesses many valuable properties and characteristics, chief among which are its quick action and low persistency which makes it suitable as an offensive chemical agent. There is a great tactical need for a quick-acting nonpersistent vesicant and, while the vesicant action of ethyldichlorarsine is secondary to its lung-injurant action, it is, nevertheless, not inconsiderable. We may, therefore, expect to find this compound given careful consideration in any estimate of chemical warfare in the future.

Phenyldibromarsine ($C_6H_5AsBr_2$)

This was the last type of lung-injurant gases of the toxic variety used in the World War. It was introduced by the Germans in September, 1918, and there is very little information as to its effectiveness.

The compound is a colorless or faintly yellow liquid, boiling with slight decomposition at 285°C. (545°F.), and having a density of 2.1 at 15°C. (59°F.). When dispersed by heat, the fumes are slightly lacrimatory and somewhat sternutatory, although this latter effect is very much less than diphenylchlorarsine. A concentration of 0.020 mg. per liter is fatal on 10 minutes' exposure; hence its toxicity exceeds that of any of the lung-injurant agents used in the war.

It was the opinion of the Allies that phenyldibromarsine had very little value during the war. This was no doubt due chiefly to its high boiling point, low vapor pressure, and the relative ease with which it was *decomposed* in the field. However, definitive data as to the value of this compound are lacking, so that no definite conclusions can be drawn.

COMPARATIVE TOXICITIES OF LUNG INJURANTS

As the lung injurants are compounds of relatively low boiling points and high vapor pressures, their volatilities are well above their lethal concentrations, and therefore the casualty and fatality powers of these agents are in proportion to their minimum lethal concentrations. On this basis, the foregoing lung injurants are arranged in the descending order of their fatal concentrations as shown on page 169.

USE OF LUNG INJURANTS IN WORLD WAR

As a group, the lung injurants were used to a larger extent than any other type of gas and secured the bulk of the gas fatalities in the war.

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Agent	Minimum Lethal Concentration on 10 Minutes' Exposure, Mg. per Liter
Phenyldibromarsine	0.200
Phenyldichlorarsine	0.260
Dibromethyl ether	0.400
Dichlormethyl ether	0.470
Ethyldichlorarsine	0.500
Phosgene	0.500
Trichlormethylchloroformate	0.500
Dimethylsulfate	0.500
Phenylcarbylamine chloride	0.500
Monochlormethylchloroformate	1.000
Ethylsulfuryl chloride	1.000
Methylsulfuryl chloride	2.000
Chlorpicrin	2.000
Perchlormethylmercaptan	3.000
Chlorine	5.600

Thus it is estimated that, altogether a total of 100,500 tons of these gases were used in battle during the late war and caused 876,853 casualties, or an average of one casualty per 230 lb. of gas. While the ratio of casualties to pounds of gas employed is much lower than in the case of the vesicant gases, it must be remembered that the latter, on account of high persistency, cannot be used on the tactical offensive, whereas the lung-injurant agents are generally nonpersistent and may be employed in any situation.

FUTURE OF LUNG INJURANTS

As the lung injurants were the principal nonpersistent casualty gases of the war and are the only casualty gases suitable for use in the tactical offense when friendly troops are required to occupy terrain within a few minutes after gassing, the lung-injurant agents will continue to play a major role in gas warfare of the future.

The *toxic* lung injurants were but little used during the late war, and their possibilities were not extensively explored. Their high toxicities, dual physiological effects, and other properties are very favorable to offensive chemical warfare, and this field is one from which new and more effective chemical agents may be expected to be drawn in the future.

For a summary of the properties of the principal lung-injurant agents, see Table IV.

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CHAPTER VIII

SYSTEMIC TOXIC AGENTS

The systemic toxic agents are those compounds which, instead of confining their dominant action to some particular organ or part of the body, usually near the point of impact, have the power to penetrate the epithelial lining of the lungs without causing local damage. They then pass into the blood stream, whence they are diffused throughout the whole interior economy of the body and exercise a general systemic poisoning action which finally results in death from paralysis of the central nervous system. The systemic toxics were the third type of compounds to appear in the World War, the first member of the group being introduced July 1, 1916. The group is very small, consisting of the following compounds used in the war:

Agent	Introduced by	Date
Hydrocyanic acid	French	July 1, 1916
Cyanogen bromide	Austrians	September, 1916
Cyanogen chloride	French	October, 1916
(Phenylcarbylamine chloride)*	Germans	May, 1917

* Primarily a lung injurant.

The systemic toxics are nonpersistent and were used tactically in the same way and for the same purposes as the lung-injurant agents. Their appearance and use in the war was also concomitant in point of time with the lung injurants, and they may, therefore, be tactically regarded as supplementing the lung-injurant group rather than as a separate and distinct group of agents. On the other hand, their physiological effect is quite different from that of the lung injurants and, since our classification is based primarily on physiological effect, with the systemic toxics assigned as a separate subclass under the nonpersistent agents, it is logical to treat them as a separate group.

GROUP CHARACTERISTICS

Chemically, the systemic toxics are closely related. They are all derivatives of the compound cyanogen (C_2N_2) and are divided into two classes: (1) those containing the radical (—C≡N), called *nitriles;* and

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(2) those containing the radical (—N≡C), called *isonitriles* or *carbylamines.* All are commonly known as *cyanides.*

Physically, the systemic toxics are all light liquids with relatively low boiling points, high vapor pressures, and high volatilities. They are the least persistent of all of the combat agents.

Physiologically, they are, in general:

1. Specialized in their action on the body for, while they pervade the entire circulatory system, they act primarily on the nerve centers and cause death by paralysis of the central nervous system.

2. Extremely quick acting when present in lethal concentrations. A few breaths are sufficient to cause death, which occurs within a few minutes.

3. Reversible in action below a certain critical concentration (about 0.030 mg. per liter), for below this concentration the body appears to have the power to neutralize and eliminate the poison. Hence with the systemic poisons, Haber's simple generalization, that the degree of intoxication equals the toxic concentration times the time of exposure, does not hold true, and an additional factor enters the equation. This is known as the elimination factor* and is specific for each compound, being the quantity which the body can constantly eliminate by reversing the toxic action. Below the critical concentration no lesions are formed by the poison in the body. Even after acute poisoning, few organic lesions are found, for above the critical concentration asphyxiation is so rapid that they do not have time to form.

* See p. 13.

4. Of relatively low threshold of action. Thus, hydrocyanic acid is effective down to the critical concentration of 0.030 mg. per liter.

5. Exceedingly toxic, a concentration of 0.012 mg. per liter of hydrocyanic acid being fatal in from 30 to 60 minutes.

6. Insidious in action, causing practically no premonitory symptoms until after serious poisoning has ensued.

Hydrocyanic Acid (HCN)

French: "Vincennite" and "Manganite"

For over a hundred years before the World War, hydrocyanic acid was known in industry as one of the most virulent of all poisons. During the latter part of 1915, in the race to produce more deadly chemical-warfare gases, it was inevitable that attention would be turned to this compound because of its high toxicity. The French were the first to consider it and were in fact its only exponent during the war. Since the practical difficulties encountered in its use in the field soon convinced the other belligerents that this gas was not suitable for war use, it was never used by them.

Dr. Hanslian, citing a French authority, says that as early as the end of 1915 the French had filled great quantities of gas shells with hydrocyanic acid (Special Shell 4) and phosgene (Special Shell 5), but hesitated to authorize their use at the front because of their

high degree of toxicity and lack of splinter effect. In this connection, it will be recalled that the signatories to the Hague Conventions of 1899

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and 1907 had agreed not to use *shell*, the sole purpose of which was to diffuse asphyxiating gases, and had laid down the rule that a shell in which the toxic-gas effect was greater than the splinter effect came within the prohibited category. It is, however, difficult to understand the hesitancy of the French to make use of gas shells containing hydrocyanic acid and phosgene in view of their earlier use of gas shell filled with such compounds as ethylsulfuryl chloride and perchlormethylmercaptan, and the prior German use of gas shells filled with bromacetone. To be sure, these earlier compounds were sufficiently lacrimatory to be regarded as such, but they were also toxic enough to cause serious casualties and deaths in ordinary field concentrations and hence could not properly be excluded from the class of asphyxiating shell prohibited by the Hague Conventions.

Regardless of whatever scruples the French may have had against the use of hydrocyanic acid and phosgene shells, they commenced their use in 1916. The phosgene shells were first employed at the front at Verdun on Feb. 21, 1916, and the hydrocyanic acid (Vincennite) shells in the battle of the Somme, July 1, 1916. In view of the superior combat properties of phosgene, which antedated the introduction of hydrocyanic acid, it is not clear why the French ever decided to use the latter. Perhaps the only valid reason is to be found in the fact that the German masks of early 1916 afforded adequate protection against phosgene, but very little protection against hydrocyanic acid. Even this advantage, however, was short-lived for the Germans learned of the contemplated French use of hydrocyanic acid a week before its introduction at the front and soon equipped their troops with mask filters capable of holding back this gas. These filters contained 1 gram of pulverized silver oxide scattered through the potash layers and afforded adequate protection against hydrocyanic acid.

Hydrocyanic acid is derived by distilling a concentrated solution of potassium cyanide with dilute sulfuric acid and absorption of the vapors in water. The anhydrous form used in battle was obtained by subsequent fractional distillation from the aqueous solution. When pure, hydrocyanic acid is a colorless liquid, of 0.7 specific gravity, which boils at 26°C. (79°F.), yielding a light vapor, only 0.93 as heavy as air, with a faint odor resembling bitter almonds. The vapor is exceedingly volatile (873 mg. per liter at 20°C.) and persists in the open only a few minutes after release. In order to prevent the too rapid diffusion of its vapors in the air, hydrocyanic acid was not used in pure form but was mixed with stannic chloride, with the addition of chloroform as a stabilizer to counteract a tendency to polymerize. This mixture was known as "Vincennite," and was used on a large scale in artillery shell by the French. Later, hydrocyanic acid was also mixed with arsenic trichloride,

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and known as "Manganite." Hydrocyanic acid is miscible with water in all proportions, but is slowly decomposed thereby with the formation of ammonium cyanide. Anhydrous hydrocyanic acid is extremely unstable and is quickly decomposed with the formation of a black resinous mass. However, it can be stabilized by the addition of small percentages of strong acids and by dissolving it in arsenic trichloride or stannic chloride.

According to Hederer and Istin, the toxic action of hydrocyanic acid is typical of the protoplasmic poisons. It suspends certain functions of the living cells, notably oxidation. By inhibiting the action of the respiratory ferments, it brings about a true internal asphyxiation. Under its influence, the tissues become incapable of utilizing the oxygen of the blood and an analysis of the venous blood shows that in oxygen and carbonic acid contents it is very close to the arterial blood. With the higher animals and above all with man, it strikes the central nervous system. After a short period of excitation, the pneumogastric nerve centers, as well as the vasomotor and respiratory centers, are paralyzed. Then the poison, following its general action, gradually arrests cytoplasmic oxidation, and all the tissues suffer from an acute lack of oxygen. But, as the nerve cells are more sensitive than the others, they pay first tribute to the increasing asphyxiation. Their functional death is then shown by noisy symptoms which dominate the scene and mask the divers accompanying troubles.

Hydrocyanic acid is one of the most virulent poisons known. When injected under the skin 0.05 gram is lethal and Vedder (25, page 186) says: "The lethal dose by respiration is usually believed to be less than the above and our figures confirm this view."

However, unlike most toxics, the poisoning effect of hydrocyanic acid is not cumulative, so that Haber's simple generalization does not apply. On the contrary, the body seems to be able to neutralize the effects of this gas up to a critical concentration of about 0.030 mg. per liter. Below this level, the poison is eliminated from the body as rapidly as it is absorbed and no serious toxic effects are produced. Above the critical concentration, however, there is a very rapid poisoning effect and death ensues in a few minutes when the concentration reaches 0.300 mg. per liter. The lethal concentration for 10 minutes' exposure is 0.200 mg. per liter and for 30 minutes' exposure, 0.150 mg. per liter.

Because of its extreme volatility and the fact that its vapors are lighter than air, it is almost impossible to establish a lethal concentration of hydrocyanic acid in the field, and this is particularly true when the gas is put over in artillery shells. This difficulty, coupled with the peculiar action of hydrocyanic acid wherein it produces no casualties until a lethal concentration is established, made the use of this gas in artillery

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shell a tragic mistake on the part of the French. Despite the vociferous controversies among the Allies as to the effectiveness of hydrocyanic acid on the field of battle, the evidence from all sources is now convincing that extremely few casualties were caused by the French artillery shell containing hydrocyanic acid, although the French used over 4,000 tons of this gas in the war.

Cyanogen Bromide (CNBr)

Austrians: "Ce"; British: "CB"; Italian: "Campillit"

The Austrians introduced cyanogen bromide in September, 1916, shortly after the French brought out hydrocyanic acid. Cyanogen bromide was first employed in a mixture with bromacetone and benzene (25 per cent CNBr to 25 per cent CH_3COCH_2Br and 50 per cent C_6H_6). Later, as a result of poor storing qualities and a resulting decrease in toxic effect, cyanogen bromide and bromacetone were loaded separately into shells. Cyanogen bromide was also used on the Western Front by the British (CB shell).

Cyanogen bromide is made by treating a concentrated solution of potassium cyanide with bromine at 0°C. When freshly sublimed, it is a white crystalline solid, of 2.02 specific gravity, which melts at 52°C. (125.6°F.), and boils at 61.3°C. (142°F.), yielding a vapor 3.4 times heavier than air with a piquant odor and bitter taste. It is soluble in alcohol and in water, but hydrolizes in the latter, yielding a nontoxic hydrate. At 20°C. (68°F.) its vapor pressure is 92.00 mm. Hg and its volatility is 200.00 mg. per liter. Thus, as compared to nonpersistent gases, generally it is highly volatile, yet it is only about one-fourth as volatile as hydrocyanic acid.

The effect of cyanogen bromide on the body is similar to that of hydrocyanic acid. It is, however, less toxic, but has, in addition, a lacrimatory and strong irritant effect. A concentration as low as 0.006 mg. per liter greatly irritates the conjunctiva and the mucous membranes of the respiratory system, while 0.035 mg. per liter is unbearable. Its lethal concentration for 10 minutes' exposure is 0.400 mg. per liter, which makes it somewhat more toxic than phosgene, but only about one-third as toxic as hydrocyanic acid. Moreover, it corrodes metals and suffers decomposition thereby; it also is unstable in storage and gradually polymerizes into a physiologically inert substance. In view of the above, cyanogen bromide is rather unsuitable for use as a chemical agent and the success obtained from its employment in the World War was so slight that the Austrians abandoned it in favor of the German Green Cross (diphosgene) ammunition.

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Cyanogen Chloride (CNCl)

French: "Mauguinite" and "Vitrite"

Almost at the same time that the Austrians introduced cyanogen bromide, the French brought out cyanogen chloride, in an attempt to

secure a systemic toxic gas that did not have the disadvantages of hydrocyanic acid, *i.e.*, a heavier and less volatile gas with cumulative toxic effects in low concentrations.

Like its bromine analogue, cyanogen chloride is produced by the direct chlorination of a saturation solution of potassium cyanide at 0°C. It is a colorless liquid, of 1.22 specific gravity, which boils at 15°C. (59°F.), yielding a volatile irritant vapor 1.98 times heavier than air. At 20°C. (68°F.) the vapor pressure of cyanogen chloride is 1,000 mm. Hg and its volatility is 3,300 mg. per liter, so that it is more volatile than hydrocyanic acid.

Although cyanogen chloride is but slightly soluble in water, it dissolves readily in the organic solvents. It is chemically unstable and on storage polymerizes into cyanogen trichloride $(CNCl)_3$, which is physiologically far less active. When mixed with arsenic trichloride, which increases the density of its vapors, cyanogen chloride is far more stable, and for that reason it was used in this mixture by the French under the name of "Vitrite."

The toxic action of cyanogen chloride is similar to that of hydrocyanic acid, but it is much more effective in low concentrations on prolonged exposure. Like hydrocyanic acid, in high concentrations it kills by rapid paralysis of the nerve centers, especially those controlling the respiratory system, but, unlike hydrocyanic acid, in low concentrations (0.010 to 0.050 mg. per liter) it is also irritant to the eyes and lungs and has a retarded toxic effect somewhat resembling that of the lung-injurant compounds. Its lethal concentration for 10 minutes' exposure is 0.40 mg. per liter the same as that of cyanogen bromide. Cyanogen chloride is also a moderate lacrimator, 0.0025 mg. per liter producing copious lacrimation in a few minutes.

Phenylcarbylamine Chloride ($C_6H_5CNCl_2$)

This compound has already been considered under the lung-injurant group, as its predominant action is against the pulmonary system. It does, however, have a subsidiary effect resembling that of the systemic toxics, which is attributable to the fact that it is chemically an isonitrile and, therefore, belongs to the family of cyanides. Its systemic toxic effect is not important and it is mentioned here in order to complete its classification.

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FUTURE OF SYSTEMIC TOXICS

The systemic toxics are as a class the most virulent poisons known. They are, however, extremely volatile and their vapors are very light and diffuse into the atmosphere with extraordinary rapidity. They are also practically noneffective until a certain critical concentration is reached and then they strike with great speed and vigor. Hence, in order to use them effectively in the field, it is necessary to establish the concentration with a high density in a minimum of time and under favorable meteorological conditions, so that the enemy will receive a lethal dose in a few breaths before the concentration falls below its critical effective strength. Because of these requirements concerning its use, the systemic toxics are neither economical nor certain of results on the field of battle. At the same time, their toxicities and rapid actions make them very effective against small well-defined targets, especially where men are sheltered in dugouts, deep trenches, woods, etc., where high concentrations may be established and maintained for several minutes.

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CHAPTER IX

VESICANT AGENTS

By the term *vesicant agents* we denote those compounds which vesicate (blister) the human and animal body on any surface, either exterior or interior, with which they come in contact. This type of compound constitutes the fourth class of combat gases used in the World War. Most of them are highly toxic substances and nearly all produce multiple physiological effects. Thus, some are fairly lacrimatory, others exert marked lung-injurant effects, while still others are systemic poisons. However, in all compounds classed as *vesicants*, the vesicant effect is so much more pronounced than their other effects as to constitute their dominant characteristic. Where the vesicant effect of a compound is subordinate to its other physiological effects, the compound is classified in some other class, *e.g.*, ethyldichlorarsine is somewhat vesicant, but its primary physiological action is on the pulmonary system of the body, and it is, therefore, considered a lung-injurant agent (see Chap. VII).

At the outbreak of the World War, over 70 vesicant compounds were known to science; yet only five were identified with the war. Of these, but two—dichlorethyl sulfide (mustard gas) and ethyldichlorarsine—were actually used, while the other three—chlorovinyldichlorarsine (lewisite), methyldichlorarsine, and dibromethyl sulfide—were in process of investigation or manufacture at the end of the war and were not actually used in battle. Of the first two, ethyldichlorarsine was primarily a lung injurant and was used only to a limited extent as a vesicant agent. While it proved to be quite effective, it did not play a very important role in the war. On the other hand, mustard gas was widely used by both sides and proved to be so effective that it became the principal battle gas of the last year of the war. In fact, so completely did mustard gas dominate the field of vesicant agents that the story of mustard is practically the story of vesicants in the World War.

GROUP CHARACTERISTICS

While the vesicant agents, in addition to vesication, exert divers complex physiological effects, their physical, chemical, and toxic properties are such that they form a well-defined group with many characteristics in common, and for this reason they were grouped by the Germans under the general name of "Yellow Cross" substances.

Thus, the vesicants, although very soluble in the substance of animal tissues, have weaker chemical affinities for living matter than the lung-

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injurant agents. They, therefore, disintegrate more slowly and penetrate further into the tissues of the body, thus greatly enlarging their field of action.

Vesicants, in general, are:

1. Nonspecialized in their action on the body, as they destroy the cellular structure of the tissues wherever they come in contact with them.
2. Slow acting, in producing physiological effects on the body. Thus, their toxic effects do not commence to manifest themselves until from 6 to 24 hours after exposure. They are seldom fatal (less than 2 per cent deaths).
3. Nonreversible in action, for their injury to the cellular structure of the tissues is permanent. The lesions produced heal in time, depending upon the depth of penetration of the vesicant agent, but the reaction upon the original cells is irreversible.
4. Low in threshold of action. Thus, mustard gas produces definite incapacitating effects in concentrations as low as 1:100,000 (0.0065 mg. per liter) with 60 minutes' exposure, and on longer exposure equal results are obtained with proportionately lower concentrations.
5. High in boiling point.
6. Low in vapor pressure and volatility.
7. High in persistency.
8. Insidious in action, giving little or no warning of their presence until injury is sustained.

CLASSIFICATION OF VESICANTS

The vesicants may be divided into two classes: (1) simple vesicants which exert a local action only; and (2) toxic vesicants which, in addition to local action, also exert a systemic poisoning effect. The distinction is not of great practical importance since all the simple vesicants of which there is any record of use in the war exert their vesicant effect in a subordinate manner only. That is to say, the known simple vesicants are predominantly compounds of other classes. Thus, dimethyl sulfate, the only simple vesicant used in battle during the war, is a much more powerful lung injurant than a vesicant agent, and for that reason it is generally regarded as a lung-injurant compound (see Chap. VII). On the other hand, mustard gas and the postwar vesicants are all of the toxic variety, so that from a practical-use viewpoint, we may regard the vesicant agents generally as toxic compounds. We do not mean to say, however, that this will always be the case, for it is entirely possible that some new compound will be discovered, the vesicant action of which is simple yet so predominant as clearly to entitle the compound to be classed as a simple vesicant agent.

Dichlorethyl Sulfide ($S(CH_2CH_2)_2Cl_2$)

German: "Lost"; French: "Yperite"; British and American: "Mustard Gas"

The introduction of mustard gas by the Germans on the night of July 12, 1917, in the form of an artillery bombardment against the

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British front near Ypres in Flanders, marked the beginning of a new phase of gas warfare. It came as a complete surprise to the Allies and caused thousands of casualties before any form of defense could be devised against it. Its tremendous effectiveness perfectly illustrates the ever-threatening potential power of chemical warfare.

During 1916 and the first half of 1917, the principal battle gases used were of the lung-injurant type, and these were based on the principle of attacking the respiratory organs, for which purpose they must necessarily be inhaled. But by the summer of 1917 the gas mask had been so improved that it furnished full protection against all the known lung-injurant gases, so that the only casualties produced by these gases were those where men were caught by surprise and were gassed before they could adjust their masks. In other words, gas defense had caught up with the offense. To break this deadlock, one of two things was necessary—either to find a lung-injurant type of gas that would penetrate the mask or to discover an entirely new type of gas that would go around the mask and incapacitate by attacking some other part of the body. The German chemists solved both of these problems simultaneously by bringing out diphenylchlorarsine (Blue Cross), which, when properly dispersed, would penetrate any of the masks as they were constructed in 1917, (see Chap. X), and mustard gas, which would go through clothing and even rubber and leather boots and produce incapacitating burns on any part of the body with which its vapors came in contact. In addition to its vesicant properties, mustard gas was exceedingly toxic, so that it also caused serious casualties when breathed, even in very minute concentrations. It was, therefore, an almost perfect battle gas, particularly in view of the total absence of any means of protecting the body against it, even though the mask furnished adequate protection for the lungs. There is small wonder, therefore, that mustard gas was soon recognized as the "king of battle gases," and maintained this superior position throughout the remainder of the war.

The gas shells used in bombardment at Ypres on the 12th and 13th of July, 1917, were of 77- and 105-mm. caliber and were marked on the base or side with a yellow cross. The vapors arising from these bursting shells had no immediate irritating action on the eyes or chest, and so at first the troops in the bombardment suffered no discomfort from the gas, except irritation of the nose which caused sneezing. In the course of an hour or two, however, the signs of mustard poisoning began to appear in the form of inflammation of the eyes and vomiting, followed by erythema of the skin and blistering. The conjunctivitis was marked and, by the time the gassed cases reached the casualty clearing stations, the men were virtually blind and had to be led about.

The Ypres area was shelled with mustard gas each night beginning July 12, 1917, until the end of the month. On the nights of the July 21

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and 22 a particularly heavy bombardment with Yellow Cross shells was directed on Nieuport, which resulted in a heavy toll of casualties of a more serious character than the casualties from the first mustard-gas bombardment at Ypres.

Armentières was shelled with mustard gas on the night of July 20–21, 1917, and on the night of July 28–29 a heavy Yellow Cross bombardment was directed on both Armentières and Nieuport. From then on, Yellow Cross shells were used by the Germans extensively. It was not until July, 1918, that mustard-gas shelling of this type showed any marked diminution, and this was undoubtedly caused by a shortage of Yellow Cross shells.

During the first three weeks of the mustard-gas period (July 12 to Aug. 1, 1917) 14,276 cases of gas-shell poisoning were admitted to the British casualty clearing stations and about 500 deaths occurred among these cases. In this brief period, therefore, the Yellow Cross shelling had accounted for more casualties and practically as many deaths as the entire previous shelling with lung injurants. The total gas-shell casualties admitted to British clearing stations from July 21, 1917, to Nov. 23, 1918, were 160,970, of which number 1,859 died. Seventy-seven per cent of these casualties were due to mustard-gas poisoning, 10 per cent were due to Blue Cross (dichlorethylarsine) gas poisoning, and 10 per cent to Green Cross gas poisoning (phosgene, diphosgene, chlorpicrin).

Concerning the important role played by mustard gas in the war, Dr. Mueller says:

> The German Front would never have succeeded in withstanding the powerful onslaught of the concentrated forces and war materials of almost the whole world if German chemists had not at that moment held the protecting shield of the "Yellow Cross Substance" (mustard gas) before the German soldiers and at the same time thrust into their hands a new sharp sword in the form of the "Blue Cross Substance."

Altogether about 12,000 tons of mustard gas were used in the war and this caused a total of 400,000 casualties, from which it is seen that one casualty was produced for every 60 lb. of mustard used, as compared to one casualty for every 230 lb. of lung injurants used in the war.

Like the other World War gases, mustard was not a new or unknown compound. On the contrary, it was discovered sixty years before the outbreak of the war, and its chemical and physiological properties had been studied and were known to science for many years. Mustard gas was first obtained (in an impure form) by Richie in 1854 (15, page 235). In 1860 it was independently prepared by Guthrie and Niemann by passing ethylene into sulfur chloride; both of these chemists accurately and almost prophetically describing its high toxic and vesicant properties. Thus Guthrie says: "Even the vapors of this substance when in contact with the more delicate parts of the skin of

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the body cause the most serious destruction." In 1886 the German chemist, Victor Meyer, prepared mustard gas by the action of hydrochloric acid on thiodiglycol and described the terrible effects of the product. Finally, in 1891 the opthalmologist, Theodore Leber, made a summary study of the toxicity of mustard gas.

In searching for a more effective combat gas, therefore, the Germans had available many data in the literature concerning mustard and had only to make it in quantity production and test it in the field. This they did quite secretly in the spring of 1917 and were so well satisfied with the results obtained that they adopted it as an artillery-shell filling and accumulated a large quantity of these (Yellow Cross) shell before the Allies were aware of this development.

In its pure state, dichlorethyl sulfide is a transparent amber oily liquid, of 1.27 specific gravity, which boils with slight decomposition at 217°C. (422.6°F.), yielding a vapor 5.5 times heavier than air. It is almost odorless in ordinary field concentrations and in strong concentrations resembles horse-radish or mustard. Hence the origin of the English name—"mustard gas"—although this substance has no relation chemically to the true mustard oils. It solidifies at 14°C. (57°F.) to form white crystals, and for this reason was used by the Germans diluted with a solvent to lower its freezing point and maintain it in a uniform (liquid) state under all ordinary temperatures.

The vapor pressure and volatility of mustard gas are low, as shown by the following tabulation:

Temperature		Vapor pressure, mm. Hg	Volatility, mg. per liter
°C.	°F.		
0	32	0.0260	0.250
5	41	0.0300	0.278
10	50	0.0350	0.315
15	59	0.0417	0.401
20	68	0.0650	0.625
25	77	0.0996	0.958
30	86	0.1500	1.443
35	95	0.2220	2.135
40	104	0.4500	3.660

Because of its low volatility, mustard gas is very persistent in the field, varying from one day in the open and one week in the woods in summer to several weeks both in the open and in the woods in winter. Its great persistency is the principal limitation on its use, as it cannot be used on the tactical offensive where friendly troops have to traverse or

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occupy the infected ground. However, by the same token, mustard is

peculiarly adapted for use in the tactical defensive, particularly to prevent the occupation by hostile troops of ground evacuated on a withdrawal.

Dichlorethyl sulfide (mustard gas) was made by two radically different processes during the war. The Germans used the more complicated process of Victor Meyer because they had already available facilities for manufacturing the principal components and had only to erect facilities for the final step in the process. The German process was briefly as follows:

1. Ethylene chlorhydrin was converted into thiodiglycol by sodium sulfide according to the equation

$$2(ClCH_2CH_2(OH)) + Na_2S = S\begin{<}CH_2CH_2(OH)\\CH_2CH_2(OH)\end{>} + 2NaCl$$

2. The thiodiglycol was chlorinated by treatment with gaseous hydrochloric acid, according to the equation

$$S\begin{<}CH_2CH_2(OH)\\CH_2CH_2(OH)\end{>} + 2HCl = S\begin{<}CH_2CH_2Cl\\CH_2CH_2Cl\end{>} + 2H_2O$$

The German process had two outstanding advantages, *viz.*: (1) the intermediate products possessed no dangerous properties, and hence there was no danger to personnel working in the plants on any of the intermediate steps. The only danger involved in the whole process was in the last step of chlorinating the thiodiglycol to form mustard gas. This was a relatively simple reaction that was easy to control, and hence the danger to personnel was far less than in many of the steps of the other process. (2) The yield was high and the product pure, since the only other end product was water, which was easily separated by distillation.

On the other hand, the German method had the formidable objection of being a very complicated process, particularly in the method of making the chlorhydrin. To make this intermediate, three steps requiring careful control were necessary: (1) alcohol was split into ethylene by passing its vapors over aluminum oxide at 300°C.; (2) the ethylene gas was pumped into large reactors containing chloride of lime paste which was carefully cooled during the process; (3) the resulting ethylene chlorhydrin was forced out of the lime paste by steam.

While the foregoing steps in the German process of making mustard gas seem simple, in reality they were very difficult and only a chemical technique excellently organized and backed by a wealth of experience could successfully cope with the technical difficulties encountered.

Lacking the facilities and experience in making the intermediates required in the German process, the Allies turned to the older process of

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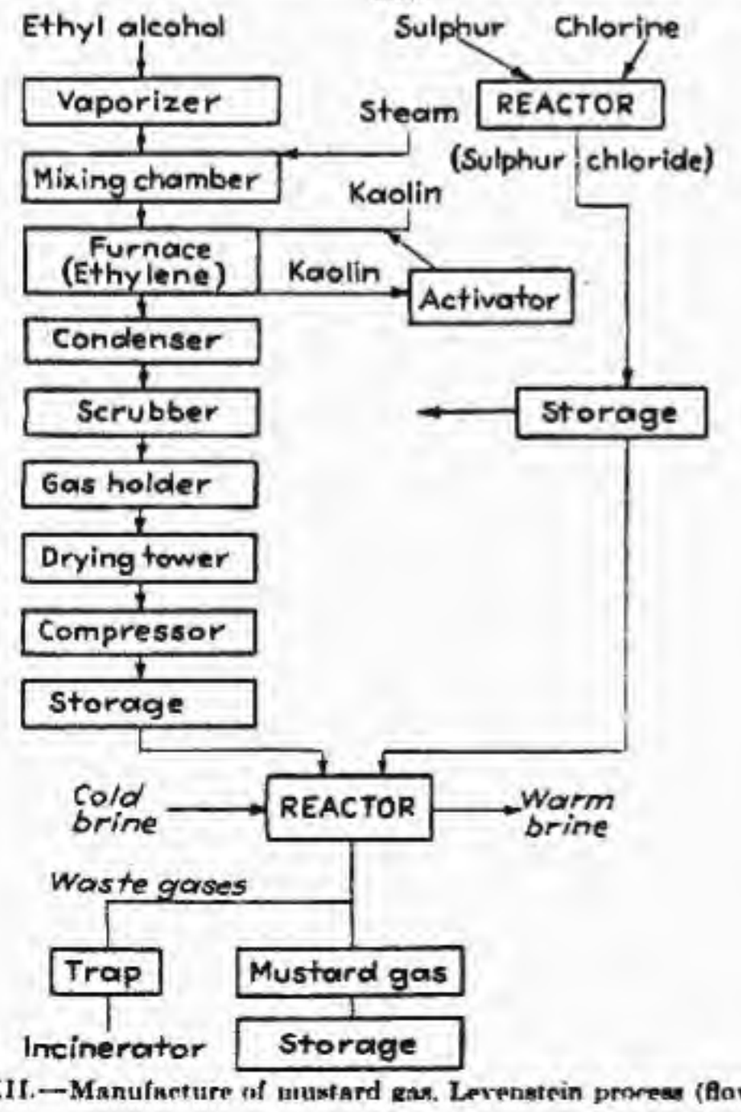

CHART XII.—Manufacture of mustard gas. Levenstein process (flow sheet).

Guthrie and Niemann, in which dichlorethyl sulfide is formed by the direct action of ethylene gas on sulfur monochloride (see Chart XII), according to the equation:

$$2C_2H_4 + S_2Cl_2 = S\begin{<}CH_2CH_2Cl\\CH_2CH_2Cl\end{>} + S$$

While this reaction under proper conditions proceeds smoothly, there are actually encountered in quantity-production operations several very formidable difficulties. Thus, the reaction occurs spontaneously with the evolution of much heat. Sulfur is set free, and the temperature must be carefully controlled in order to keep the sulfur in colloidal suspension and thus prevent its precipitation in solid form in the reaction vessels and connecting pipes. There is also considerable difficulty in separating the mustard gas from the colloidal sulfur, so that the resulting

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product was not so pure as that from the German process, although it seemed to be equally as effective in the field.

It is difficult to emphasize sufficiently the extreme danger that is involved in working with mustard gas even under the best of conditions. The workmen must be equipped with masks and the most efficient protective clothing, and everything coming in contact with even the vapors of mustard gas must be decontaminated at once with chloride of lime or other neutralizing agents. Notwithstanding all these precautions, casualties will occur owing to carelessness, and only the most rigid discipline can keep them within reasonable bounds.

While mustard gas is only slightly soluble in water, it is slowly decomposed thereby. When it is cold, the rate of decomposition is approximately 1 gram of mustard per liter of water in 30 minutes. When it is warm, the decomposition proceeds more rapidly with saponification and the formation of thiodiglycol and hydrochloric acid, according to the reaction:

$$S\begin{<}CH_2CH_2Cl\\CH_2CH_2Cl\end{>} + 2H_2O = S\begin{<}CH_2CH_2(OH)\\CH_2CH_2(OH)\end{>} + 2HCl$$

This hydrolysis takes place on contact with moisture in the air or with water on the ground and thus mustard gas is slowly destroyed wherever these conditions are encountered; the rate of destruction depends upon the amount of water and the temperature. The hydrolysis of mustard gas is also accelerated in the presence of alkalies, alkaline carbonates, and the solvents of mustard that are miscible with water, such as alcohol. It is rapidly dissolved by the organic solvents, such as ether, chloroform, and acetone, by the light paraffin hydrocarbons, and by all of the organic fats, both animal and vegetable. It is, however, soluble only with difficulty in the mineral oils and in vaseline and paraffin.

Mustard gas is also progressively soluble in gums, such as caoutchouc and rubber; it easily goes through leather and fabrics of cotton and linen. Hence mustard readily penetrates leather and rubber boots and gloves and all articles of clothing, especially if these are brought in direct contact with liquid mustard. It is because of these remarkable powers of solubility and penetration that mustard gas is so difficult to protect against. In fact, the only reliable protection is the destruction of the mustard-gas molecule by decomposing it into its relatively harmless constituents.

In striking contrast to its marked physical activity in solution and penetration, the chemical activity of mustard gas is rather limited, *e.g.*, its slow hydrolysis in contact with water. Its great chemical stability increases the difficulty of decontaminating infected materials with hypochlorites. However, mustard reacts violently with the evolution

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of great heat, the resulting products being mustard sulfoxide and calcium chloride, in accordance with the equation:

$$CaOCl_2 + S\begin{<}CH_2CH_2Cl\\CH_2CH_2Cl\end{>} = SO\begin{<}CH_2CH_2Cl\\CH_2CH_2Cl\end{>} + CaCl_2$$

As the sulfoxide is nontoxic, calcium chloride has been widely used to destroy mustard. On the other hand, when very strong oxidizing agents are used, two atoms of oxygen are fixed to the sulfur atom and the

resulting product, called *mustard sulfone*, is very toxic. This curious phenomenon adds further difficulties to the problem of decontaminating material infected with mustard.

Chlorine also attacks mustard vigorously and converts it into harmless higher chlorides, according to the equation:

$$Cl_2 + S\begin{matrix}\diagup CH_2CH_2Cl \\ \diagdown CH_2CH_2Cl\end{matrix} = S\begin{matrix}\diagup CH_2ClCHCl \\ \diagdown CH_2ClCHCl\end{matrix}$$

The danger of dissociating mustard into toxic products is, therefore, avoided by the use of chlorine or chlorinating agents, such as dichloramine T and sulfur dichloride.

Mustard gas is lethal in concentrations varying from 0.006 to 0.200 mg. per liter, depending upon the time of exposure. Generally speaking, when inhaled, 0.15 mg. per liter is fatal on 10 minutes' exposure and 0.07 mg. per liter on 30 minutes' exposure. Concentrations as low as 0.001 mg. per liter on 1 hour's exposure, will attack the eyes and render the victim a casualty from conjunctivitis. Mustard is thus five times more toxic than phosgene, which adds greatly to its effectiveness as a combat agent.

Concerning the complex physiological action of mustard gas, we cannot do better than to quote General Gilchrist as follows:

> Mustard is classified as a vesicant gas. . . . At first it acts as a cell irritant, and finally as a cell poison. The first symptoms of mustard-gas poisoning appear in from 4 to 6 hours, but a latent period up to 24 hours may occur. The length of this latent period depends upon the concentration of the gas. The higher the concentration the shorter the interval of time between the exposure to the gas and the first symptoms arising as a result of mustard-gas poisoning.
>
> The physiological action of mustard gas may be classified as local and general. The local action results in conjunctivitis or inflammation of the eyes; erythema of the skin, which may be followed by blistering or ulceration and inflammatory reaction of the nose, throat, trachea, and bronchi. . . .
>
> It is of interest that racial susceptibility to the toxic action of mustard gas exists; whites are more susceptible than negroes. There is also an individual susceptibility to the toxic action of mustard gas, particularly of the skin, and also of the respiratory tract.

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A great deal of time has been devoted to a study of the mechanism of action of vesicants in general and mustard gas in particular, and a number of theories have been propounded to explain the toxic action of mustard on the living organism. Space does not permit a detailed account of these theories here. Suffice it to say that the simplest and most generally accepted theory is that the toxic effects of mustard are caused by the protoplasmic hydrolysis of the dichlorethyl sulfide molecule and the liberation of free hydrochloric acid in the living cell. Concerning this theory Vedder says:

> Dichlorethyl sulphide is very slightly soluble in water and freely soluble in organic solvents, that is, has a high liquid solubility or partition coefficient. It would, therefore, be expected to penetrate cells very rapidly. Its rapid powers of penetration are practically proved by its effects upon the skin. Having penetrated within the living cell, hydrolysis might occur. The liberation of free hydrochloric acid within the cell would produce serious effects and might account for the actions of dichlorethyl sulphide. The mechanism of the action of dichlorethyl sulphide according to this theory appears to be as follows:
>
> *a*. Rapid penetration of the substance into the cell by virtue of its high lipoid solubility.
>
> *b*. Hydrolysis by the water within the cell, to form hydrochloric acid and dihydroxyethyl sulphide.
>
> *c*. The destructive effects of hydrochloric acid upon some part of the mechanism of the cell.
>
> This theory is very simple, and has been very generally accepted.
>
> Whatever the theory of action, mustard is a cell poison, exerting its necrotizing action on all cells with which it comes directly in contact, including the skin and mucous membranes, with all their structures. The capillaries and other organs that mustard reaches become paralyzed.
>
> It is well known that the injuries produced by mustard heal much more slowly than burns of similar intensity produced by physical or other chemical agencies. This characteristic is explained by this action of mustard on the blood vessels which are rendered incapable of carrying out their functions of repair; and by the fact that necrotic tissue acts as a good culture medium. Hence the great liability to infection of mustard burns.

One of the greatest dangers from mustard gas is the lack of any positive means of identifying it in low concentrations in the field. While it has a characteristic odor resembling mustard or horse-radish in strong concentrations, this odor is very faint in concentrations which are still dangerous on exposures of more than 1 hour. Thus, the odor is said to be detectable at 0.0013 mg. per liter, but a concentration of 0.0010 mg. per liter will cause casualties from conjunctivitis on 1 hour's exposure, and such a concentration cannot be detected even by the keenest perception. Moreover, the sense of smell for mustard gas is quickly dulled after initial exposure, so that much stronger concentrations go unnoticed.

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Also, many odors, such as those produced by the stronger lacrimators, mask the odor of mustard gas so that it became a common practice to use lacrimators with mustard for this purpose.

The impossibility of detecting mustard gas in the field and the insidious action of this gas, which causes no noticeable symptoms until several hours after exposure, resulted in thousands of casualties in the war which might have been prevented had there been any positive means of detecting mustard and warning troops of its presence. The great importance of this problem caused much effort to be expended in attempts to devise a reliable chemical detector which was practicable for use at the front, but these efforts proved fruitless and the problem still remains unsolved.

Since mustard freezes at 14°C. (57°F.), it is desirable to add to it a small percentage of solvent to keep it in a liquid state at all temperatures ordinarily encountered in the field. If a solvent is not used and the mustard-gas filling in artillery shell changes from a liquid to a solid, with change in temperature, the ballistic behavior of the shells is seriously affected. For this reason, both the Germans and French added from 10 to 25 per cent of some easily volatile solvent such as carbon tetrachloride, chlorbenzene, or nitrobenzene. The Americans found that chlorpicrin could also be used as a solvent with equally satisfactory results and with the additional advantage that the solvent was toxic.

Not only does the addition of a solvent facilitate the ballistic behavior of mustard-gas shells, but it also increases the volatility of the mustard charge in winter weather and renders it more effective on the terrain. Depending upon the solvent used and the force of explosion of the bursting charge in the shell, the mustard-gas solution is scattered in the form of gas clouds, or a finely divided spray composed of liquid particles varying in size from an atomized mist to droplets resembling fine rain. These liquid particles are very stable against humidity and cling firmly to the ground and vegetation. The clouds of mustard vapor formed by the explosion of shells are not at all visible in dry weather and only slightly visible in damp weather. They are effective for about 6 hours on open terrain and for 12 to 24 hours in places protected by vegetation from the wind and sun.

The mustard-gas drops penetrate with great speed and facility any objects with which they come in contact. They easily penetrate leather and rubber boots, uniforms, and other articles of equipment worn by soldiers. The mustard liquid is thus easily carried about by soldiers and spread and evaporated in other previously uninfected places. Frequently in the late war all the occupants of a dugout were contaminated and made ill by the mustard adhering to the clothing of a single soldier who was not even aware of its presence.

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Not only is mustard gas spread over the battlefield and surrounding areas by the transfer of droplets and the carrying of the liquid substance in clothing, etc., but also by the wind blowing across infected areas and saturating the air more or less with the evaporating mustard fumes. Practical field tests have shown that winds not exceeding 12 miles per hour, blowing over a normally saturated terrain, may transfer concentrations of mustard vapor sufficiently strong (0.070 mg. per liter) to cause death within 30 minutes, for from 500 to 1,000 yd. downwind. Consequently, every mustard-gas bombardment has a direct or immediate effect produced by the liquid spray and the resulting gaseous cloud, as well as an indirect or continued effect produced by the evaporation of the liquid substance from the infected area. The latter may be transferred by the wind in effective concentrations to a distance of from 500 to 1,000 yd. downwind or by men who come in contact with the liquid droplets scattered over the infected area and carry them to other places

on clothing and other material.

With its far-reaching diffusion over the battlefields, its insidious action, and its manifold physiological effects, it is no wonder that mustard gas became the "king of battle gases" and, pound for pound, produced nearly eight times the number of casualties produced by all the other battle gases combined.

Compared with the properties of the ideal battle gas, as set forth in pages 47 and 48 of Chap. II, mustard gas meets the following requirements:

1. Very high toxicity (0.15 mg. per liter is fatal in 10 minutes).
2. Extreme multiple effectiveness.
3. Very persistent, which greatly limits its use in the tactical offensive but increases its value on the defensive.
4. Effects of long duration, but not permanent.
5. Effect is delayed for from 6 to 24 hours, which reduces its offensive battle power.
6. Extremely insidious in action. No warning properties or symptoms.
7. Volatility is low. The maximum field concentration is 3.66 mg. per liter on a hot day. This is sufficient for from 10 to 50 times a fatal dose.
8. Extremely penetrative to all forms of organic matter.
9. Vapor is invisible in dry weather and only faintly visible in damp weather.
10. Practically odorless in ordinary field concentrations.
11. Ready availability of raw materials (alcohol, sulfur, and chlorine).
12. Difficult to manufacture, but process is now well worked out in all principal countries.
13. Chemical stability is very high.
14. Hydrolyzes only very slowly at ordinary temperatures.
15. Withstands explosion without decomposition.
16. Not a solid at temperatures above 57°F.
17. Melting point is not above maximum atmospheric temperatures. Hence, use of solvent is advisable.
18. Boiling point, 217°C. (422.6°F.) is very high.

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19. Vapor pressure is low but sufficient to establish lethal concentrations at ordinary temperatures.
20. Specific gravity (1.27) is below 1.50.
21. Vapor density is 5.5 times that of air.

From the foregoing summary, it may be seen how close mustard gas approaches the ideal battle gas in most of the important requirements. For this reason and the fact that it is extraordinarily difficult to protect against, mustard gas is assured of a secure position in the future, and it is safe to predict that mustard gas will play a dominant role in future chemical warfare until replaced by a more effective agent which has not as yet made its appearance.

Ethyldichlorarsine ($C_2H_5AsCl_2$)

German: "Dick"

Ethyldichlorarsine is a difficult gas to classify according to physiological action as its effects fall in three different classes. It acts as a lung-injurant agent with a toxicity about the same as that of phosgene; it is also a powerful sternutator with about one-fifth the irritant effect of diphenylchlorarsine; and, finally, it is a moderately powerful vesicant, with about two-thirds the skin-irritant power and one-sixth the vesicant power of mustard gas. However, since its casualty power is chiefly by reason of its lung-injurant effect, it is logical to regard this compound as primarily a lung-injurant agent with secondary sternutatory and vesicant effects, and it is accordingly grouped with the lung injurants in Chap. VII. Ethyldichlorarsine is again referred to here, not only because it is fairly vesicant, but also because its origin and early history are associated with the vesicant agents.

The experience of the Germans with the use of mustard gas during the latter half of 1917 showed that a vesicant type of gas was the most effective casualty producer yet devised but, on account of the great persistency of mustard gas, it could not be used on the tactical offensive, where the infected ground had to be immediately traversed or occupied by friendly troops, without prohibitive losses. Mustard also had the further disadvantage that its effects were delayed several hours and therefore it did not immediately incapacitate men so as to make it of any great assistance in local attacks. Having in mind the grand offensive planned for the spring of 1918, Germany called upon her chemists to produce a quick-acting nonpersistent vesicant agent that could be used to better advantage in offensive tactical operations. Ethyldichlorarsine was the answer to this demand and was introduced by the Germans in March, 1918, at the beginning of their great spring offensive on the Western Front.

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To distinguish it from mustard gas, ethyldichlorarsine was first called "Yellow Cross 1," and it was intended to be used as a typical offensive combat agent along with the "Green Cross" (phosgene type) shells. Somewhat later it was found that the effects of ethyldichlorarsine were not primarily vesicant, but rather lung-injurant, and the vast majority of the casualties produced were from the latter effect. Accordingly, the classification designation of this gas was changed from "Yellow Cross 1" to "Green Cross 3," and it was used as a lung-injurant type of gas during the remainder of the war.

For further information concerning ethyldichlorarsine, see pages 166 *et seq.*

Chlorvinyldichlorarsine ($CHClCHAsCl_2$)

American: "Lewisite"

Chlorvinyldichlorarsine is America's principal contribution to the *materia chemica* of the World War. It was first prepared in 1917 by Dr. W. Lee Lewis (from whom it takes its name), in an effort to create a compound that would combine the vesicant action of mustard gas with the systemic poisoning effect of arsenic. Lewisite is a typical example of the evolution of chemical agents. It will be recalled that in the summer of 1917 the Germans had introduced two radically different types of agents: (1) a vesicant gas (mustard), which penetrated the clothing and burned the body wherever it came in contact and thus produced casualties without having to penetrate the mask; (2) a sternutatory gas (diphenylchlorarsine), which contained arsenic and, when properly dispersed, easily penetrated all existing masks.

Mustard gas was tremendously effective as a casualty producer but had two serious defects from a tactical viewpoint. It was too persistent to be used on the offensive, and its physiological effects were not manifest for several hours after exposure, so that it could not be counted upon to produce casualties during the progress of the attack. On the other hand, diphenylchlorarsine was very disappointing. Owing chiefly to technical errors in the method of its dispersion, it was surprisingly ineffective on the battlefield, although it was highly toxic, was nonpersistent, and readily penetrated the mask.

The year 1917 then closed with the Germans in possession of the most effective defensive chemical agent yet devised (mustard gas), but with no satisfactory offensive agent, since the masks of 1917 afforded adequate protection against all the lung-injurant gases in use. During the winter of 1917–1918, the German High Command was planning the great spring offensive to commence in March, 1918, and must have been much impressed with the vast number of casualties produced by mustard gas during the stabilized warfare in 1917. It was therefore only natural

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for it to call upon the German chemists for a *nonpersistent* vesicant that would produce immediate casualties. Ethyldichlorarsine was the result of this demand.

This compound was nonpersistent, quick-acting, highly toxic, and contained arsenic. However, it was only about one-sixth as vesicant as mustard gas, did not penetrate clothing to anything like the same extent, and was completely stopped by the existing gas masks. Ethyldichlorarsine proved to be such a disappointment that, when the spring offensive of March 1918, was launched, the Germans resorted to the use of a combination of Yellow, Green, and Blue Cross shells as their principal offensive weapons. The Yellow Cross (mustard gas) were used on sectors not to be penetrated by the Germans during the attack, and the Green Cross (diphosgene) and Blue Cross (diphenylchlorarsine) were used as the main artillery preparation in sectors where the attacks were to be launched.

Closely watching these developments during the spring of 1918, the Americans became convinced that what was most needed was a more effective gas of the ethyldichlorarsine type, *i.e.*, a highly toxic, nonpersistent, quick-acting, vesicant compound containing arsenic. Lewisite was the result of an intensive effort to produce such a compound. How well they succeeded only time can show, as lewisite was produced too late

for use at the front. It was not until October, 1918, that the manifold technical difficulties of mass production were finally overcome and manufacture commenced. The first lot manufactured was ready for shipment in November when the Armistice intervened, and it was destroyed at sea.

Curiously enough, the Germans claim that they not only knew about lewisite before the American discovery, but had actually manufactured it during 1917 and 1918. Thus, Hanslian says:

> It is evident from the publications of the German chemist, H. Wieland, (H. Wieland and A. Bloemer: "Über die Synthese der organischen Arsenderivate" in "Liebigs Annalen der Chemie," vol. 451, page 30) that even before the American discovery chlorvinyldichlorarsine was manufactured during the war in 1917 and 1918 in Germany, according to the Germans' own special methods and independently of Lewis' synthesis.

If this is true, it would seem that Germany made a serious error in not employing lewisite in the offensives of 1918, as comparative tests have shown its superiority, in many respects, over the compounds used in 1918. That this opinion is shared by the French may be inferred from the following paragraph from Hederer and Istin.

> The true vesicant arsines have not yet submitted to the proof of battle. They, nevertheless, merit attention by reason of their strong activity and their multiple effects. One can already consider them as persistents of rapid aggressiveness, capable of playing eventually a military role of the first order.
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The method of making lewisite was suggested by the analogous method of mustard-gas manufacture used by the Allies. Thus, mustard is formed by the action of ethylene on sulfur monochloride, while lewisite is produced by action of acetylene on arsenic trichloride in the presence of aluminum trichloride acting as a catalyst. The dark brown viscid liquid which results from this latter reaction is decomposed by treatment with hydrochloric acid at 0°C. (32°F.), and an oil is obtained which can be fractionated by distillation in vacuo into three chlorvinyl derivatives of arsenic trichloride. These derivatives, which differ from each other only by the successive addition to the arsenic trichloride of one, two, or three molecules of acetylene, are as follows (see Chart XIII):

$$C_2H_2 + AsCl_3 = ClCH{:}CH.As\begin{matrix}Cl\\Cl\end{matrix}$$

(β-Chlorvinyldichlorarsine)
(Primary lewisite)

$$2(C_2H_2) + AsCl_3 = \begin{matrix}ClCH{:}CH\\ClCH{:}CH\end{matrix}\!\!>AsCl$$

(ββ′-Dichlorvinylchlorarsine)
(Secondary lewisite)

$$3(C_2H_2) + AsCl_3 = \begin{matrix}ClCH{:}CH\\ClCH{:}CH\\ClCH{:}CH\end{matrix}\!\!>As$$

(ββ′β″-Trichlorvinylarsine)
(Tertiary lewisite)

During the initial reaction considerable heat is liberated and great care must be taken to keep the temperature from rising by regulating the current of acetylene, as otherwise violent explosions may occur. The reaction products are also explosive, and for that reason it is impossible to separate them by direct distillation. Hence, they must be treated with hydrochloric acid until all the aluminum compounds are dissolved. During the distillation of the resulting oily liquid, the unconverted arsenic trichloride passes over first (up to 60°C.); next follows the primary lewisite (up to 100°C.); finally, the balance passes over above 100°C. as a mixture of secondary and tertiary lewisites. The initial distillation yields only about 18 per cent primary lewisite, which is the most active and the preferred product. However, the secondary and tertiary fractions are subsequently converted into the primary form by heating under pressure to 210°C. with an excess of arsenic trichloride, so that the ultimate loss is small.

All the lewisites are liquids at ordinary temperatures, having boiling points ranging between 190° and 260°C., and all are irritating and

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poisonous compounds but not to anything like the same extent. Thus, primary and secondary lewisites are both highly toxic vesicants, the primary form being more toxic and less vesicant than the secondary, while the tertiary form is very much less active and is practically of no value as a chemical agent. As the primary form is by far the most active, it is the form into which the mixture was practically all converted. Thus, wherever the term, "lewisite" is used without qualification, it will be understood to refer to primary lewisite (β-chlorvinyldichlorarsine).

Pure lewisite is an oily colorless to light amber liquid, of 1.88 specific gravity, which boils at 190°C. (374°F.), yielding a dense vapor 7.1 times

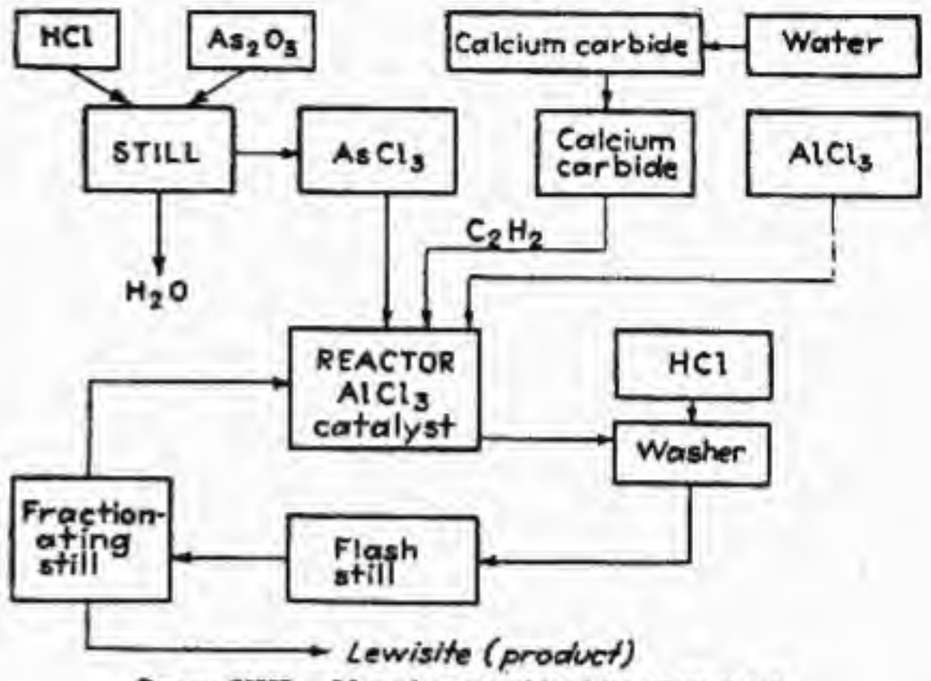

CHART XIII.—Manufacture of lewisite (flow sheet).

heavier than air with a faint odor resembling geraniums. It is readily soluble in the usual organic solvents and petroleum, but is not dissolved by water or weak acids. It is, however, rather easily and quickly decomposed by hydrolysis, yielding hydrochloric acid and an oxide of chlorvinylarsine, according to the equation:

$$ClCH{:}CH.As{:}Cl_2 + H_2O = 2HCl + ClCH{:}CH.As{:}O$$

However, unlike mustard gas, one of the hydrolysis products of lewisite (ClCH:CH.AsO) is a vesicant nonvolatile toxic which is not readily washed away by rains. Hence, while lewisite may be quickly destroyed by hydrolysis in moist air and on watery terrain, its combat value is not lost, since ground which has been contaminated with lewisite will remain dangerous from its oxides for long periods of time. In other words, one should not regard hydrolysis as immediately destructive of the toxic and vesicant powers of lewisite, but as a process in which the compound

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changes its state, while at the same time retaining its physiological powers in a new form. This view is important in arriving at the true combat value of lewisite, as far too much emphasis has been placed upon its suceptibility to hydrolysis, quite overlooking the fact that, in addition to the combat value of its hydrolysis products, the vast majority of situations in which lewisite would be used would not involve sufficient moisture to destroy it. Most terrains over which armies fight are moderately dry, and the great majority of the days in most parts of the north temperate zone are clear. Also, it must be remembered that in cold frozen countries and hot dry countries hydrolysis is of little importance.

Like mustard gas, lewisite is almost immediately decomposed in the presence of alkalies, such as caustic soda (5 per cent solution) or ammonia, and by active oxydants, such as chloride of lime and the hypochlorites, the reaction being greatly accelerated by heat. Hence terrain and material contaminated with lewisite are decontaminated with the same materials as mustard gas. Also, like mustard, lewisite readily penetrates clothing, leather, rubber, and the tissues of the body, and hence is just as difficult to protect against.

The vapor pressure of lewisite is very much higher than that of mustard. At 0°C. (32°F.) its vapor pressure is 0.087 mm. Hg, as compared to 0.026 mm. Hg for mustard; at 20°C. (68°F.), it is 0.395 mm. Hg, against 0.065 mm. Hg for mustard. The volatility of lewisite at 20°C. (68°F.) is 4.50 mg. per liter, as compared to 0.625 mg. per liter for mustard, and the persistency of lewisite is correspondingly much less than that of mustard. On the basis of Leitner's Formula (see page 21), the persistency of lewisite at 20°C. (68°F.) is 9.6 times that of water, while

the persistency of mustard is 67 times that of water.

The freezing point of lewisite is −18°C. (0°F.), which is well below ordinary atmospheric temperatures, so that it is a liquid at all times, except in very cold weather, and hence does not require a solvent as does mustard. Like mustard, lewisite is stable in storage and does not react with iron and steel.

Physiologically, lewisite acts similarly to mustard gas and in addition is a systemic poison when absorbed into the body through the skin or lungs. It may, therefore, be classed as primarily a vesicant, secondarily a toxic lung injurant, and tertiarily a systemic poison when absorbed in the tissues. The mechanism of the physiological action of lewisite is also like that of mustard; both are cell poisons and both undergo endoplasmic hydrolysis within the living cell and release hydrochloric acid in accordance with the following equation (lewisite):

$$ClCH{:}CH.As\begin{matrix}Cl\\Cl\end{matrix} + H_2O \rightarrow ClCH{:}CH.AsO + 2HCl$$

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In the case of lewisite, however, the other hydrolysis product—*β*-chlorvinylarsine oxide—is itself necrosant, and the arsenical residue of this oxide passes into the circulation, fixes itself in various organs, and sets up a general systemic poisoning, typical of arsenal compounds.

Lewisite is then both a local and general toxic of great deadly strength. Thus, a dose of 0.0173 gram per pound of body weight, externally applied, is fatal, so that an average man, weighing 150 lb., would be killed by 2.6 grams (30 drops) applied to his skin. The minimum irritating concentration of lewisite (0.0008 mg. per liter) is far below the minimum concentration at which it can be detected by its odor (0.014 mg. per liter), so that the warning effect of its odor has been greatly exaggerated by some authors. Its blistering (vesicant) concentration (0.334 mg. per liter) is less than 10 per cent of its saturation concentration in the air at 20°C. (68°F.), so that field concentrations ten times that required for vesication are possible. When inhaled, 0.120 mg. per liter is fatal in 10 minutes, and 0.048 mg. per liter is fatal in 30 minutes. Its toxicity thus slightly exceeds that of mustard gas.

Lewisite is quicker acting than mustard gas, as shown by the following comparison, based on experimental tests in which a drop of each agent was placed on the forearm of a man.

Lewisite was completely absorbed in five minutes with a slight burning sensation, while mustard required from twenty to thirty minutes for absorption and produced no noticeable sensation. With lewisite, the skin commences to redden at the end of thirty minutes; then the erythema increases and spreads rapidly and occupies a surface of 12 by 15 centimeters towards the end of the third hour. With mustard, the reaction (salmon colored) does not appear until two hours, and during the third hour covers a surface of only 3.5 by 4 centimeters. The vesiculation of lewisite appears at the end of about thirteen hours and consists of a large blister, the size of a cherry, which soon absorbs all the surrounding small blisters, forming about the twenty-fourth hour, a single, large, bulging, vesicle, surrounded by a reddened fringe which merges with the healthy skin at its outer edge. On the other hand, the first mustard blisters gradually appear in the form of a ring around the infected spot towards the end of the twenty-fourth hour. In the center the lesion is depressed and of a yellowish gray color.

In the absence of a secondary infection, the wounds from lewisite heal more rapidly than those of mustard, but whether these conditions would actually obtain on the field of battle is doubtful, and the probabilities are that in war the wounds of lewisite would be as serious and durable as those of mustard.

The future role of lewisite is uncertain. Under favorable conditions it is undoubtedly superior to any of the other World War gases. The question as to whether or not it would be used in a future war would seem, therefore, to depend primarily upon the meterological conditions to be encountered in the Theater of Operations. In cold countries and in hot

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dry countries it would be very effective, but in wet rainy countries much less effective.

Dr. Mueller thinks lewisite would have been a great disappointment to the Americans had it been actually used on the Western Front in the World War. While the climatic conditions in that Theater of Operations were, on the whole, rather unfavorable, it by no means follows that lewisite would have been ineffective if used intelligently, and this is particularly true in view of the highly toxic character of its hydrolysis products which infect contaminated ground for long periods. On the whole, we are inclined to believe that lewisite must be taken *into* serious consideration in any chemical warfare estimate of the future.

Methyldichlorarsine ($CH_3As.Cl_2$)

This compound is the methyl analogue of ethyldichlorarsine and the properties and characteristics of the two are very similar (see page 166). It was under intensive study by the Americans during the last months of the war, and Flury (28) includes it among the World War toxic gases, although, as a matter of fact, there is no record of its actual use by either side in the war. The preference of the Germans for ethyldichlorarsine, instead of the methyl compound, is difficult to understand in view of the superior properties of the latter, as shown by a comparison of their characteristics. Fries (9, page 181) attributes the German preference for ethyldichlorarsine to the difficulty of manufacturing the methyl compound, but the differences in difficulty of manufacture are so slight as to be no obstacle whatever to the genius of the German chemists who succeeded in solving many more formidable problems.

Like most of the chemical agents used in the war, methyldichlorarsine was not a new compound. It was discovered in 1858 by Baeyer who described its pronounced irritating effects.

The method of manufacture of methyldichlorarsine is complicated and comprises the following principal steps:

1. Sodium arsenite is prepared by dissolving arsenic trioxide in caustic-soda solution, as indicated in the following reaction:

$$6NaOH + As_2O_3 = 2Na_3AsO_3 + 3H_2O$$

The reaction proceeds readily evolving considerable heat.

2. The sodium arsenite solution is next methylated by adding dimethyl sulfate at 85°C

$$Na_3AsO_3 + (CH_3)_2SO_4 = Na_2CH_3AsO_3 + Na.CH_3SO_4$$

3. The disodium methyl arsenite is converted to methyl arsenic oxide by sulfur dioxide, as indicated

$$Na_2CH_3AsO_3 + SO_2 = CH_3AsO + Na_2SO_4$$

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4. Methyl arsine oxide is finally converted to methyldichlorarsine by passing hydrogen chloride gas through the mixture, when the following reaction takes place:

$$CH_3AsO + 2HCl = CH_3AsCl_2 + H_2O$$

Methyldichlorarsine is a colorless liquid, of 1.85 specific gravity, which boils at 132°C. (269.6°F.), yielding a vapor with a powerful burning odor. At 20°C., its vapor pressure is 8.50 mm. Hg and its volatility is 75.00 mg. per liter. This compound is chemically very stable, being only slightly soluble in water, though soluble in organic solvents. It does not corrode iron and steel.

Like the ethyl compound, the methyldichlorarsine is a vesicant, toxic lung injurant, and respiratory irritant. A concentration as low as 0.002 mg. per liter causes quite a severe irritation in the nose which produces sneezing and finally extends to the chest where it gives rise to pain. A concentration of 0.009 mg. per liter is distinctly sternutatory; 0.025 mg. per liter is unbearable when inhaled for more than 1 minute, and leads at once to painful attacks of asthma and marked dyspnea which often lasts for 24 hours. Still higher concentrations cause serious injuries to the lungs, 0.56 mg. per liter being fatal on 10 minutes' exposure and 0.12 mg. per liter fatal on 30 minutes' exposure.

Methyldichlorarsine is thus about half as toxic as the ethyl compound and when liquid is less irritant to the skin. On the other hand, its vapors are as irritating to the skin as the vapors of mustard gas and, when liquid it penetrates fabrics much faster than does liquid mustard gas.

The vesicant action of methyldichlorarsine is very similar to mustard, but its lesions are much less severe and heal more rapidly than mustard-gas lesions.

The vapor of methyldichlorarsine is hydrolyzed by moisture, but not rapidly enough to destroy the gas before it can exert its physiological action. Owing to its great volatility, methyldichlorarsine persists in the

open for only about 1 hour in warm weather and 2 to 3 hours in cold weather.

Although not proved on the field of battle in the late war, it is believed that, taking everything into consideration, methyldichlorarsine is probably superior to mustard gas and lewisite for producing *rapid* vapor burns of the skin. For this reason, together with its low persistency, it should have a high value for offensive military purposes.

Dibromethyl Sulfide ($S(CH_2CH_2)_2Br_2$)

German: "Bromlost"

The last of the vesicant agents usually identified with the World War, although, strictly speaking, belonging to the postwar period, is the bromine analogue of mustard gas, dibromethyl sulfide, called by the Germans "Bromlost."

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This compound was studied by the Germans during the closing days of the war in an effort to find a vesicant compound more persistent than mustard gas, for use on the tactical defensive where it was desired to contaminate ground yielded to the enemy for as long a period as possible.

The three elements which destroy mustard on the ground are humidity, temperature, and wind. A compound less susceptible to hydrolysis and of higher boiling point and lower vapor pressure would, it was thought, persist longer than mustard and be a more effective chemical agent on the tactical defensive. The substitution of bromine for the chlorine atoms in mustard gas was expected to produce such a compound, but dibromethyl sulfide did not measure up to expectations.

Dibromethyl sulfide is a solid at ordinary temperatures, which melts at 21°C. (70°F.) and boils (with decomposition) at 250°C. (464°F.). It has a specific gravity of 2.05 and a volatility of about 0.400 mg. per liter, as compared with 1.27 specific gravity and 0.600 mg. per liter volatility of mustard. It is also far more susceptible to hydrolysis than mustard.

The physiological action of dibromethyl sulfide is very similar to that of mustard gas, but to a far less degree. Its greater density permits about 50 per cent greater amounts to be loaded in the same shell, and this partially offsets its inferior physiological activity. But its sensitiveness to destruction by moisture is a net loss compared with mustard, so that, on the whole, dibromethyl sulfide was not a real advance over mustard gas and would in all probability never be used in war.

COMPARISON OF THE VESICANTS

Considering the factors: (1) rapidity of action; (2) extension of rubefaction, swelling, and edema; and (3) time of healing of lesions, the World War vesicants and those compounds having subsidiary vesicant action may be arranged in descending order of their skin-irritant efficiency as follows:

1. Mustard.
2. Lewisite.
3. Phenyldichlorarsine.
4. Methyldichlorarsine.
5. Ethyldichlorarsine.
6. Phenyldibromarsine.
7. Dibromethyl sulfide.

On the basis of relative toxicity, the above agents would rank as follows:

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Agent	Minimum Lethal Dose (10 Minutes' Exposure) Mg. per Liter
Lewisite	0.120
Mustard	0.150
Phenyldibromarsine	0.200
Phenyldichlorarsine	0.260
Ethyldichlorarsine	0.500
Methyldichlorarsine	0.560
Dibromethyl sulfide	1.000

USE OF VESICANTS IN THE WORLD WAR

The vesicants rank second in the extent of use in the war, being exceeded in tonnage by the lung injurants only. Altogether, about 12,000 tons of vesicants were used in battle, and of this quantity it is estimated that mustard was fully 95 per cent. No separate records are available as to the exact quantities of the minor vesicants that were used, or as to the casualties produced by them. Mustard gas so nearly completely dominated the vesicant field that all such casualties are generally credited to mustard. The vesicants produced 400,000 casualties, or nearly one-third of the total gas casualties, although the amount of vesicants used in battle was less than 10 per cent of the total gas used. The vesicants secured one casualty per 60 lb. of gas, which was nearly four times the ratio of casualties to gas for the lung injurants.

During the war, the vesicants were used only in artillery and trench-mortar shells, as they were unsuitable for cloud-gas projection, owing to low vapor pressures. By the same token, however, they are well adapted for dispersion by airplane sprays and bombs, and it is accordingly probable that in the future they will be largely employed by the air force, as well as by the artillery.

FUTURE OF THE VESICANTS

The vesicants introduced a new principle in chemical-warfare offense in that they readily penetrated clothing and produced casualties by body burns. Masks, therefore, were wholly inadequate for protection against these agents, and special protective clothing was resorted to. Such clothing is very uncomfortable, especially in hot weather, and greatly lowers the combat ability of troops. It also enormously increases the problem of protection from contamination, not only for men and animals but also for material. Food and water supplies in particular must be specially protected and ready means must be devised to decontaminate enormous quantities of material and large areas of ground.

The introduction of vesicants in the war tilted the scales heavily in favor of the chemical offense, and the war closed leaving the problem

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of adequate defense against the vesicants largely unsolved. Since the war all nations have expended much time and effort in trying to solve this complex problem. How well they have succeeded only the future can show.

In the meantime, vesicants occupy the center of the stage of chemical armaments and it is a foregone conclusion that they will figure largely in wars of the future. Fortunately for the nations of the world, they exemplify the most humane method of waging war yet devised.

For a summary of the principal properties of the vesicant agents, see Table IV.

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CHAPTER X

RESPIRATORY IRRITANT AGENTS (Sternutators)

The fifth and last class of toxic agents used in the World War was the respiratory irritants, often called *sternutators* (sneeze producers). They form a small well-defined group having many properties in common and were generally designated by the Germans as "Blue Cross" substances.

By the summer of 1917, the gas masks of all of the belligerents had been developed to a stage where they furnished adequate protection against the lung-injurant gases. Also, the lung-injurant gases theretofore employed were slow acting and did not incapacitate until several hours after exposure. The problem was, therefore, to find a quick-acting nonpersistent gas that would penetrate the mask, and the respiratory irritants were the solution of the German chemists to this problem. While the respiratory irritants produced few serious casualties, by quickly penetrating the mask, nauseating the soldier, and causing frequent vomiting, they usually made it impossible to wear the mask, and upon its removal the soldier soon fell a victim to the lung-injurant agents (Green Cross substances) which were fired simultaneously with the respiratory-irritant agents (Blue Cross substances).

The first large-scale gas attack featuring respiratory-irritant compounds was directed by the Germans against the Russians while crossing the Dvina River at Uexhuell in September, 1917. The Germans employed a combined Green Cross and Blue Cross bombardment against

the Russian batteries which commanded the place of crossing. The bombardment lasted for 2 hours and the Russian batteries were silenced with the exception of a few guns which had not been recognized and therefore were not included in the areas shelled.

The great German offensive of Mar. 21, 1918, was based chiefly on the effect of gas. The Allied flanks on the attacking salients were cut off by mustard gas, while the main force was shelled by a mixture of Blue Cross and Green Cross shells. The Allies were at first absolutely defenseless against the respiratory-irritant substances and, had the Germans been able to atomize and disperse their toxic smokes into minute particles, the result would have been disastrous. Toward the end of the war, the Allies incorporated in their gas-mask canisters a mechanical filter, consisting of wadding and layers of felt, and in this way provided adequate protection against these toxic dusts.

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The Allies claimed that the German Blue Cross shells were not effective, and based their opinion upon the fact that the high explosive in the shell did not sufficiently atomize the toxic chemical to create a dust fine enough to penetrate the mask. There were but 577 casualties and 3 deaths in the American Expeditionary Forces owing to gassing with respiratory-irritant compounds. Deaths from these compounds were very rare.

GROUP CHARACTERISTICS

In general, the respiratory irritants were all solids with high melting points and negligible vapor pressures. They were, therefore, dispersed by heavy explosive charges, in the form of a finely pulverized dust. The particulate clouds thus created lasted only a few minutes in the open, and they were accordingly classed as nonpersistent agents. They were, however, immediately effective and readily penetrated the existing gas masks of the Allies. It was due chiefly to these properties that they were introduced by the Germans on the night of July 11, 1917.

Chemically, all the respiratory irritants belong to the family of arsines (AsH_3) and are compounds consisting of trivalent arsenic in which the arsenic atom is linked by one valence to a halogen atom, or to a monovalent active group, and by two other valences to two atoms of carbon of two carbonyl radicals, thus:

$(C_6H_5)_2$>As—Cl (Diphenylchlorarsine)

$(C_6H_5)_2$>As—CN (Diphenylcyanarsine)

The respiratory irritants have the power to irritate certain tissues of the body without producing notable lesions, *i.e.*, without injury, at the point of contact when employed in concentrations above their thresholds of action, which are extremely low. They act only on the ends of the sensory nerves, which are anatomically poorly protected against chemical attack, and give rise to more or less acute pains accompanied by muscular reflexes and various secretions, depending upon the nature of the compound and the region infected. The mucous membranes of the respiratory system (nose, larynx, trachea, bronchial tubes, and lungs) are thin and sensitive, and their moist surfaces facilitate the fixation and dissolution of these gases. They, therefore, furnish an excellent field for the action of the respiratory-irritant compounds and are, accordingly, the members chiefly affected by these compounds. Based upon extensive experiments, Flury sums up the physiological action of these compounds, as follows:

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The intensive cell toxic effect is seen everywhere where the substances come in contact with the living cells in the solid, liquid or gaseous state. They are distinguished from the strong corrosive substances by the fact that even when used in the very lowest concentrations they cause inflammatory phenomena and necrosis in the affected tissues. From the qualitative standpoint, there are no great differences from the effects of the other irritants. The arsenic compounds also act on the respiratory passages and the lungs, the organs of sight and the outer skin, thus causing an acute toxic lung edema, serious injuries to the capillaries, the formation of false membranes in the air passages, inflammation of the conjunctiva and necrosis of the corneal epithelium in the eye, and sometimes also inflammation of the outer skin with the formation of blisters and the deeper destruction of the tissues. The general character of the effect now is more like that of phosgene, again more like that caused by the sulfur-containing irritants such as dichlorethylsulfide. Despite that, there are certain peculiarities to the poisoning caused by the arsenic compounds. The irritation to the sensitive nerves far surpasses in intensity the effect of any chemically accurately defined compounds heretofore known. The irritant action, however, extends not only to the portions of the mucous membranes affected directly by the poison but in a characteristic way also attacks the so-called accessory cavities.

As a rule, the respiratory irritants are nonlethal in concentrations ordinarily employed in battle and have the following properties in common:

1. Their thresholds of action are extremely low; a few thousandths of a milligram per liter produce certain and useful results.
2. They are immediately effective; an exposure of 1 to 2 minutes being sufficient to produce positive effects.
3. Their action is reversible, since the irritation produced disappears rapidly after termination of exposure. They do not destroy the nerve ends and, after the reflexes caused by the irritation, the nerves recuperate their normal functions.
4. Their action is elective, for they affect only the nerve tissues and especially those controlling the respiratory system.

From a physiological viewpoint, the respiratory-irritant agents may be divided into two groups: (1) the simple respiratory irritants, and (2) the toxic respiratory irritants. The first cause only a local irritation of the respiratory system, while the second go further and set up a systemic arsenical poisoning. Only the first group (1) are primarily respiratory irritants, as the compounds in the second group (2) primarily exert other effects and their respiratory-irritant action is only subsidiary. Compounds in the second group, therefore, belong primarily to other groups of agents and are only secondarily regarded as respiratory irritants.

WORLD WAR RESPIRATORY IRRITANTS

The principal respiratory-irritant agents, in order of their chronological appearance in the World War, were:

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Agent	Introduced by	Date
Simple respiratory irritants		
Diphenylchlorarsine	Germans	July, 1917
Diphenylcyanarsine	Germans	May, 1918
Ethylcarbazol	Germans	July, 1918
Diphenylaminechlorarsine	Americans	Postwar
Toxic respiratory irritants		
Phenyldichlorarsine*	Germans	September, 1917
Ethyldichlorarsine*	Germans	March, 1918
Ethyldibromarsine*	Germans	September, 1918

* Primarily toxic lung injurants.

Diphenylchlorarsine ($(C_6H_5)_2AsCl$)

German: "Clark I"

Diphenylchlorarsine was introduced simultaneously with mustard gas as an offensive companion thereto, since mustard gas was too persistent to be used on the tactical offensive. The purpose of diphenylchlorarsine was to penetrate the Allies' masks, which successfully protected against all the lung-injurant agents. This was accomplished by dispersing the chemical substance in the form of a *dust* which, not being a vapor or gas, was not absorbed by the charcoal and soda lime in the gas-mask canister.

Diphenylchlorarsine was discovered in 1881 by Michaelis and LaCoste. During the war it was manufactured by the Germans in accordance with a complicated process, of which the following were the principal steps:

1. Benzene diazonium chloride was treated with sodium arsenite to form sodium phenylarsenate

$$C_6H_5—N_2Cl + Na_3AsO_3 = C_6H_5AsO_3Na_2 + NaCl + N_2$$

2. Sodium phenylarsenate was converted to phenylarsenic acid by treatment with hydrochloric acid

$$C_6H_5AsO_3Na_2 + 2HCl = C_6H_5AsO_3H_2 + 2NaCl$$

3. Phenylarsenic acid was reduced to phenylarsenious acid by treatment with sulfur dioxide and water

$$C_6H_5AsO_3H_2 + SO_2 + H_2O = C_6H_5AsO_2H_2 + H_2SO_4$$

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4. Phenylarsenious acid was treated with sodium hydroxide to form sodium phenylarsenite

$$C_6H_5AsO_2H_2 + 2HaOH = C_6H_5AsO_2Na_2 + 2H_2O$$

5. Sodium phenylarsenite was converted to sodium diphenylarsenite by treatment with benzene diazonium chloride

$$C_6H_5AsO_2Na_2 + C_6H_5N_2Cl = (C_6H_5)_2AsO_2Na + NaCl + N_2$$

6. Sodium diphenylarsenite was treated with hydrochloric acid to form diphenylarsenic acid

$$(C_6H_5)_2AsO_2Na + HCl = (C_6H_5)_2AsO_2H + NaCl$$

7. This acid was reduced to diphenylarsenious oxide by treatment with sulfur dioxide and water

$$2(C_6H_5)_2AsO_2H + 2SO_2 + H_2O = [(C_6H_5)_2As]_2O + 2H_2SO_4$$

8. Diphenylarsenious oxide was converted to diphenylchlorarsine by chlorination with hydrochloric acid

$$[(C_6H_5)_2As]_2O + 2HCl = 2(C_6H_5)_2AsCl + H_2O$$

Diphenylchlorarsine may also be prepared by a much simpler process, as follows:

1. Triphenylarsine is formed by acting on chlorbenzene and arsenic trichloride with sodium.

2. The triphenylarsine is then heated under pressure with more arsenic trichloride and diphenylchlorarsine is thus obtained.

While the latter was the laboratory method of making diphenylchlorarsine, there appears to be no inherent reason why it could not be used as a basis for a successful commercial method of manufacture and thus greatly simplify the production problem. It was stated that the Germans adopted the more complicated method outlined above because they had previously manufactured several of the intermediates in this process and that the equipment of their chemical plants was peculiarly adapted to this process. Undoubtedly, if diphenylchlorarsine were manufactured in quantity in the future, especially outside of Germany, a simpler and more direct process would be employed.

In the pure state, diphenylchlorarsine is a white crystalline solid, of 1.4 specific gravity, which melts at 45°C. (113°F.), although the somewhat impure commercial substance used during the war melted at 38°C. (100°F.). It boils with decomposition at 383°C. (720°F.). It is insoluble in water, but is readily soluble in organic solvents, including phosgene and chlorpicrin. It decomposes rapidly in contact with water, yielding hydrochloric acid and phenylarsenic oxide which is toxic, but this action is very slow in a merely humid atmosphere. As it is a solid,

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its vapor pressure (0.0005 mm. Hg at 20°C.) is negligible and its volatility at 20°C. is only 0.00068 mg. per liter.

When diphenylchlorarsine is volatilized by heating, its vapors condense in the air to form very fine liquid droplets or solid particles (depending upon their temperature) which float like particles of smoke or dust in the air; but in order to volatilize and convert this compound into the form of smoke (particulate clouds of solid particles), it is essential that the substance pass through the actual gas or vapor stage. That is to say, a preliminary heating process is necessary. It is impossible to convert this compound by atomization at a low temperature into real smoke, even if it is dissolved in a volatile solvent.

The reason for these peculiarities undoubtedly lies in the size of the particles given off when this substance is distilled by heating, as compared to the smallest sized particle that can be produced by atomization. When volatilized by heat, the particles formed are extremely small, having a diameter of only 10^{-4} to 10^{-5} cm. On the other hand, when dispersed by explosion, the time of detonation is too brief for an appreciable amount of heat to be transmitted to the chemical substance, and the dispersion of the chemical is thus almost entirely due to the physical force of the explosion. The result is that the particles of diphenylchlorarsine dispersed by explosion were many times larger than those resulting from heat distillation. Similarly, when diphenylchlorarsine is dissolved in a liquid solvent and sprayed by a mechanical sprayer, even the best sprayers send out droplets many times larger than the true smoke particles.

These facts were apparently not appreciated by the Germans at the time they adopted diphenylchlorarsine as a filler for their Blue Cross shell, for they first attempted to dissolve this compound in some easily volatilized solvent, such as diphosgene, and disperse it as a liquid spray. When this proved unsatisfactory, they then attempted to disperse it by the use of heavy charges of high explosive which also subsequently proved ineffective on the field of battle. In loading diphenylchlorarsine into the shell, another error was made in placing the explosive charge around, instead of within, the chemical charge. With the explosive surrounding the chemical charge, the force of explosion tended to compress the chemical particles, instead of blowing them apart.

Subsequent experiments by the Allies proved that diphenylchlorarsine was extremely effective in the field when dispersed (by heat distillation) as a true toxic smoke, and they were preparing toxic smoke candles, embodying this principle of dispersion, when the Armistice intervened and prevented their use at the front. The failure to adopt a proper means of dispersing diphenylchlorarsine stands out as one of the few technical mistakes in chemical warfare that the Germans made dur-

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ing the World War. But it was a costly mistake, as no less than 14,000,000 artillery shells were loaded with this substance (and its analogue, diphenylcyanarsine) and great reliance was placed upon its supposed offensive-combat power in the German drives in the spring of 1918. The evidence of the Allies' casualties from German Blue Cross shell, however, is conclusive that these shell were largely ineffective, notwithstanding the known very powerful physiological properties of these compounds.

When diphenylchlorarsine is pulverized and dispersed by the explosion of a high-explosive charge, and, to a far greater extent, when thermally distilled as a toxic smoke, it is broken up into microscopic particles that float in the air, easily penetrate the ordinary gas-mask canister, and exert their effects directly on the respiratory tract. When used in minimum concentrations, this compound causes great irritation to the upper respiratory tract, the sensitive peripheral nerves, and the eyes; it also irritates the outer skin, but not to so great an extent; when present in stronger concentrations or when inhaled in weaker concentrations for a long time, it attacks the deeper respiratory passages. The irritation begins in the nose, as a tickling sensation, followed by sneezing, with a flow of viscous mucous, similar to that which accompanies a bad cold. The irritation then spreads down into the throat and coughing and choking set in until finally the air passages and the lungs are also affected. Headache, especially in the forehead, increases in intensity until it becomes almost unbearable, and there is a feeling of pressure in the ears and pains in the jaws and teeth. These symptoms are accompanied by an oppressive pain in the chest, shortness of breath, and nausea which soon causes retching and vomiting. The victim has unsteady gait, a feeling of vertigo, weakness in the legs, and a trembling all over the body.

Flury gives the German experience with diphenylchlorarsine:

> In addition to the phenomena of sensory irritation, inhalation of diphenylchlorarsine may lead to serious disturbances of the nervous system from absorption of the poison. These show themselves as motor disturbances, uncertain gait, swaying when standing, and sometimes complete inability to walk. As a rule they are accompanied by severe pain in the joints and limbs. Inhalation of very high concentrations is also often followed by giddiness, attacks of faintness, and loss of consciousness, which may last for many hours. When considerable quantities of diphenylchlorarsine or related organic arsenical compounds are taken through the skin nervous disturbances of various types may arise, and these are to be ascribed not to a local action of the poison but to its general absorption. Hyperesthesia, anesthesia and paresthesia of definite areas of the skin, especially of the lower extremities, could frequently be observed. Twitching of the muscles and convulsions may occur in very severe cases of poisoning by similar substances.

The remarkable part of the effects above described is that they usually set in about 2 or 3 minutes after 1 minute of exposure to the gas

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and usually reach their culmination in about 15 minutes after exposure ceases. After 15 minutes in uncontaminated air, the symptoms gradually disappear and in from 1 to 2 hours recovery is complete in the average case. In extreme cases, in enormously high concentrations, sufficient arsenic may be absorbed to produce systemic arsenical poisoning, which then produces the typical aftereffects of such poisoning.

Diphenylchlorarsine is effective in extremely low concentrations. Thus, a concentration as low as 1:25,000,000 (0.0005 mg. per liter) is sufficient to produce marked irritation of the nose and throat, while 0.0012 mg. per liter becomes unbearable after 1 minute. A concentration of 1.50 mg. per liter is lethal after 10 minutes, and 0.60 mg. per liter after 30 minutes' exposure. Since the volatility of diphenylchlorarsine is only 0.00068 mg. per liter, it is impossible to attain even an intolerable concentration in the air in *vapor* form. However, there is theoretically no limit to the concentration which may be built up in the form of *solid* particles suspended in the air, as this is merely a function of the amount of the substance distilled into a given volume of air. Nevertheless, under the actual conditions obtaining on the battlefield, it is very difficult to set up a lethal concentration, and there were few deaths from this gas in the World War.

Diphenylcyanarsine [$(C_6H_5)_2AsCN$]

German: "Clark II"

Diphenylcyanarsine was developed and adopted by the Germans in May, 1918, as an improvement over diphenylchlorarsine to which it is closely related. The main purpose for this development was to correct one of the serious weaknesses of diphenylchlorarsine, *viz.*, its ready decomposition by water. The new compound not only overcame this defect, but also proved to be physiologically more active than its chlorine analogue and was, in fact, the strongest of all the irritant compounds used in the war.

Diphenylcyanarsine was prepared by acting on diphenylchlorarsine with a saturated aqueous solution of sodium or potassium cyanide, during which reaction, the chlorine atom in the latter is replaced by the cyanogen group, thus

$$(C_6H_5)_2AsCl + NaCN = (C_6H_5)_2AsCN + NaCl$$

In a pure state, it is a colorless crystalline solid, of 1.45 specific gravity, which melts at 31.5°C. (91°F.) and boils with decomposition at 350°C. (662°F.), yielding a vapor 8.8 times heavier than air with a characteristic odor of garlic and bitter almonds.

It is not dissolved by water and is hydrolyzed so slowly as to be negligible. Chemically very stable, it is readily soluble in the organic

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fats and solvents, especially chloroform. Its vapor pressure is negligible and its volatility is even lower than its chlorine analogue, being only 0.0015 mg. per liter at 20°C. (68°F.).

The physical and chemical behavior and the physiological effect of diphenylcyanarsine are exactly like those of the chloro-compound except that the last is more intense and somewhat more enduring. The lowest irritant concentration of diphenylcyanarsine is 0.0001 mg. per liter, and its intolerable concentration (0.00025 mg. per liter) which is one-fourth that of diphenylchlorarsine. The toxicity of diphenylcyanarsine for 10 minutes' exposure is 1.00 mg. per liter as compared to 1.50 mg. per liter for the chlorine analogue. The former is, therefore, about 50 per cent more toxic than the latter, but this is not of great practical importance since these lethal concentrations are far above the limit of actual attainment in the field, except in very unusual circumstances, such as where a shell bursts in an inclosed space so that a supersaturated concentration is obtained. Such concentrations may also exist for a few seconds immediately adjacent to the point of burst of the shell, but on the whole are extremely rare, as is shown by the Allies' casualties from Blue Cross shell, which were surprisingly small in comparison with the vast quantities of these shell used, and the percentage of deaths was almost negligible.

On the other hand, owing to the ease with which diphenylcyanarsine penetrated gas-mask canisters in use in 1917 and the early part of 1918, it temporarily put out of action large numbers of troops during the initial period of a bombardment; where such bombardments were immediately followed by infantry assaults, considerable tactical advantage was thus derived. Also, the difficulty of retaining the mask after penetration by this agent undoubtedly increased the number of casualties from lung-injurant (Green Cross) agents which were simultaneously employed.

Owing to the fact that diphenylcyanarsine was effective in extremely small concentrations (1:10,000,000), it was the agent per excellence for general harassment of troops. Even a few shell, scattered over a wide area compelled all troops therein to mask and thus greatly hampered their combat efficiency and effectiveness. It was thus particularly effective against artillery and Blue Cross shell were largely employed in counterbattery fire.

Notwithstanding that the German Blue Cross shell did not disperse its chemical contents in a very efficient form, the Allies were so impressed with the possibilities of DA and CDA that they immediately started to work to devise the most effective means for their employment against the Germans.

The British were particularly active in pushing the development of a toxic candle which would by progressive burning distill off the chemical

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as a true smoke, in which form it was found to be far more effective than when dispersed by explosion from artillery shells. Speaking of this development, General Foulkes says:

> When the DA was scattered by the high explosive it was liberated not in the form of a gas, but in fine particles; these were not sufficiently minute to penetrate the box respirator completely, and absolute protection was very soon obtained by adding an extension to the box which contained a cheesecloth filter.
>
> Colonel Watson, who was the head of the Central Laboratory at Hesdin, had suggested in September 1917 the study of particulate clouds; and one of my officers, Sisson, in a sp rit of investigation, put a pinch of DA which had been extracted from a German shell on the hot plate of a stove in his room at my headquarters. The result was so remarkable that everyone was driven out of the house immediately, and it was found that the latest pattern of German mask, even when fitted with the extension that had been supplied to give protection against Blue Cross shells, gave no protection whatever against the DA cloud produced in this way.
>
> This was the germ of a new and very valuable idea, and steps were taken immediately to investigate how DA could be best volatilized in the most highly effective and penetrant form by bringing it in contact with the heat evolved from the combination of a suitable mixture of chemicals; and a "thermo-generator" was soon designed, which consisted of a tin containing the DA and the heating mixture in separate compartments and which weighed two or three pounds.
>
> The plan of attack was similar to the one previously put forward for gas; but as the particulate cloud was effective in one-hundredth the concentration of the gas cloud, and the German protection against it was nonexistent, complete success was absolutely certain if only the secret could be kept.
>
> The proposed assembly of the infantry assaulting columns would be simpler than in the former proposal, because there was no longer any need to use a retired line for the discharge. In fact, it was not even desirable, because the discharge would now be a much shorter one, and the "M" device (as the thermo-generators came to be called) would have to be used on a grand scale—hundreds of thousands being set alight with a simple friction lighter, as in the case of the familiar smoke candles—so that the infantry themselves would be called upon to assist the Special Brigade in handling the tins. The latter were not dangerous under artillery bombardment, like gas cylinders, and in any case the hostile fire would be silenced in the course of a few minutes by the cloud and by our own intensive gas bombardment.
>
> The "M" device was never used in France; but if its secret had been kept there is not the slightest doubt that its effect on the enemy, both moral and physical, would have been overwhelming; and if it had been properly and fully exploited it would have had a more important bearing on the course of the war than any other measure that was put to a practical trial on the battlefield or that was even considered.

In diphenylcyanarsine, we have the extreme limit of effectiveness in low concentrations of all chemical agents used in the war. Thus, a concentration of 0.00025 mg. per liter is intolerable if inhaled for 1 minute. As a man at rest normally inhales 8 liters of air per minute, he would absorb only 0.0002 mg. of the substance in that time. This is, however, sufficient to incapacitate him for an hour. For an average man, weighing

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154 lb. (70,000,000 mg.), this means that diphenylcyanarsine is effective in the ratio of 1:35,000,000 of body weight, which makes it the strongest

of all the known irritants.

Ethylcarbazol ($(C_6H_4)_2NC_2H_5$)

The last of the simple respiratory irritants used in the World War was ethylcarbazol, introduced by the Germans at the battle of the Marne in July, 1918. This compound is a white flaky solid which melts at 68°C. (149°F.) and boils at 190°C. (374°F.), yielding a vapor seven times heavier than air. It is soluble in alcohol and ether, but is insoluble in water and is practically unaffected thereby.

Very little information is available concerning the use of this substance or the reason for its introduction since it was by no means as irritant as either diphenylchlorarsine or diphenylcyanarsine with which it was mixed in the Blue Cross shell. Hanslian says, "As a matter of fact, it was not irritant at all, but merely served as a solvent for the arsine." This explanation, however, throws little light upon the subject since ethylcarbazol was itself a solid and was loaded in mixture with solid diphenylchlorarsine as a solid charge in the Blue Cross shell. It is, therefore, not clear as to how it could be used as a solvent. Moreover, it did have a decided irritant effect alone, although much less than any of the other respiratory-irritant substances.

The appearance of ethylcarbazol on the scene in the World War remains as one of those peculiar phenomena which seem altogether lacking in justification. It was used only to a limited extent and did not achieve any notable results. It is mentioned here only to complete the record.

Diphenylaminechlorarsine ($(C_6H_4)_2NHAsCl$)

American: "Adamsite"

When the Allies found that diphenylchlorarsine could be made very effective by distilling it into the air and projecting it as a particulate cloud, they decided to use it against the Germans in this manner, but they had had no previous experience in the mass production of this compound, or even of its principal intermediates. The German process was so complicated that it was soon realized that a simpler method of making it must be developed. In seeking to find such a method, the British and American chemists simultaneously discovered that a slightly different, though closely related, compound could be easily manufactured in large quantities, and that this substitute compound had very similar properties and seemed to be equally effective as a respiratory-irritant chemical agent. This new compound was diphenylaminechlorarsine which

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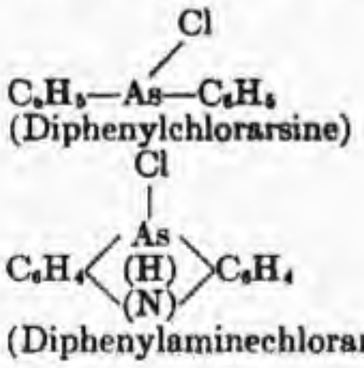
differs from the German substance, diphenylchlorarsine, only by the addition of an amino (NH) group to the latter compound, thus



While this chemical difference is very slight, it immensely simplified the problem of manufacture, since all that is required is to mix together and heat diphenylamine and arsenic trichloride and a smooth reaction proceeds in accordance with the following equation (see Chart XIV):

$$(C_6H_5)_2NH + AsCl_3 = (C_6H_4)_2NHAsCl + 2HCl$$

The resulting product is a dark green molten mass which can be purified by recrystallization from benzene and glacial acetic acid. The Americans named this compound "Adamsite," after its American discoverer, Major Roger Adams.

Not only is the process of manufacture simple but the two ingredients are readily obtainable in large quantities. Diphenylamine is a common intermediate widely used in the dye industry and is also required in large quantities in time of war as a stabilizer in the manufacture of smokeless powder, while arsenic trichloride is obtained by chlorinating white

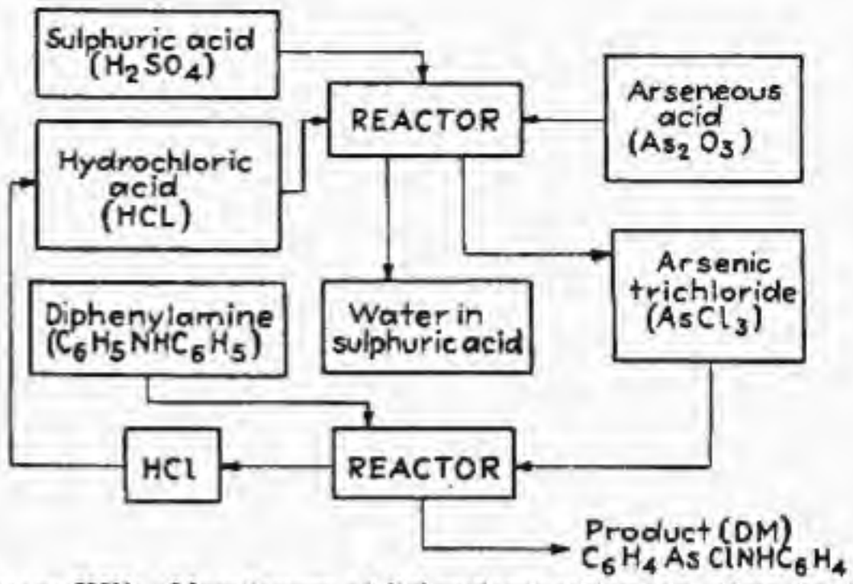


CHART XIV.—Manufacture of diphenylaminechlorarsine (flow sheet).

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arsenic (AS_2O_3). Of all the arsenical chemical agents, diphenylaminechlorarsine is the most easily manufactured.

In addition to the research and development work of the British and Americans on diphenylaminechlorarsine during 1918, the Germans claim to have previously discovered, manufactured, and tested this compound. Thus, Dr. Mueller (21, page 108) says: "A method for its manufacture was patented by the Leverkusen Farbwerk as early as 1915 (German Patent 281,049)" and Dr. Hanslian says: "In Germany it was manufactured and tested even during the war by Wieland; however, it was not used in the field." Dr. Mueller says it was not used in the field because of the readiness with which it is decomposed when heated. In view, however, of the small difference in this regard between diphenylchlorarsine and diphenylaminechlorarsine, the substantially equal capability of the latter as a chemical agent, and its far greater ease of manufacture, it would seem that there was little justification for the German use of diphenylchlorarsine, which was so much more difficult to produce. Dr. Hanslian also says that the commercial method of manufacture of diphenylaminechlorarsine was greatly simplified and perfected by the Italian chemists Contardi and Fenaroli, and that certain Russian publications state that this compound was actually used by the Italians during the latter part of the war. This latter statement is, however, improbable as no Italian authorities make such a claim, nor is there any record of the tactical use of this compound by the Italians in the war.

When pure, diphenylaminechlorarsine is a yellow crystalline solid, of 1.65 specific gravity, which melts at 195°C. (387°F.) and boils (with decomposition) at 410°C. (770°F.) under normal pressure. It has practically no vapor pressure or vapor density, as it distills into the air in the form of minute solid particles. The impure commercial product used in chemical warfare is a dark brownish green crystalline mass which partially liquefies at 160°C. (320°F.), but the major portion does not melt until a temperature of 190°C. (374°F.) is reached. It is chemically a very stable compound, being unaffected by the humidity of the air or precipitation. It is insoluble in water and hydrolyzes very slowly and with great difficulty, yielding hydrochloric acid and a toxic oxide $[(C_6H_4)_2NHAs]_2O$. It is also very slightly soluble in the ordinary organic solvents and is not readily dissolved in any of the liquid chemical agents. The fumes of diphenylaminechlorarsine are much less inflammable than those from diphenylchlorarsine, so that there is much less risk of its inflaming when dispersed by heat. It acts on metals, corroding iron, steel, bronze, and brass. Upon dissemination in the air, it persists for about 10 minutes in both hot and cold weather, so that it is classed as a nonpersistent agent.

The physiological effects of diphenylaminechlorarsine are in general very similar to those of diphenylchlorarsine. Like the latter it strongly

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irritates the eyes and mucous membranes of the nose and throat and causes violent sneezing and coughing. It then produces severe headaches, acute pains and tightness in the chest, and finally nausea and vomiting. The irritation of the eyes and the respiratory tract is at first weak, but within a minute or so it increases in severity so that it becomes unbearable. The acute effects usually last about 30 minutes after the victim has left the contaminated atmosphere. Qualitatively, the physiological effects of diphenylaminechlorarsine differ somewhat from those

of diphenylchlorarsine, in that they appear more slowly and last longer; also coughing and a burning pain in the nose and throat are less intense. During the time of exposure, the effects of the latter are more apparent, but in higher concentrations the effects of the latter were more immediate and just as severe, but not as persistent as the former. The longest period of incapacitation from diphenylchlorarsine was about 1 hour, while that from diphenylaminechlorarsine was about 3 hours. The latter is then more efficient as a casualty producer since men gassed therewith are put out of action for three times as long a period.

To the average person, diphenylaminechlorarsine is odorless in ordinary field concentrations, and one is not aware of breathing this gas until sufficient has been absorbed to produce its typical physiological effects. It irritates the nose and throat in concentrations as low as 0.00038 mg. per liter (1:30,000,000), and causes irritation of the lower respiratory tract at a concentration of 0.0005 mg. per liter. A concentration of 0.65 mg. per liter is lethal on 30 minutes' exposure, while the lethal concentration for 10 minutes' exposure is 3.0 mg. per liter.

Like diphenylchlorarsine, diphenylaminechlorarsine is most effective when disseminated as a smoke, but when atomized, either by explosion or distillation, it readily penetrates the gas-mask canister unless fitted with the most efficient type of dust filter. Such filters have been developed by all modern armies but they always increase the breathing resistance of the canister and add to the difficulty of securing adequate protection.

As diphenylaminechlorarsine appears to be fully equal to diphenylchlorarsine and is much easier to make, it bids fair to remain as the standard respiratory-irritant compound, at least until it is replaced by a more effective one.

In addition to its value as a chemical-warfare agent, diphenylaminechlorarsine has proved to be very effective in suppressing riots and civil disturbances of a more serious character. For this purpose, it is usually mixed with tear gas (chloracetophenone) and loaded in hand grenades which function by progressive burning and distill off the irritant compound in its most effective form.

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Phenyldichlorarsine ($C_6H_5AsCl_2$)

German: "Blue Cross No. 1"; French: "Sternite"

This compound is primarily a toxic lung injurant and is therefore treated in Chap. VII, page 165. In addition to its lung-injurant effect, however, it also exerts a considerable respiratory-irritant action, and for that reason, was used by the Germans in "Blue Cross 1" shell in mixture with, and as a solvent for, diphenylcyanarsine.

As phenyldichlorarsine was not used alone during the war, there is no war data available as to its effectiveness by itself. When mixed with diphenylchlorarsine or diphenylcyanarsine, in approximately equal proportions, as it was used in the war, the mixture appears to have a more irritating and toxic effect than either of the latter compounds when used alone. The 50–50 mixture produces toxic smokes similar in character to those produced by pure diphenylchlorarsine, but somewhat denser and slightly less penetrating as regards the gas mask.

Because of its high toxicity and not inconsiderable vesicant effect, in addition to its respiratory-irritant action, phenyldichlorarsine is to be ranked among the most valuable of the World War gases.

Ethyldichlorarsine ($C_2H_5AsCl_2$)

German: "Dick"

This compound is also primarily a toxic lung injurant and has been treated as such in Chap. VII. It is also a rather powerful respiratory irritant. A concentration as low as 0.0038 mg. per liter (1:1,900,000) produces a slight irritation of the throat; 0.0125 mg. per liter (1:570,000) strongly irritates the nose and throat and produces a burning sensation in the chest which persists for about an hour after exposure ceases.

Ethyldichlorarsine was introduced by the Germans in an attempt to produce a quick-acting nonpersistent vesicant and was first called "Yellow Cross 1." It was soon found, however, that it was not very effective as a vesicant, but proved to be highly toxic and its classification was changed to "Green Cross 3." It was thereafter used primarily as a lung-injurant agent.

Its combined toxic, irritant, and vesicant effects, together with its low persistency and quick action make it a valuable war gas for offensive use.

Ethyldibromarsine

This compound is the bromine analogue of ethyldichlorarsine and its properties are almost identical therewith. It was used in the war only as a mixture with ethyldichlorarsine in "Green Cross 3" shell and data

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as to its effectiveness alone are lacking. From its chemical structure, it should be slightly more powerful than the chloro-compound, but as bromine compounds usually attack iron and steel, any such advantage would be more than offset by the disadvantage of its corrosive properties. The reason for its use in the war is not apparent.

COMPARATIVE EFFECTIVENESS OF RESPIRATORY IRRITANTS

The effectiveness of the respiratory irritants depends primarily upon their minimum effective concentrations, since such concentrations are generally sufficient to incapacitate men for the period during which the irritants are effective. Accordingly, the lower the minimum effective concentration, the greater the effectiveness of the respiratory-irritant agent. On this basis, the foregoing respiratory irritants are arranged below in descending order of their effectiveness.

Agent	Minimum effective concentration	
	Milligrams per liter	Parts per million
Diphenylcyanarsine	0.00020	1:50,000,000
Diphenylaminechlorarsine	0.00038	1:30,000,000
Diphenylchlorarsine	0.00043	1:25,000,000
Phenyldichlorarsine	0.00500	1:2,000,000
Ethyldichlorarsine	0.00716	1:1,000,000
Ethyldibromarsine	0.01080	1:1,000,000
Ethylcarbazol	0.01596	1:500,000

USE OF RESPIRATORY IRRITANTS IN THE WORLD WAR

Based upon the total amount used in battle, the respiratory irritants constitute the third largest group of chemical agents used in the war. The Germans loaded no less than 14,000,000 Blue Cross shells, of which only a very small part remained on hand at the time of the Armistice. It is estimated that a total of 6,500 tons of respiratory irritants were used in the war and produced 20,000 casualties, among which the deaths were negligible. On the basis of casualties, therefore, it required 650 lb. of respiratory irritants to produce one casualty, as compared to 230 lb. of lung injurants and 60 lb. of vesicants per casualty. However, the tactical value of the respiratory irritants was far greater than simply their casualty value, as they were certainly very effective in counter battery fire and for general harassment of troops. Also they undoubtedly helped to secure a far larger number of lung-injurant casualties by penetrating the mask and causing its removal in the presence of lung-injurant gas concentrations. All in all, the respiratory agents played a major

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role in the last year of gas warfare; while they were not used in their most effective form technically, it cannot be said that they were not successful tactically.

FUTURE OF RESPIRATORY IRRITANTS

The future of the respiratory irritants is somewhat difficult to estimate. The experimental work done by the Allies toward the end of, and since, the World War showed conclusively that these compounds are tremendously effective when thermally distilled and disseminated as toxic smokes; while all modern masks contain special filters for protecting against these smokes, the protection is only relative and greatly adds to the breathing resistance of the mask. All things considered, it is believed that these compounds are destined to play an important part in gas warfare of the future.

For a summary of the principal properties of the respiratory irritants, see Table IV.

SUMMARY OF GASES

We have now completed a survey of the 38 compounds which constitute the entire group of World War toxic agents. For convenience of reference, a consolidated list of these compounds is given below, arranged in groups by physiological classification, in order of their chronological appearance (of the group) in the war, as treated in the foregoing chapters.

I. Lacrimators

Simple

1. Ethylbromacetate.
2. Xylyl bromide.
3. Benzyl bromide.
4. Brommethylethyl ketone.
5. Ethyliodoacetate.*
6. Benzyl iodide.
7. Brombenzyl cyanide.*
8. Chloracetophenone.*

Toxic

9. Chloracetone.
10. Bromacetone.*
11. Iodoacetone.
12. Acrolein.

II. Lung Injurants

Simple

1. Chlorine.*
2. Methylsulfuryl chloride.
3. Ethylsulfuryl chloride.
4. Monochlormethylchloroformate.

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5. Dimethyl sulfate.
6. Perchlormethylmercaptan.
7. Phosgene.*
8. Trichlormethylchloroformate.*
9. Chlorpicrin.*
10. Phenylcarbylamine chloride.
11. Dichlormethyl ether.
12. Dibrommethyl ether.

Toxic

13. Phenyldichlorarsine.
14. Ethyldichlorarsine.*
15. Phenyldibromarsine.

III. Systemic Toxics

1. Hydrocyanic acid.
2. Cyanogen bromide.
3. Cyanogen chloride.

IV. Vesicants

1. Dichlorethyl sulfide.*
2. Chlorvinyldichlorarsine.
3. Methyldichlorarsine.
4. Dibromethyl sulfide.

V. Respiratory Irritants

1. Diphenylchlorarsine.*
2. Diphenylcyanarsine.*
3. Ethylcarbazol.
4. Diphenylaminechlorarsine.

The 38 compounds listed above were selected from over 3,000 substances which were investigated to determine their value in chemical warfare, but only a small number, marked with an asterisk (*), achieved any noteworthy results in the war. The few really successful compounds, however, produced such astonishing results as to change the whole character of modern warfare (see Chap. XXIV).

Even these successful agents were not used efficiently so as to really develop their full possibilities. Much work has been done in the principal countries since the war to develop more effective ways and means of using the successful World War agents, and great progress has been made in this field. Aside from perfecting the various means of projecting chemicals used in the war, great stress has been laid upon developing effective means of dispersing chemicals from airplanes. This new development bids fair to become one of the most formidable weapons of the future, the ultimate effect of which no man can safely predict.

In addition to increasing the effectiveness of the World War agents, all nations have continued research to find still more powerful compounds for chemical warfare. Necessarily, the results of this research are kept

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profound secrets and nothing has been published concerning the progress made in this field except sensational articles in popular magazines and newspapers, which are not only grossly exaggerated, but are utterly unreliable. Hardly a month passes but the public is apprised under lurid headlines of some new supergas a few hundred pounds of which dropped from airplanes could destroy New York. These startling announcements are invariably the figments of the imaginations of sensation writers who really have no technical or professional knowledge of chemical warfare, and, when their statements are analyzed, they are found to be without the slightest foundation in fact.

While these press reports of supergases are not to be taken seriously, it should be borne in mind that industrial research is constantly producing chemical compounds of ever increasing physiological power. We have seen in our survey of the World War chemical agents how the effective strengths of these agents progressively increased as each new one was brought out. Thus, it required a concentration of 5.6 mg. per liter of chlorine to render a man a casualty on 10 minutes' exposure, while a concentration of only 0.0002 mg. per liter of diphenylcyanarsine would cause a casualty on a 1-minute exposure. It was also stated that the respiratory irritant agents are effective in the ratio of 1:35,000,000 of body weight. This was considered in the war as the extreme limit of effectiveness in low concentrations. Since the war, however, chemicals have been discovered which are effective in far smaller doses—now in the order of 1:1,000,000,000 of body weight. Thus, 1 oz. of irradiated ergosterol, the new cure for rickets, will produce the same effect on the human body as 6 tons of cod liver oil! When we remember that one tablespoonful is the normal dose of cod liver oil, we can readily appreciate how tremendously powerful is this new drug and what vast progress has been made in this field in the few years that have elapsed since the war. As General Hartley says:

> Scientists are making very rapid advances, and many of these will have a direct bearing on the next war. It is absolutely essential to make adequate provision to continue research on gas warfare problems, as otherwise all preparations for defence may prove valueless. . . . Such research can only be made effective by the closest sympathy and cooperation between soldiers and scientists, and unless their cooperation is much closer than it was before the late war, there will be little chance of success. It is for the scientists to explore the possibilities and to develop such as are thought likely to be of value, and for the soldiers to apply the results to their investigation of war problems.

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CHAPTER XI

SMOKE AGENTS

CLASSIFICATION

Smoke is the second member of the tripartite chemical arm. From a chemical-warfare viewpoint, smoke is a concentration of exceedingly minute solid or liquid particles suspended in the air. Its purpose is to obscure the vision of the enemy or to screen friendly troops and terrain from enemy observation. Its mission is thus essentially defensive and in this respect is directly opposite to that of gas, for, while gas disables and kills men, smoke protects them by a sheltering mantle of obscurity.

Tactically, we distinguish two kinds of smoke, depending on how it is placed with respect to enemy or friendly troops. A smoke cloud laid close to an enemy for the purpose of blinding him, or at least greatly restricting observation and thus crippling his fighting power, is termed a *blanketing* cloud; a smoke cloud generated close to friendly troops to conceal and protect them from the sight and aimed fire of the enemy, is called a *screening* cloud.

Since the special group of *toxic* smokes are employed like gases for their physiological effects and not for their incidental obscuring powers, it is more logical to consider them as translucent gases and they are so treated in Chap. X. When the simple term "smoke" is used, it will be understood as referring only to harmless obscuring smoke.

Physically, we distinguish two general types of smoke, according to whether it consists of (1) solid particles or (2) liquid particles. The first type comprises the smokes of combustion, while the second comprises

the fogs and mists produced by chemical reactions not involving combustion. Each type may be used either for blanketing or screening, so this physical classification has no tactical significance.

HISTORICAL

As with gas, the methodical planned use of smoke in battle was a development of the World War. History does record sporadic attempts to use smoke tactically in combat, as when, in 1700, King Charles XII of Sweden crossed the Dvina River in the face of the opposing Polish-Saxon army under the protection of a smoke screen generated by burning large quantities of damp straw. But the results of such early, isolated incidents were always too uncertain to justify the adoption of smoke as a recognized agency of warfare.[221]

As a matter of fact, for a century prior to the World War the dense clouds of smoke generated by the increasing quantities of black powder used in battle had been a growing nuisance. They obscured the field of vision, interfered with the aiming and firing of weapons, and hampered the movement and maneuver of troops. By the time of American Civil War, this had become such a formidable problem as to force the invention of smokeless powder in order to restore visibility to the field of battle.

Because smoke had so long been regarded as a tactical handicap to land warfare, development of methods for its artificial generation for military purposes prior to the World War had been constantly neglected. Actually, the first experiments in this direction were made under naval auspices, a fact testifying to the importance of concealment in naval tactics.

Two methods were employed to generate smoke screens at sea. One, used by the British and American navies, was the simple expedient of limiting the admission of air to fires under ships' boilers, so that, owing to incomplete combustion of the fuel, a dense black smoke issued from the funnels. This was done as early as August, 1913, in the course of United States Navy maneuvers off Long Island.

The second method was to produce a white smoke by the reaction of certain chemicals, such as sulfur trioxide and chlorsulfonic acid, in special generators placed on the aft deck of the ship. The German Navy made experiments with such chemical-smoke producers as early as 1906 to 1909.

According to Dr. Hanslian during the World War the German Navy used smoke screens with great success on several cruisers in 1915, particularly in the battle of Jutland in 1916, when smoke was generated from sulfur trioxide and chlorsulfonic acid on board ship and from floating containers. During the summer of 1916, the Austrian fleet also successfully covered its retreat from the French fleet in the Mediterranean by the skillful use of a smoke screen. The regularly planned tactical use of smoke on land commenced in the summer of 1915, closely coinciding with the introduction of gas warfare.

Without doubt, the gas-cloud method of attack directed attention to the possibilities of smoke for screening parts of the battlefield from enemy observation. The dense clouds produced in damp weather by the release of chlorine served to mask the advance of the German infantry which followed behind them, to demonstrate clearly the tactical advantage of concealment during the offensive.

The British were the first to use smoke clouds artificially generated from special apparatus so as to mask their gas attacks and lead the Germans to believe a gas attack was being put over where actually no gas was used.[222] In such operations the British were able to advance unmasked behind the harmless smoke while the Germans, fearing gas, were put to the disadvantage of wearing masks. Smoke was also used for other deceptive purposes such as to draw wasteful artillery fire on unoccupied sectors by generating a smoke screen to indicate that an attack was imminent. The Germans soon adopted these same tactics and in turn used them effectively.

The first special smoke device used on land during the war was the British smoke pot containing a mixture of pitch, tallow, black powder, and saltpeter, which was introduced in July, 1915. The first large-scale smoke operation occurred during the attack of the Canadians against Messines Ridge on Sept. 20, 1915, where several thousand smoke shell were fired from trench mortars.

During the latter part of 1915 and in 1916, the use of smoke extended rapidly throughout all the principal belligerent armies. Not only were special smoke generators employed by each, but smoke fillings were loaded into every form of projectile. By the end of 1916 smoke was a standard filling in hand and rifle grenades, trench-mortar bombs, artillery shell, and even aviation bombs, and smoke tactics contributed to the successes of both sides in many important battles.

By the fall of 1917, the tactical use of smoke on the Western Front had become so well established that General Pershing cabled the War Department on Nov. 3, 1917, asking that large quantities of phosphorus be quickly manufactured for filling smoke ammunition for the American Army.

Following are some outstanding examples of successful large-scale tactical use of smoke during the World War.

The capture of the German position on the edge of the Oppy Forest by the 15th British Infantry Brigade on June 23, 1917, under cover of a smoke screen erected with artillery and trench-mortar smoke shell, succeeded with few losses after previous assaults without smoke had failed.

The maneuvers of the 9th and 29th British Divisions south of Meteran on Aug. 25, 1918, and the advance of the 1st, 2d, and 3d Canadian Battalions, at Vis en Artois sector, were conducted with great success by the aid of smoke. In both cases, under the cover of a dense smoke screen, the German Front was penetrated and from 300 to 500 prisoners brought in.

In crossing rivers, constructing bridges, and establishing bridge heads, smoke was frequently employed with excellent results as in the following instances:

The Austrian crossing of the Piave from Vidor to San Giovanni on June 15, 1918, was, in the opinion of eyewitnesses, successfully made chiefly because of a smoke screen so dense that it was impossible for the excellently located Italian machine-gun flanking units to see.[223]

The success with which the Germans in 1918 screened with smoke their preparations for the transportation of troops over the Marne at Dormans-Vincelles-Vernouil was most noteworthy.

Smoke was also successfully employed in a number of tank attacks by the Allies of which the following are outstanding examples:

In the battle at Malmaison, October, 1917, a smoke screen including in part natural mist, concealed the majority of the French tanks so that the German Artillery had little effect against them and their losses were correspondingly small.

The British tank attack at Cambrai on Nov. 20, 1917, was also favored by dense morning mist that was increased by intensive fire of smoke shell by the British Artillery. In this attack 350 British tanks moved forward in several waves and completely broke through the German defenses.

French army officers report that in the battle of Metz, June 9–12, 1918, the French counterattack against the right flank of the German advance, made with four divisions with 12 tank sections and two regiments of horse artillery, was able to surprise the Germans and force them to retreat because of the protection afforded the counterattack by smoke.

By the fall of 1918 the planned use of artillery smoke shell by the French had become normal. On Sept. 2, 1918, in the combats at Somey and Soissons, three battalions of light tanks advanced behind a rolling-smoke barrage; despite German heavy standing barrages and a well-organized tank defense, the German lines were broken and 1½ kilometers of ground gained. In the hard fighting of the French Fourth Army in 1918 in the Champagne, the loss in tanks from artillery fire was greatly reduced by the general use of artillery smoke shell.

Concerning the penetration of the German front by the British at Amiens, on Aug. 8, 1918, during which 330 tanks, most of them heavy, pushed through the German lines by surprise, General Fuller emphasizes that: "The only artificial element in this successful attack was the ordinary smoke barrage inserted into our artillery plan, which fire increased the haziness of the early morning hour and the confusion." In the battle of Cambrai-St. Quentin, Sept. 27 to Oct. 9, 1918, tanks of the Ninth Tank Battalion made repeatedly successful use of smoke screens produced from the exhausts of their own engines and thus pre-

vented losses from the fire of German close-range guns.

During the German drives in the spring and summer of 1918, smoke shell were used in large quantities to blind observation posts and strong points of resistance. Also in the German retreats in the fall of 1918, smoke was used very generally to cover withdrawal from covering posi-

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tions, notably after the retreat from the Marne in 1918 and from the hill to the east of Beaumont Hammel in the same year. On both of these latter occasions, by developing dense smoke screens, the Germans were able to escape with small losses.

Smoke was also widely employed by the British and by our own gas troops in conjunction with their gas attacks. In smoke operations the British Special (Gas) Brigade used over 40,000 4-in. Stokes smoke bombs, and in one such operation, just north of Armentières on Sept. 26, 1918, 15,000 smoke candles were lighted by a single company.

Although drop bombs filled with white phosphorus were used to some extent in the World War, the tactical employment of smoke by airplanes was not developed to any appreciable degree.

On the whole, the tactical use of smoke during the World War lagged behind the tactical use of gas. It is safe to say the possibilities of the planned use of smoke in battle were only beginning to be realized at the close of the war.

It is a fact that, while the Germans took and held the initiative in the use of gas throughout the World War, the Allies excelled the Germans in the use of smoke, both from a qualitative and quantitative standpoint. This is explained by the Germans as owing to the lack of phosphorus in Germany and its availability and employment in enormous quantities by the Allies.

Since phosphorus was lacking in Germany and Austria, these countries had to resort to sulfur trioxide and other smoke-producing acids which were inferior to phosphorus. Nevertheless, the Central Powers made extensive and generally effective use of smoke during the last two years of the war.

Since the war distinct progress in the development of smoke technique and tactics has been made, particularly in the United States, Great Britain, and Germany. Not only have the World War means of using smoke been greatly improved, but an entirely new method of laying smoke screens by spraying from airplanes has been developed in all important armies.

NATURE OF SMOKE

We have already pointed out that the military term "smoke" comprehends two basically different phenomena: (1) an aerial concentration of minute *solid* particles resulting from combustion, and (2) an aerial concentration of minute *liquid* particles resulting from chemical reactions not involving combustion. Neither of these phenomena can be scientifically classified into any of the three standard physical states of matter. On the contrary, both are "dispersed" forms of matter, known as *colloidal* suspensions or solutions.

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The colloidal state of matter is characterized by an intimate admixture of at least two phases—the dispersed phase and the dispersion medium. by a *dispersion* of this kind is meant the regular distribution of one substance into another in such a way that the individual particles of the one substance are suspended separately from each other in the second substance—in this case, the air. In this sense smoke is to be regarded as a two-phase colloid whose dispersion medium (air) is in the gaseous state and whose dispersed phase is a *solid* or a *liquid*. So-called *colloidal* solutions of this kind have physical and chemical behavior entirely different from normal solutions (such as sugar in water), in that the size of the particles may vary within certain limits without causing the solution to lose its colloidal character.

The particles of a smoke or fog vary in size from those just large enough to be perceived by the unaided eye to those that approach the size of single molecules. In general, smoke particles are intermediate in size between dust particles (10^{-4} cm.) and gas particles (10^{-7} cm.) and average about 10^{-5} cm. in diameter. As a rule, the smaller the particles in a given quantity of smoke, the greater is their obscuring power; hence the aim is to generate a smoke consisting of the maximum number of particles of minimum size.

Since smoke is a suspension of minute solid or liquid particles, it is not a true gas and does not follow the law of gaseous diffusion. However, owing to the collisions of the molecules of air with the smoke particles, the latter exhibit Brownian movements as the result of which they gradually diffuse and spread. Because of their greater mass and inertia and the resistance of the air, the larger particles of smoke diffuse more slowly than the smaller ones. But, compared with the effects of wind and convection currents, diffusion plays an almost negligible part in the dispersion of smokes; even in very dense smokes, the weight of the smoke particles is only a small fraction of 1 per cent of the weight of the air it occupies, so that a smoke cloud is distinguished from the surrounding atmosphere only by the small amount of suspended foreign material.

If smoke is released in warm air, it will rise as the warm air expands, i.e., becomes lighter than the surrounding air and rises. If released in cold air, where these upward convection currents are absent, the smoke will spread out in a horizontal layer and cling to the ground. The movement of the cloud is therefore merely the movement of the air, which accounts for the characteristic behavior of smoke clouds.

Since floating smoke particles are themselves heavier than air they gradually fall, although at a very slow rate that varies with the size of the particles. Thus, according to Grey and Patterson (31) a smoke particle having a diameter of 10^{-4} cm. (the most common size of smoke

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particles) falls about 0.071 in. per minute, which is so slow as to be negligible for practical purposes.

In the same manner as particles in colloidal solution, smoke particles tend to unite and increase in size by cohesion and coalescence as they come in contact with each other by Brownian movements or air currents. This agglomeration takes place much more rapidly in a dense than in a thin smoke. When the smoke particles are completely dry, agglomeration is not observed; but when the particles are liquid, or of a deliquescent solid with condensed surface moisture, this is more pronounced. The increase in the number and size of the larger at the expense of the smaller particles increases the rate of settling and decreases the concentration of the cloud. Also, the smaller smoke particles vaporize more rapidly because their surfaces are greater in proportion to their weight. From the foregoing it follows that a smoke is most stable when its particles are of the minimum size and consist of a dry nondeliquescent solid material.

OBSCURING POWER

Smoke obscures visibility by obstructing the rays of light and diffracting them by reflection from the individual smoke particles. As the obstruction and diffraction of the light rays is dependent primarily upon the number of smoke particles in a given volume, a maximum number of the minimum-size particles produces the greatest obscuration.

The tactical value of a smoke is measured by its power to obscure objects behind it. The term for such measurement is T.O.P. (total obscuring power). The T.O.P. of any smoke is the product of (1) the volume produced per unit weight of material used and (2) the density of concentration. The *density* of a smoke is the reciprocal of the smoke layer (in feet) necessary to obscure the filament of a 40-watt Mazda lamp, and a cloud of unit density is one of which a 1-ft. vertical layer will just obscure the filament. If the volume of smoke per unit weight of inert smoke material is expressed in cubic feet per pound and the density in reciprocal feet, the unit of T.O.P. is square feet per pound. The T.O.P. of a smoke is therefore the area in square feet covered by the smoke from 1 lb. of smoke-producing material, spread out in a layer of such thickness and density that it will exactly obscure the filament of a standard 40-watt lamp.

Factors Affecting T.O.P.—The three factors that most affect the T.O.P. of a smoke are (1) rate of settling, (2) humidity, and (3) temperature.

By rate of settling is meant the velocity with which the smoke particles fall to the ground under the influence of gravity. This increases with the size and density of the smoke particle. For particles larger

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than 10^{-4} cm. (the most common size), Stokes law gives for the rate of settling (in air of spheres of unit density) a velocity

$$V = 3 \times 10^{-3} \text{ cm. per second}$$

This law does not hold accurately for particles smaller than 10^{-4} cm., the steady velocity of fall here being greater than indicated by the law. But since convection currents are usually greater than the rate of settling

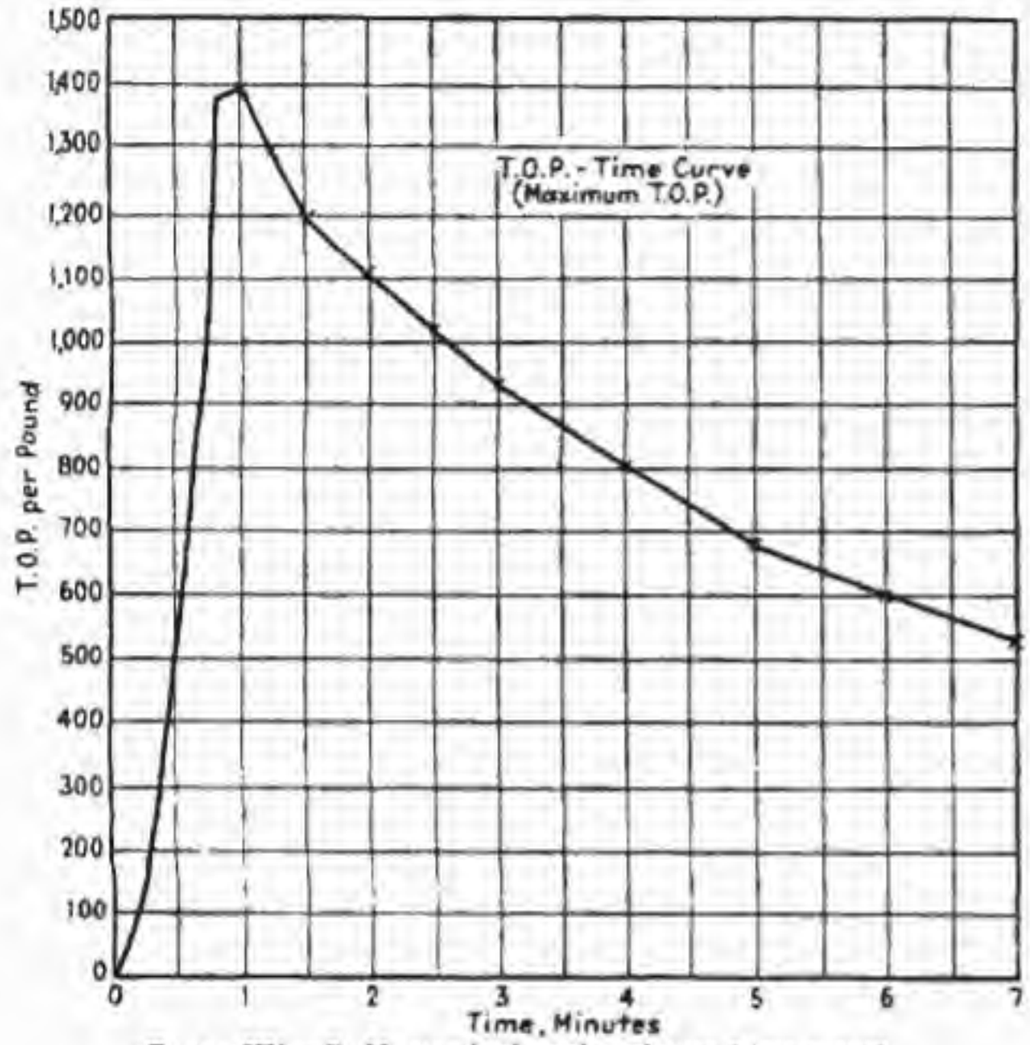

CHART XV.—B. M. standard smoke mixture (time curve).

of particles 10^{-4} cm. in diameter (11 cm. per hour), it is evident that such particles would never settle in ordinary atmosphere. Hence, except in very quiet air, smoke particles must grow to the order of 10^{-4} cm. before appreciable settling can occur. In quiet air, after some time, particles of order 10^{-4} cm. may settle out in appreciable quantities, but particles of order 10^{-5} cm. are probably precipitated only as a result of diffusion and convection (31).

Chart XV shows the relation between T.O.P. and elapsed *time* after initial formation of a standard smoke, due to settling out of the smoke

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particles. Chart XVI shows the effect of *humidity* on the T.O.P. of a standard smoke, temperature being constant. Chart XVII shows the effect of *temperature* on the T.O.P. of a standard smoke mixture, humidity remaining constant.

From Chart XV it will be observed that T.O.P. at first sharply increases and then progressively decreases with elapsed time after generation of the smoke; Chart XVI shows that T.O.P. varies directly with humidity; Chart XVII shows that T.O.P. varies inversely with temperature.

These charts indicate typical relations between T.O.P. and the factors that principally affect it. While these relations apply in general to all smokes, there are some notable exceptions; the T.O.P. of phosphorus, *e.g.*, is unaffected by temperature, and the T.O.P. of ammonium chloride is unaffected by humidity. However, these are not important, for, while there are a few exceptions to the T.O.P.-temperature law shown in Chart XVII, ammonium chloride and carbon smokes (such as those generated by crude oil) are the only smokes that depart from the T.O.P.-humidity law, shown in Chart XVI.

Another useful measure for comparing the obscuring values of smokes is the so-called *standard smoke*, defined as one of such density that a

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25-candle-power electric light is just invisible through a layer of smoke 100 ft. thick.

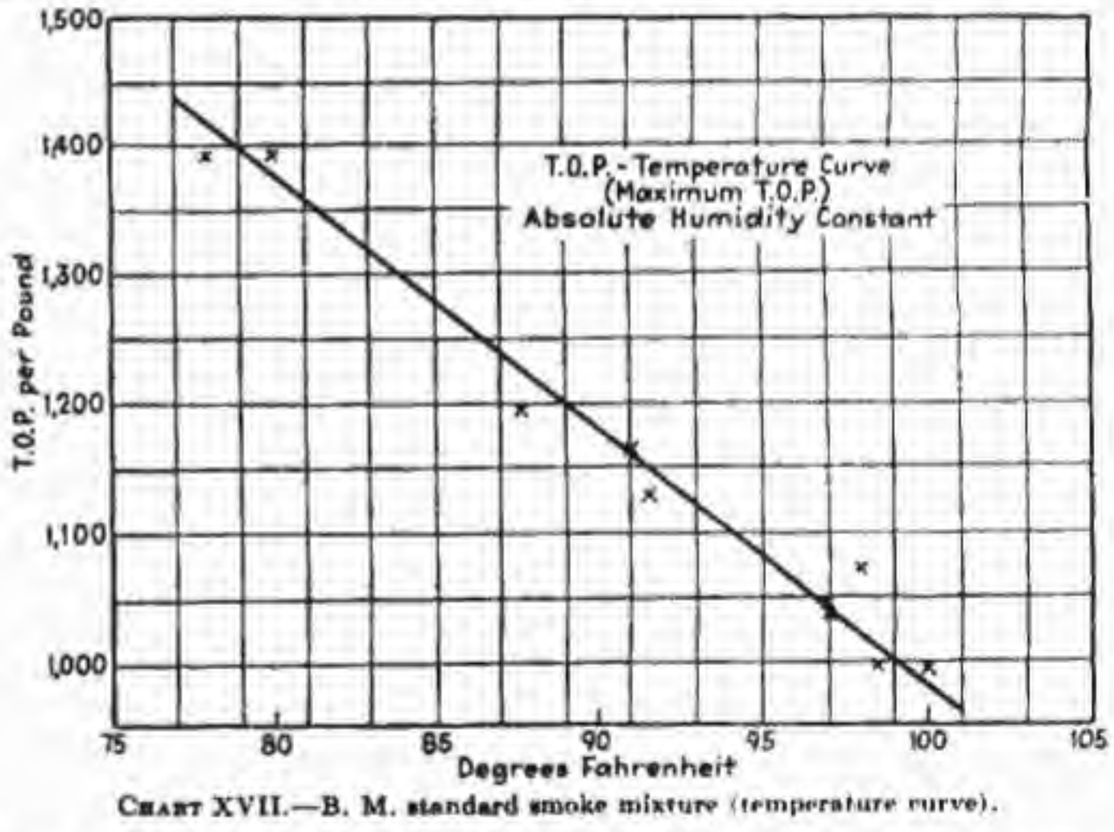

CHART XVII.—B. M. standard smoke mixture (temperature curve).

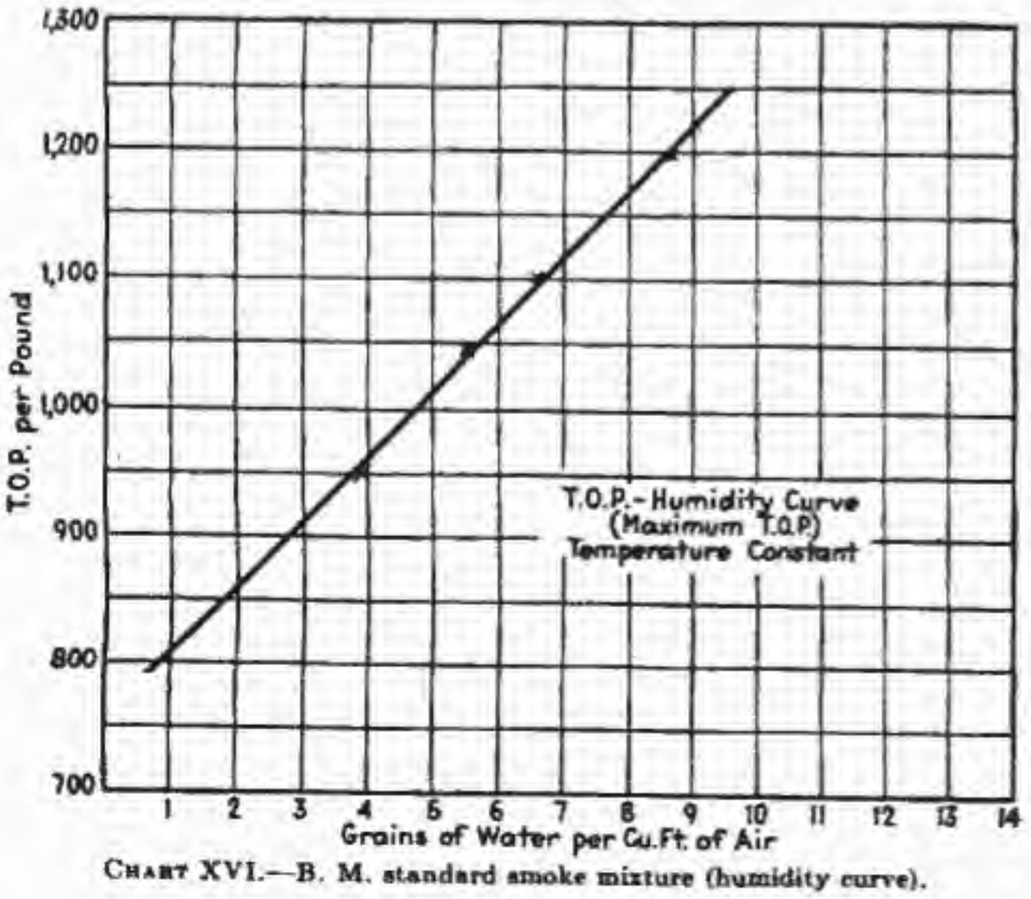

CHART XVI.—B. M. standard smoke mixture (humidity curve).

PRINCIPLES OF SMOKE PRODUCTION

A satisfactory smoke cloud requires, in the first place, density; a relatively thin layer of the smoke must completely obscure any object behind it. In the second place, the cloud must be inherently stable; it must not quickly dissipate or dilute, nor must it settle out. Third, the cloud must easily be produced without complicated apparatus or difficulties of manipulation. Finally, the materials required for producing the cloud must be readily available, easy of transportation, and not dangerous to handle.

Any smoke fulfilling these requirements must be composed of extremely small liquid or solid particles dispersed in the air. The individual particles must be large enough to disperse and diffuse light; but otherwise the smaller the particles, the greater the obscuring power for a given concentration of smoke in air and the more stable the smoke. The diffusing power of a given particle is probably not greatly influenced by its size, provided the particle is large enough to diffuse light at all. The problem of smoke formation, therefore, reduces itself to the problem of producing a suspension of extremely small particles of the smoke-forming substance in air. Successful smoke production depends upon appreciation and application of the following generalization.

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Every particle of liquid, or solid, in contact with a gas is surrounded by a film of gas closely adhering to it and capable of removal or penetration only by the projection of another solid or liquid particle through it. This film serves as an effective insulator, separating the particle from the

gas around it, and breaking down only through mechanical rupture. When such a particle travels through the gas, the film moves with it; when the gas moves past the particle, the film is distorted and made thin, but in no case completely removed. The protective action of this film upon the solid or liquid surface can never be lost sight of if the phenomena of cloud and smoke formation are to be appreciated.

Such particles of solid or liquid suspended in gas do not diffuse. This fact in connection with the insulating power of the gas film around them makes the removal of them from the gas extremely difficult. For example, gas containing a small amount of HCl can be washed free from the acid by bubbling through water, even though the rate of bubbling be very high. On the other hand, a gas containing a fume of NH_4Cl can be bubbled through water almost indefinitely without appreciable removal of the fume. The HCl being a gas, diffuses with extreme rapidity through the stationary film of air on the surface of the water in contact with the bubbles and in this way is effectively removed, and the solid particles incapable of diffusion pass through unabsorbed.

Such small suspended particles of either liquid or solid have also practically no tendency to coalesce. Even should two such particles tend to approach each other, they are held apart by the cushion or buffer effect of the air films around them. If, however, the particles be large, two particles approaching each other may have sufficient momentum to penetrate mechanically the surrounding gas films and in this way come together. Particles large enough to evidence this phenomenon to any considerable degree are too coarse to be described as smokes or fumes.

A smoke or fume, once formed, can undergo growth of the particles only through condensation of gaseous or vapor components in the air around them. Thus, a particle of NH_4Cl can grow only by the diffusion into it through the gas film surrounding it of gaseous NH_3 and HCl. A particle of water in a fog grows only by the infusion of atmospheric water vapor through the air film surrounding the drop. In other words, in order to build up a particle of smoke or fume, that particle must be formed by the condensation of gaseous components. It cannot be produced from liquid or solid reagents.

In illustration, a fume of NH_4Cl is formed only by the interaction of the vapors of its components; SO_3 cannot be absorbed by water because it reacts with the water vapor above the liquid surface to form a fog of sulfuric acid, the water vapor being continually replenished as fast as it is exhausted by evaporation of the water and diffusion of the water vapor

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through the stationary film of air about the liquid; and HCl can be readily absorbed by aqueous ammonia, because of formation of a fog by interaction with the ammonia vapor from the solution. Only substances which volatilize before burning, such as soft coal, phosphorus, and the like, produce a cloud or smoke upon combustion.

To produce a smoke composed of particles of suitable minuteness, it is necessary that the components from which the smoke is formed be diluted with some inert gas before condensation. If this precaution is not observed, the particle of smoke initially formed will grow with extreme rapidity, owing to further condensation of its components, so that a large particle results. Only when the particle first formed finds the space around it depleted of its components, does it cease to grow. It is therefore self-evident that to produce a high-grade smoke, a diluted gas must be employed.

One of the most striking illustrations of this is the fact that phosphorus burned in a large excess of air, with good circulation, produces an extremely stable smoke; in insufficient air, with poor circulation, the smoke settles rapidly and has little obscuring power. Every smoke thus far studied shows very markedly the beneficial effect of dilution, even up to a dilution of several hundred times. Many reacting gases when diluted with 100 times their volume of air show from 20 to 50 times the T.O.P. obtained when the gases are diluted with but two or three volumes of air.

In general, dilution is beneficial up to a point where the reaction begins to be incomplete. This occurs much sooner when a large number of molecules must participate in the reaction than when the reaction is a simple one. For example, the first step of the reaction between chlorine and ammonia is $3Cl_2 + 2NH_3 = 6HCl + N_2$; the rate of this fifth-order reaction drops off as the fifth power of the concentration, and therefore begins to be complete before the full beneficial effects of dilution can be realized. On the other hand, HCl and NH_3 can be diluted to a very high degree without preventing complete reaction, and therefore the obscuring power per pound can be made three times as great as that for ammonia and chlorine, although the substances formed are exactly the same.

If the smoke consists of a nonvolatile solid, it makes practically no difference how the diluent air is distributed between the two reacting gases, any method of dilution being about equally effective in the production of a larger number of small particles. On the other hand, if there is the possibility of forming at any stage of the process liquid drops that grow in the presence of an excess of either component or if there is the possibility of forming two different compounds, the method of dilution becomes quite important and the best method must be determined by a study of the reaction in question.

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In order that a smoke shall have reasonable stability, it must be nonvolatile, or nearly so. A smoke produced by the condensation of HCl and water vapor clears up rapidly in ordinary air, owing to complete evaporation of the mixture. The same is true of a smoke of ammonium carbonate and similar substances. Such smokes will also frequently block out the particles growing by the following mechanism; a small particle has a higher vapor pressure than a large one; such a small particle tends, therefore, to evaporate and to diffuse through the stationary air films surrounding it, condensing later upon some larger particle. This results in the disappearance of the smaller particles and growth of the larger ones. Thus, $SnCl_4$ reacts with water vapor to make a fog, consisting of a mixture of particles of stannic hydrate and a solution of HCl in water; this fog is poor because the stannic liquid particles rapidly and completely evaporate in unsaturated air. The use of ammonia in the production of this fog greatly improves it by introducing stable ammonium chloride particles.

Other things being equal, liquid particles are poorer than solid particles because they tend to condense into themselves any one of their components that may be present in excess, while a solid particle will only condense in a very small excess of one component before ceasing to grow. For example, a fume formed from HCl and water vapor will condense either water vapor or HCl almost indefinitely, whereas one of ammonium chloride will not grow in the presence of either component. Deliquescent solids are, of course, open to the same objection, since they continue to absorb moisture and grow to small drops of saturated solution.

SUBSTANCES USED AS SMOKE AGENTS

The substances that have been successfully used as smoke agents fall into five main groups, *viz.*, smokes that owe their obscuring power to: (I) particles of colloidal *carbon* suspended in air; (II) particles of phosphoric acid; (III) sulfuric acid; (IV) hydrochloric acid; and (V) zinc chloride.

Each of these groups appeared about in the order named and, except for phosphorus (the best of all smoke producers), each was an improvement upon its predecessor.

Group I

Crude Oil (CO)

The earliest modern method of producing artificial smoke was by the incomplete combustion of the crude-oil fuel under the boilers of naval vessels, especially destroyers. Crude-oil smoke was used by the Germans in the Battle of Jutland (1915) to cover a turning movement that enabled the German High Seas Fleet to escape from the pursuing British. It is now used by all navies to erect smoke screens at sea.

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The oil used for this purpose is the mixture of hydrocarbons known by the trade name of *crude oil*. It is a liquid of 0.8 specific gravity which solidifies at −20°C. (−3°F.) and boils at 200°C. (392°F.). When incompletely burned it evolves a dense black smoke that derives its opacity from particles of colloidal carbon floating in the air. Oil smoke is slightly suffocating when dense, but has no other deleterious physiological effects. It is one of the few artificial smokes that are not affected by the humidity and is noncorrosive to material.

The smoke produced from crude oil may be generated in three ways:

1. The oil may be evaporated by heat and condensed again in the air to form small droplets. Such smokes are, however, very unstable owing to the vapor pressure of the oil, which causes it to assume the gaseous state with consequent disappearance of the colloidal carbon particles that constitute the smoke.

2. The oil may be only partially burned, the carbon thus separated in solid particles which at first float in the air and form a dense smoke. The solid particles soon coagulate into flakes that quickly settle out and drop to the ground. Such smoke is therefore quickly dissipated and has poor screening value.

3. The best method is a combination of the first two; *i.e.*, there is an imperfect combustion of the oil and at the same time an evaporation of the excess oil. In this case the liquid particles surround the solid particles of carbon and prevent their coagulation into flakes. Such a smoke is grayish black and is far more stable.

Notwithstanding the tendency to clog up the flues by depositing solid carbon therein, all modern navies use this method of producing smoke screens at sea. It requires no special apparatus, is cheap, and can readily generate large screens in a short time. Two ounces of crude oil are required to produce 1,000 cu. ft. of *standard smoke* and the cost is 8 cents; this is therefore the cheapest of all artificial smoke producers.

British Type S Mixture

The first material used in the World War for the generation of artificial smoke on land was the British Type S smoke mixture. This was used as a filling for the first smoke candles, called "Smoke Torch, Mark 1, Type S," and consisted of the following ingredients:

	Per Cent by Weight
Potassium Nitrate	45
Sulfur	12
Pitch	30
Borax	9
Glue	4

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Later in the war these ingredients were somewhat modified for the Smoke Candle, Mark II, Type S-I, to include:

	Per Cent, by Weight
Niter	40
Sulfur	14
Pitch (hard)	29
Borax	8
Coal dust	9

The ingredients were ground, mixed, screened, and, while still in a plastic condition, pressed into a 3-lb. tin container.

These candles burned vigorously for about 3 minutes and generated a large volume of yellowish brown smoke. The obscuring power of the smoke was due principally to the incomplete combustion of the solid carbon particles in the pitch. Its T.O.P. was quite low (460) and its screening properties were unreliable since the smoke had a tendency to rise rapidly, break up, and leave gaps in the screen. Yet the agent was cheap, easily produced from readily available materials, and had good keeping properties. These candles were therefore used in large quantities through the war by both the British and American armies.

Group II

White Phosphorus (WP)

One of the earliest and by far the most efficient material used in the war for generating artificial smoke was phosphorus. This element exists in two allotropic forms: white phosphorus and red phosphorus. White phosphorus, the normal and common form, was discovered in 1669 by the German chemist, Brand, who noted that it is spontaneously inflammable at ordinary temperatures and burns with a dense white smoke. While both white and red phosphorus were used in the war, white phosphorus was by far the most effective and the most widely employed and is the form now generally denoted by the word *phosphorus*.

Phosphorus is produced on a large scale in industry by heating phosphate rock (calcium phosphate) in an electric furnace. Such phosphates exist in enormous quantities in the United States and North Africa.

White phosphorus is formed by quickly cooling the vapors distilled from the phosphate rock. When pure it is a waxy solid, of 1.8 specific gravity, which melts at 44°C. (111°F.) and boils at 287°C. (549°F.). It is chemically very active and combines readily with oxygen in the air, even at room temperature. The greater the surface exposed to the air, the more rapid is the reaction. Upon oxidation the phosphorus becomes luminous and in a few minutes bursts into vigorous flames that can only be quenched by complete submersion in water. It must therefore be

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stored and worked entirely under water. White phosphorus is insoluble in water but readily soluble in fats and in carbon bisulfide.

Red phosphorus is produced by heating white phosphorus to a temperature of from 250° to 300°C., out of contact with air, and then dissolving out the small traces of unchanged white phosphorus with suitable solvents. Red phosphorus is a reddish brown amorphous powder, of 2.3 specific gravity, which is chemically much less active than white phosphorus. In contact with air at ordinary temperatures, it remains unchanged for a long time; it does not appreciably dissolve in carbon bisulfide and the ordinary solvents for white phosphorus; it does not become luminous; and it can be heated to 260°C. before it ignites. Its vapors are not toxic as are the vapors of white phosphorus.

Both forms of phosphorus combine with oxygen in the air to form phosphorus pentoxide:

$$4P + 5O_2 = 2P_2O_5$$

The phosphorus pentoxide is then converted by the moisture in the air to phosphoric acid:

$$2P_2O_5 + 6H_2O = 4H_3PO_4$$

Thus 1 lb. of phosphorus combines with 1.33 lb. of oxygen and 0.9 lb. of water to form 3.23 lb. of phosphoric acid, which makes phosphorus the best smoke producer, pound for pound, of any known material. The red phosphorus does not equal white phosphorus for generating smoke and for that reason is seldom used alone, but it has been mixed with white phosphorus in the ratio of 1:2 in artillery and trench-mortar smoke shell.

While the vapors of white phosphorus are exceedingly toxic, these vapors are so quickly oxidized to phosphorus pentoxide and phosphoric acid as to be harmless to men and animals in ordinary field concentrations. There is some difference of opinion as to the physiological effect of phosphorus smoke because of the possibility of the continued presence of phosphorus vapors therein. Extensive field tests, however, have shown no injurious effects from phosphorus smoke under conditions which obtain in the field.

In addition to its smoke value, phosphorus is of tactical importance because of its burning effect upon both personnel and material. In contact with the body, phosphorus produces burns that are slow and difficult to heal; thus the firing of phosphorus against personnel has a psychological value that greatly increases its tactical effectiveness. Against material, however, the incendiary effect of phosphorus is limited, as it ignites only readily combustible materials, so that here it is inferior to thermite and other primarily incendiary materials.

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The principal disadvantages of phosphorus are: (1) the difficulty of storage and handling; (2) the bright flame produced when burning; and (3) that it is a solid and cannot be sprayed without dissolving in highly inflammable and dangerous solvents. In spite of these drawbacks, phosphorus remains today one of the most efficient smoke-producing materials.

Group III

Sulfuric Trioxide (SO_3)

Sulfuric Anhydride

Next to phosphorus, sulfur trioxide was the best smoke producer used in the war, notwithstanding that it requires humid air to develop its full effect. It is prepared by passing a mixture of sulfur dioxide and oxygen

over a catalyst (such as sponge platinum) at a temperature of from 400° to 450°C. It may also be obtained by the catalytic combustion of sulfurous acid in special contact ovens. When pure, sulfur trioxide is a mobile colorless liquid, of 1.92 specific gravity, which boils at 45°C. (113°F.) and freezes at 18°C. (60°F.) into a transparent solid of 2.75 specific gravity. It also polymerizes spontaneously into an asbestoid crystalline mass, $(SO_3)_2$, of 1.97 specific gravity, which melts at 40°C. (104°F.) into the liquid commercial product. On contact with the air it fumes vigorously and throws off dense white clouds composed of minute droplets of sulfurous and sulfuric acids.

Sulfur trioxide produces its smoke effect by the formation of fine droplets of sulfurous and sulfuric acids that remain suspended in the air for some time because of their minute size, and then are not volatilized because of the low vapor pressure of these acids. As the SO_3 fumes combine with moisture in the air, concentrated sulfuric acid is formed, which *attracts more moisture* and tends to become diluted, until finally an equilibrium is established between the moisture in the air and the sulfuric acid droplets, the latter being concentrated in proportion to the humidity of the air. Sulfuric acid is not so hygroscopic as the phosphoric acid formed by burning phosphorus, and the formation of its droplets stops sooner, so that sulfur trioxide smoke is less stable than phosphorus smoke.

Since sulfurous and sulfuric acid are corrosive, the SO_3 smoke has a somewhat irritant effect upon the respiratory organs and the skin. A concentration of even 0.010 mg. per liter causes a hacking cough which is much aggravated in higher concentrations. A concentration of 0.030 mg. per liter completely obscures objects 20 ft. distant. In humid weather sulfur trioxide has an obscuring value equal to 70 per cent of that of phosphorus.

During the war sulfur trioxide was used as a filling for German artillery and trench-mortar smoke shell. Since the war extensive experi-

ments have been made in Germany, England, and America in spraying sulfur trioxide and other liquid smoke-producing materials from airplane tanks for the production of smoke screens. Various portable devices have also been invented for evaporating and spraying SO^3 to form smoke concentrations on the ground.

Oleum ($SO_3 + H_2SO_4$)

Fuming Sulfuric Acid

Oleum is a solution of sulfur trioxide in concentrated sulfuric acid, the proportions of SO_3 varying from 20 to 40 per cent. It is a dense liquid that fumes vigorously on contact with air. During the war, for producing smoke screens on land and sea, the Germans used special smoke generators (*Nebelkalkraketen*), in which oleum was brought in contact with quicklime. In these generators the oleum was permitted to drip on a bed of quicklime, which in a few minutes became red hot from the heat of the reaction (68,600 calories per mol) and quickly evaporated the oleum which continued to drip on it. The smoke thus formed was vigorously emitted in a very finely atomized form, free from large drops.

Oleum was also used in the war by the Americans for generating smoke from airplanes and combat tanks by squirting a small stream of it into the hot exhaust manifolds of the engines. In this way, the engine exhaust heat was used to evaporate the oleum in lieu of the heat chemically generated by quicklime in the German smoke generators.

Experiments with oleum show that its smoke-producing power is due solely to its sulfur trioxide content, the sulfuric acid itself acting only as a solvent. Pure sulfur trioxide is superior as a filling for smoke shell, while oleum gives better results when progressively evaporated by heat.

Chlorsulfonic Acid ($HClSO_3$)

Chemically and as a smoke producer, chlorsulfonic acid is very similar to sulfur trioxide. It is obtained by acting on sulfur trioxide with gaseous hydrochloric acid:

$$SO_3 + HCl = HClSO_3$$

This is a colorless liquid, of 1.77 specific gravity, which boils at 158°C (316°F.) and fumes on contact with air, forming sulfuric and hydrochloric acids:

$$HClSO_3 + H_2O = H_2SO_4 + HCl$$

Chlorsulfonic acid was first used by the Germans, who adopted it as a smoke agent early in the war, using the oleum process of dripping on

quicklime. It produces a volatile and not very dense smoke and has now been superseded by other materials.

Sulfuryl Chloride (SO_2Cl_2)

A third smoke-producing substance closely related to sulfur trioxide is sulfuryl chloride. This compound is a colorless extremely pungent liquid, of 1.66 specific gravity, which boils at 70°C. (158°F.) and decomposes on contact with moisture in air to form sulfuric and hydrochloric acids. Its efficiency as a smoke producer is very much lower than the other substances in this group and for that reason was not used alone as a smoke agent. It was, however, extensively employed by the Allies in mixture with certain toxic gases, such as phosgene and chlorpicrin, as a "fumigant" to render the toxic-gas concentrations visible.

Sulfur Trioxide–Chlorsulfonic Acid Mixture ($SO_3 + SO_3HCl$)

American: "FS"

The several disadvantages of titanium tetrachloride led to search for a substitute liquid and finally resulted in the discovery that a mixture consisting of sulfur trioxide and chlorosulfonic acid produced a superior smoke agent.

This mixture, known by the symbol "FS," is a liquid of 1.91 specific gravity, which freezes at −30°C. (−22°F.), and has a T.O.P. of 2,550 as compared to 1,900 for titanium tetrachloride. FS costs only 7.5 cents per pound as compared to 30 cents per pound for FM; it deposits no solid residue on hydrolysis and therefore flows freely from nozzles without clogging the eduction ports. There is no marked difference in the rate of settling of the two smokes, so that they are about equal in persistency.

The only disadvantage of FS is its highly corrosive action on metals and airplane fabrics, although in this respect it appears to be no worse than FM. Because of its all-around superior qualities, FS has been adopted as the standard liquid-smoke agent of the United States Army and Navy.

Group IV

Tin Tetrachloride ($SnCl_4$)

British: "KJ"; French: "Opacite"

As phosphorus was very dangerous to work with and could not be used in liquid form for spraying without extreme hazard to using troops, and since the various SO_3 compounds oxidizing sulfuric acid were very corrosive, much effort was expended toward the end of the war in finding substitute smoke agents free from these disadvantages. This resulted

in the introduction of a series of metallic chlorides of which tin tetrachloride was the first.

This compound is obtained by the direct chlorination of metallic tin. It is a liquid of 2.28 specific gravity, which boils at 114°C. (237°F.). It fumes in the air and hydrolyzes into stannic hydroxide:

$$SnCl_4 + 4H_2O = Sn(OH)_4 + 4HCl$$

The smoke thus produced is only one-half as dense as sulfur trioxide smokes, but is less corrosive and far more penetrant to the gas-mask canisters used during the war. For this last reason tin tetrachloride was employed principally in mixtures with phosgene and chlorpicrin to increase the visibility and penetrability of the gas clouds generated therewith. It is very expensive and the scarcity of tin caused other compounds to be substituted toward the end of the war.

Silicon Tetrachloride ($SiCl_4$)

The next metallic chloride used as a smoke agent was silicon tetrachloride. This compound is prepared by heating silicon or silicon car-

bide with chlorine in an electric furnace. It is a colorless liquid, of 1.52 specific gravity, which boils at 60°C. (140°F.) and fumes strongly on contact with the moisture in the air by which it is hydrolyzed:

$$SiCl_4 + 4H_2O = Si(OH)_4 + 4HCl$$

At a concentration of 0.20 mg. per liter, no further hydrolysis takes place, but an equilibrium seems to be established in which the hydrochloric acid liberated prevents further decomposition. In fact, when the hydrochloric acid becomes too great the above reaction may even be reversed and the amount of smoke actually diminished. If, however, the excess hydrochloric acid is neutralized by reaction with ammonia, hydrolysis of the silicon tetrachloride proceeds smoothly

$$SiCl_4 + 4NH_3 + 4H_2O = Si(OH)_4 + 4NH_4Cl$$

and a dense smoke is obtained. Thus, while the value of silicon tetrachloride alone as a smoke producer is limited, its smoke-generating power with ammonia vapors is five times as great as silicon tetrachloride alone and exceeds even that of phosphorus. Moreover, the smoke thus generated is much less irritant to the respiratory organs.

So closely does this smoke resemble natural fog that, when it was employed by the British in their naval attack on Zeebrugge, the German defending forces thought the smoke coming in from the sea was a natural fog, and the British thus succeeded in approaching the harbor unseen. The so-called *smoke funnels* that the British used in this attack consisted of iron cylinders 2 ft. in diameter, into which gaseous ammonia and

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silicon tetrachloride were injected, the latter by means of carbon dioxide. The results obtained were so satisfactory that small portable smoke knapsacks, embodying the same method of operation, were also constructed and frequently used with good results in the field.

The only disadvantage of the silicon tetrachloride-ammonia method of generating smoke is its complication, and for this reason other simpler methods of smoke production were developed for field use.

Owing to its comparatively high volatility, silicon tetrachloride has also been used to lay smoke screens by spraying from airplane tanks. The droplets are volatilized after falling a very short distance and good results are obtained. However, ammonia is also necessary in these devices, which constitutes an undesirable complication in the apparatus. Except for this drawback, the silicon tetrachloride-ammonia mixture is one of the most effective smoke producers so far devised.

Because of the shortage of tin toward the end of the war, silicon tetrachloride was substituted for tin tetrachloride in gas shells.

Titanium Tetrachloride ($TiCl_4$)

German: "F-Stoff"; American: "FM"

The complications involved in producing dense smoke by use of ammonia with silicon tetrachloride caused the introduction of titanium tetrachloride by the Allies, near the end of the war, as a substitute for tin and silicon tetrachlorides.

This compound is obtained from rutile TiO_2 which is found in natural beds in Norway and in Virginia. The rutile ore is first mixed with 30 per cent carbon and heated to 650°C. in an electric furnace. A fused mass is formed, consisting of titanium carbonitride ($Ti_5C_4N_4$) and titanium carbide (TiC), which is converted to $TiCl_4$ by heating with gaseous chlorine. The product is a colorless highly refractory liquid, of 1.7 specific gravity, which boils at 136°C. (277°F.) and solidifies into white crystals at −23°C. (−9°F.). It reacts vigorously with the moisture in the air, forming titanic acid hydrate and hydrochloric acid:

$$TiCl_4 + 4H_2O = Ti(OH)_4 + 4HCl$$

with the evolution of dense clouds of acrid white smoke. The titanic acid hydrate forms finely divided solid particles in the smoke while the hydrochloric acid is in the gaseous state.

Like silicon tetrachloride, complete decomposition of the titanium tetrachloride, according to the above equation, is inhibited by an excess of hydrochloric acid. Therefore, the best smoke is formed when the titanium tetrachloride is present in low concentrations and there is an excess of moisture in the air (five parts of water to one of the tetrachloride,

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instead of the theoretical four parts). Owing to these peculiarities, when it is used in concentrations under 0.060 mg. per liter and when the humidity is high, titanium tetrachloride is superior in obscuring power to sulfur trioxide; but when the concentrations are high and the humidity low, it is inferior.

On account of its hydrochloric acid content, titanium tetrachloride smoke is acrid, but in ordinary field concentrations it is not sufficiently irritating to the respiratory system as to cause coughing or other unpleasant physiological effects. The smoke can be neutralized and rendered completely harmless by the simultaneous use of ammonia which fixes the hydrochloric acid and greatly increases the density of the smoke by the addition of ammonium chloride. While the addition of ammonia almost doubles the obscuring effect of the titanium tetrachloride, the total amount of material required is doubled, so that no advantage is gained from the standpoint of weight. Also the apparatus employing two liquids is much more complicated and, as titanium tetrachloride alone is an excellent smoke producer when used in the proper proportion to the moisture content of the air, the use of ammonia is not necessary.

Because of its high boiling point and not too great volatility, titanium tetrachloride is peculiarly adapted for use in laying smoke screens from airplanes since each individual droplet can move through a great distance before it is completely volatilized and hydrolyzed. For this reason it was adopted as the standard American liquid-smoke agent for several years following the war. Because of its relatively high cost (about twenty times as much as sulfur trioxide for equal smoke effect), the fact that in hydrolyzing it deposits a gummy solid residue that clogs up the emission orifices of the sprayer, and its corrosive action (in liquid form) on metals, titanium tetrachloride has been displaced by the much cheaper and more generally satisfactory smoke agent FS.

It requires 0.15 oz. of titanium tetrachloride to produce 1,000 cu. ft. of *standard smoke*, as against 0.06 oz. of phosphorus, so that, on a basis of equal weights, the former is about 40 per cent as efficient a smoke producer as the latter.

Titanium tetrachloride, although more expensive and not otherwise superior to FS, is nevertheless used as a filler in artillery and mortar-smoke shell.

Group V

Berger Mixture ($Zn + CCl_4 + ZnO$ + Kieselguhr)

The next group of substances employed during the World War as smoke agents were compounds and mixtures containing zinc that generated the so-called *zinc smokes*. The first substance of this type to be

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introduced was a mixture containing carbon tetrachloride and zinc dust, called "Berger Mixture" after the French chemist, Berger, who invented it. The original Berger Mixture as used by the French government during the war had the following composition:

	Per Cent, by Weight
Zinc (dust)	25
Carbon tetrachloride	50
Zinc oxide	20
Kieselguhr	5

The theory of this mixture is as follows: Finely divided metallic zinc reacts vigorously with organic chlorine compounds (*e.g.* carbon tetrachloride or hexachlorethane), forming zinc chloride:

$$2Zn + CCl_4 = 2ZnCl_2 + C$$

This reaction liberates a large quantity of heat, which instantly evaporates the zinc chloride and generates a dense cloud of smoke. As the reaction quickly raises the temperature to 1,200°C., it has to be moderated by the addition of a volatile substance, such as an excess of carbon tetrachloride, that absorbs heat during evaporation. In order to prevent the heavy zinc dust from settling to the bottom of the liquid carbon tetrachloride, an absorbent, kieselguhr, is added, forming a smooth paste which cannot again be separated into its constituents. The zinc oxide used in the

original mixture was practically useless as its absorbent power is small.

In order to ignite and start the Berger Mixture to burning, an igniting composition consisting of iron dust and potassium permanganate was employed. This ignition composition was started with an ordinary match head. About 3 lb. of Berger Mixture were pressed into a tin container about the size of a large tomato can and covered with a layer of igniting mixture; in this way were obtained the smoke candles used in the World War.

Smoke candles made with Berger Mixture had many advantages over the liquid smoke producers. They were chemically inert and entirely harmless until ignited and could not be fired even if hit by projectiles. They could be stored for long periods without deterioration, occupied a relatively small storage space, and could be easily transported, handled, and operated. The smoke generated was quite harmless and produced no irritant effects until the concentration exceeded 0.100 mg. per liter, which was far in excess of ordinary field concentrations. The principal disadvantages of the Berger Mixture smoke candles were: (1) high reaction temperature and the dispersion of sparks that caused fires; (2) the mixture was somewhat erratic in burning and did not utilize all its ingredients to their full values; (3) the smoke generated was light gray with

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considerable carbon in the residue. Berger Mixture was also not suitable for use in smoke grenades, artillery shell, or airplane bombs, as it is too slow in igniting and burning.

In order to improve the performance of the original Berger Mixture, a great deal of experimenting was done and a large number of formulas for this mixture are found in chemical-warfare literature. Regardless, however, of the variations in the mixture, the general principles of operation are the same; one part by weight of zinc dust to two parts by weight of carbon tetrachloride furnish the main reaction, to which is added enough absorbent material, such as kieselguhr, to form a doughlike paste which cannot be reduced to its original ingredients.

"B.M. Mixture" ($Zn + CCl_4 + NaClO_3 + NH_4Cl + MgCO_3$)

The American improvement on the original Berger Mixture was worked out in 1917 by the U.S. Bureau of Mines, and was therefore known as "B.M. Mixture." It had the following composition:

	Per Cent, by Weight
Zinc (dust)	35.4
Carbon tetrachloride	41.6
Sodium chlorate	9.3
Ammonium chloride	5.4
Magnesium carbonate	8.3

The changes in the original Berger Mixture, shown in the foregoing formula, were made for the following reasons: The original Berger Mixture produced a gray smoke and lacked vigor in reaction. The first step, then, was to add a substance to oxidize the carbon, thereby changing the color of the smoke from gray to white and at the same time accelerating the reaction. For economic reasons, sodium chlorate was chosen for this purpose. The addition of sodium chlorate greatly increased the quantity and quality of the smoke produced, but made the rate of burning too rapid, the heat of reaction too great, and the smoke too hot. The next step was therefore the substitution of ammonium chloride for the zinc oxide of the original Berger Mixture. By absorbing a great deal of heat in its volatilization, this cooled the smoke and considerably retarded its rate of burning. It also added materially to the density of the smoke, as the obscuring power of the chloride itself is high. The last step was the substitution of magnesium carbonate for the kieselguhr in the original mixture. Kieselguhr was not satisfactory as an absorbing agent. It lacked constancy of composition, contained variable amounts of moisture and organic matter, and swelled, caked, and arched badly upon burning, thereby causing irregularities in the rate of combustion of the mixture. Magnesium carbonate proved a better absorbent, gave a smoother burn-

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ing mixture, and added to the density of the smoke by virtue of the magnesium mechanically expelled.

By reason of these changes, the T.O.P. of the smoke was increased from 1,250 to 1,400 and the smoke had far better hanging properties, was not as easily disturbed by air currents, and did not dissipate as rapidly.

In order to give a quick puff of smoke at the beginning of the reaction, when the standard B.M. Mixture was just starting to burn, a "fast" mixture was employed, having the following composition:

	Per Cent, by Weight
Zinc (dust)	30.2
Carbon tetrachloride	35.1
Sodium chlorate	24.9
Zinc oxide	9.8

This burns much more rapidly than the standard mixture, as ammonium chloride and magnesium carbonate are absent and the zinc oxide acts as the absorbent.

B.M. Mixture was employed in smoke candles, grenades, and floating boxes for naval use. These devices, in addition to the standard and fast B.M. smoke mixture, also contained two starting mixtures, as follows:

Starting Mixture 1 served to start the reaction and was of the following composition:

	Per Cent, by Weight
Powdered sulfur	20.7
Zinc (dust)	63.1
Zinc oxide	16.2

Starting Mixture 2 received the flash from the igniting match head, served to burn through the igniting cup, and ignited the Starting Mixture 1. It consisted of:

	Per Cent, by Weight
Powdered iron (reduced)	46.6
Potassium permanganate	53.4

As compared to the British smoke mixture, the B.M. smoke mixture had certain definite advantages. It burned more uniformly and freely, left a much smaller residue, and the smoke had better hanging properties and greater persistency. Moreover the T.O.P. of the B.M. smoke was 1,400 as compared to 460 for the British Type S smoke mixture. Its disadvantages were: (1) absorbents that constituted about 25 per cent of inert material; and (2) the necessity for an absolutely airtight container to prevent the evaporation of carbon tetrachloride. Nevertheless, the B.M. Mixture was the most efficient smoke producer of this type developed during the war.

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HC Mixture ($Zn + C_2Cl_6 + ZnO$)

Since the war efforts have continued in America to produce a better zinc-smoke producer by improving the B.M. Mixture.

Solid hexachlorethane (C_2Cl_6) was substituted for and found to be much superior to carbon tetrachloride. It proved to be an equally good source of chlorine and, being itself a solid, eliminated the necessity for an inert filler such as magnesium carbonate.

As an absorbent in place of sodium chlorate and ammonia chloride, zinc oxide was substituted.

The new mixture, used in smoke candles HC, MI, contained the following constitutents:

	Per Cent, by Weight
Zinc (dust)	28
Hexachlorethane	50
Zinc oxide	22

This mixture was ignited by a starting mixture composed of:

	Per Cent, by Weight
Antimony	76.4
Zinc (dust)	11.8
Potassium perchlorate	11.8

The original HC smoke mixture, as a result of continued development and improvement, has evolved to the following composition used in smoke candles HC, MII:

	Per cent	
	Fast mixture	Slow mixture

Zinc (dust)	36	36
Hexachlorethane	43	44
Ammonium perchlorate	15	10
Ammonium chloride	6	10

The filling of this smoke candle consists of about nine-tenths slow-burning mixture and one-tenth fast-burning mixture. The fast-burning mixture is placed as a layer over the slow-burning mixture and is ignited by a starting mixture consisting of:

	Per Cent, by Weight
Potassium nitrate	42
Antimony trisulfide	26
Ferrous sulfide	26
Dextrin	6

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The chemical reaction in the HC Mixture is as follows:

$$3Zn + C_2Cl_6 = 3ZnCl_2 + 2C$$

The ignition and burning processes are similar to those of the B.M. Mixture, but the reaction is less violent and no delaying agents are necessary. The mixture is also more stable and more efficient per unit weight than the B.M. Mixture.

This HC Mixture, MII, is now the standard smoke producer for smoke candles and pots in the United States Army. It requires only 0.12 oz. to produce 1,000 cu. ft. of *standard smoke* and represents the most advanced development of the zinc-smoke type of smoke agents.

COMPARISON OF SMOKE AGENTS

On the basis of total obscuring power (T.O.P.), the smoke agents discussed above, as well as other substances that have been used since the War for producing smoke, are arranged below in the descending order of their T.O.P.'s.

White phosphorus	4,600
Titanium tetrachloride and ammonia	3,030
Sulfur trioxide	3,000
Sulfur trioxide and chlorsulfonic acid (FS)	2,550
Hydrochloric acid and ammonia	2,500
HC Mixture	2,100
Silicon tetrachloride and ammonia	1,960
Titanium tetrachloride (FM)	1,900
Oleum*	1,890
Tin tetrachloride (KJ)	1,860
Phosphorus trichloride and ammonia	1,800
Chlorsulfonic acid and ammonia	1,600
Silicon tetrachloride	1,500
Sulfur chloride and ammonia	1,425
Chlorsulfonic acid*	1,400
B.M. Mixture	1,400
Berger Mixture	1,250
Titanium tetrachloride and ethylene dichloride	1,235
Sulfuryl chloride	1,200
Chlorine and ammonia	750
Arsenic trichloride	460
Type S mixture	460
Crude oil	200

* Heating to 450°F. increases T.O.P.'s from 30 to 50 per cent.

In comparing the T.O.P.'s for different smokes, the rate of burning must be considered, since a slow-burning smoke may not reach its maximum density before its particles begin to settle out. Humidity and temperature also have an important influence on the T.O.P.'s of many chemical smokes. The values given above are for average conditions of

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temperature and humidity and may vary greatly with variations of either or both.

FUTURE OF SMOKE AGENTS

During the World War obscuring smoke proved its tactical value on land and sea and won for itself an assured place as a military weapon. Since the war the development of air forces has still further enhanced the value of obscuring smoke, for not only are airplanes a means par excellence for putting down smoke screens on the field of battle, but their power of observation has greatly increased the need for obscuration. So greatly has aircraft increased the facility of observing enemy dispositions and maneuvers and of attacking troops in march and other concentrated formations, that it has become increasingly necessary to find some means of concealing and protecting ground troops from air observation and attack. Obscuring smoke is a most effective means for this purpose.

All nations are impressed with the importance of obscuring smoke and are busily engaged in developing the superior smoke agents and in devising technical means of employing them. The rapid strides made in this direction during and since the World War plainly indicate the possibilities of this field.

Detailed data concerning the most important smoke agents are presented in Table IV. The technical apparatus for producing smoke and the tactical principles involved in its use are treated in Chap. XIV.

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CHAPTER XII

INCENDIARY AGENTS

CLASSIFICATION

Incendiaries, the third member of the chemical arm, are substances used to set fire to enemy material in the Theater of War. Unlike gas and smoke, which are directed against personnel and are used chiefly on the field of battle, incendiaries are directed primarily against material, and their employment is not limited to the battle front, but extends to targets anywhere in the Theater of War that can be reached by bombing airplanes. Incendiaries may also be used to a limited extent against personnel, as in the World War, when air-burst trench-mortar shell, filled with phosphorus and thermite, were fired against enemy machine gunners sheltered from rifle and machine-gun fire.

Tactically, we distinguish two types of incendiaries: (1) the intensive type, where the heat and flames are concentrated in a limited space, in order to set fire to heavy construction and targets generally difficult to ignite; (2) the scatter type, where the incendiary materials are scattered in a number of small burning masses over a relatively large area, in order to initiate fires at a number of points simultaneously in large targets of inflammable or easily ignited materials. Another convenient tactical classification of incendiaries is by the using arm, thus:

Using Arm	Munition
Infantry	Small-arms incendiary bullets Incendiary grenades and other hand devices
Chemical troops	Chemical-mortar incendiary projectiles Livens projector incendiary drums Flame projectors
Artillery	Incendiary shell
Air force	Incendiary aircraft bombs

Technically, we distinguish four classes of incendiaries, as follows:

1. Spontaneously inflammable materials.
   a. *Solids*, such as phosphorus and sodium.
   b. *Liquids*, such as phosphorus dissolved in carbon bisulfide and zinc ethyl.
2. Metallic oxides, such as thermite.
3. Oxidizing combustible mixtures, such as barium peroxide and magnesium powder, or barium nitrate, magnesium, and linseed oil.
4. Flammable materials, used as such, *e.g.*, resins, pitch, celluloid, "solid oil," and flammable liquids and oil.

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HISTORICAL

Unlike gas and smoke, the systematic use of incendiaries in warfare is not modern, but extends back into ancient times. The early use of incendiaries in combat is easily understood when it is remembered that, from the earliest times, fire has been the most ruthless enemy of mankind, and its application to war is but further evidence of the universal dread of the Great Destroyer which has come down through the ages.

The idea of using incendiaries in battle dates back to early Biblical times when armies attacking and defending fortified cities threw upon each other burning oils and flaming fire balls consisting of resin and straw. The first flame projector was used at Delium in 424 B.C. It consisted of a hollow tree trunk to the lower end of which was attached a basin filled with glowing coals, sulfur, and pitch. A bellows blew the flame from the tree trunk in the form of a jet, setting fire to the enemy fortifications and aiding the besiegers in the capture of the city.

The next recorded use of incendiaries was by the Trojan king, Æneas,

about 360 B.C. He made use of fire compositions consisting of pitch, sulfur, tow, resinous wood, and other highly inflammable substances which were easily ignited and hard to extinguish. The incendiary composition was poured burning into pots, which were fired from the walls of besieged cities upon the attacking troops below.

Somewhat later the Romans hurled from catapults crude iron latticework bombs, about 2 ft. in diameter, filled with highly inflammable materials. These were ignited and thrown as flaming projectiles upon the enemy fortifications. Later, incendiary arrows came into use as a means of setting fire to the wooden forts sheltering the enemy. These incendiary arrows were subsequently enlarged and shot from catapults. Behind the arrowhead they carried a perforated tube containing a mixture of tow, resin, sulfur, and petroleum, which was ignited just before being shot.

The greatest impetus to the use of incendiaries in war came with the introduction of "Greek Fire," which was said to have been invented by the Syrian, Callinicus, about the year 660 A.D., although there is evidence of the use of similar materials as early as the time of Constantine the Great, in the fourth century A.D. The exact formula for "Greek Fire" has never been definitely established. The process for making it was kept a secret for several centuries and no detailed information as to its composition seems to have survived. It is certainly known to have contained readily inflammable substances such as pitch, resin, and petroleum, as well as quicklime and sulfur. The quicklime, on contact with water, generated sufficient heat to ignite the petroleum, the burning of which ignited the other combustible materials. The light vapors from the petroleum caused explosions which still further spread the flames.

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It was difficult to extinguish "Greek Fire" because water increased the reaction of the quicklime and spread the petroleum. The troops of the Byzantine Empire made such effective use of "Greek Fire" against the Saracens that it is frequently said to have saved the empire from Mohammedan domination for nearly a thousand years. At any event, "Greek Fire" was extensively employed in the wars of the Middle Ages, and its use survived until the introduction of gunpowder in the fifteenth century.

From the beginning of modern times down to the World War, incendiaries were not extensively employed, as the introduction of firearms caused armies to engage in battle at such distances that they could not be effectively reached by incendiaries. Moreover, the defensive use of armor and later of earthworks left little of combustible material on the field of battle. So formidable were the technical difficulties created by these new conditions that the successful use of incendiaries in war remained an unsolved problem until the advent of the World War, when the vast resources of modern science were utilized to effect a solution. So, while fire has been considered of military value from antiquity, means for scientifically using it in warfare were not developed until the World War.

The effectiveness of incendiaries in war is dependent upon the character of the materials employed and upon the devices used for carrying them to the target and setting them in action there. Because of the generally adverse conditions of modern warfare, the development of successful incendiary armament involves chemical and mechanical problems of great complexity, as will be appreciated from the consideration of the many rigid technical and tactical requirements which must be met. At the same time, the introduction of the military airplane has greatly increased the field of application of incendiaries, as it is now possible by such means to reach large and vulnerable incendiary targets at practically any point in the Theater of War. This was exemplified in the German air raids on Paris and London in 1915, in which incendiary bombs were frequently employed.

Although the French and Germans both had developed incendiary artillery shell before the World War, one French model dating back to 1878, such shell were not used to any extent in the early days of the war, probably because they were largely ineffective. The earliest incendiary munitions used in the war appear to be incendiary bullets and antiaircraft artillery shell directed against observation balloons.

The first incendiary attacks against ground troops were by means of flame projectors. These devices were invented by the Germans before the war (20, page 7) but do not appear to have been used until 1915.

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General Foulkes says that the Germans used their *Flammenwerfer* (flame projectors) on the French front on June 25, 1915, but it is probable that their first use was several months earlier, for it is known that the Germans had an organized detachment of *Flammenwerfer* troops as early as January, 1915, and the French made a formal protest against the use of these devices under date of Apr. 29, 1915.

The initial use of incendiaries from aircraft occurred during the first German Zeppelin raid over London on May 31, 1915, during which one airship dropped 90 incendiary bombs.

By the end of 1915, improved types of incendiary artillery shell were in use by both sides. These were soon followed by the introduction of incendiary grenades, trench-mortar shell, and projector bombs. Throughout the war, all the principal belligerents engaged in the energetic development of incendiary armament and much progress was made in improving all types of incendiary munitions, particularly aviation drop bombs.

SUBSTANCES USED AS INCENDIARY AGENTS

GROUP I. SPONTANEOUSLY INFLAMMABLE MATERIALS

Solids

Phosphorus (P)

American and British: "W.P."

While white phosphorus is primarily a smoke producer, its property of igniting spontaneously and burning vigorously when exposed to the air made it one of the first materials proposed for incendiary munitions. Experience showed that against readily combustible materials and substances which can be ignited by a brief exposure to a small flame, phosphorus is undoubtedly effective, and it was therefore the principal incendiary agent used against balloons and aircraft and for setting fire to woods, grain fields, etc. However, against wooden structures and materials relatively difficult to ignite, phosphorus proved of little value, principally because of its low temperature of combustion and the excellent fireproof protection of the phosphoric oxides formed by burning phosphorus.

In addition to its incendiary effect on material, phosphorus proved very effective in use against personnel. When scattered from overhead bursts of grenades and trench-mortar bombs, the phosphorus rained down in flaming particles, which stuck to clothing and could not be brushed off or quenched. The larger particles quickly burned through clothing and produced painful burns that were slow and difficult to heal. These properties soon became known to troops and phosphorus was justly

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dreaded and always caused a demoralizing effect far beyond the actual casualties produced.

During the war, phosphorus was extensively used in small-arms incendiary bullets and in hand and rifle grenades by all the principal belligerents; in artillery incendiary shell by the French and Germans; and in trench-mortar bombs by the British and Americans. In all munitions, except small-arms bullets, the phosphorus produced both obscuring smoke and incendiary effects and they were, therefore, variously classified as either smoke or incendiary projectiles. The physical and chemical properties of phosphorus are given in Chap. XI, page 234.

Sodium (Na)

Sodium is a light soft ductile metal of 0.97 specific gravity, which melts at 97.6°C. (208°F.) and boils at 750°C. (1382°F.). It is obtained by the electrolysis of molten sodium chloride (common salt). On contact with water, sodium decomposes it with vigorous evolution of hydrogen. The heat of reaction is sufficient to ignite the hydrogen and, hence, in the presence of moisture, sodium is spontaneously inflammable.

Sodium was used as a filling for the German 17.5-cm. incendiary shell. In that shell, which was the largest incendiary shell used during the war, the sodium was ignited by thermite. Sodium was also used in some of the spontaneously inflammable liquids of the World War to ignite the mixture on contact with water. Except for this latter use, sodium was not an effective incendiary material, as it required considerable moisture to

ignite it, which generally prevented the ignition of other materials.

Liquids

As liquids generally give better and more uniform dispersion on explosion of the container, and also have a tendency to adhere and penetrate into combustible materials, with greater chance of igniting them, they are preferred to solids as incendiary agents. Also, since spontaneously inflammable substances require no igniting device and initiate fires in several places simultaneously, a *spontaneously inflammable liquid* was sought which would: (1) ignite after short exposure to the atmosphere; (2) have a positive and effective incendiary action; and (3) be safe to transport and handle.

As phosphorus was spontaneously inflammable and was also readily soluble in carbon disulfide, this mixture was among the first spontaneously inflammable liquids tried out. It failed, however, to meet requirements in a number of particulars. First, it was no more effective as an incendiary agent than the phosphorus it contained, and therefore, had the disadvantages mentioned for phosphorus. It was also dangerous to

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transport and handle and was so volatile that it frequently burned out before heating the contacting material to the ignition point.

To correct the deficiencies of the phosphorus–carbon disulfide solution, mixtures were made by adding various combustible oils in such proportions that a homogenous mass was secured and no separation of any of the constituents occurred. It was then found that these mixtures lacked intensity of combustion, so various nitrated organic compounds were added to accelerate the reaction. Of these compounds, trinitrotoluene (TNT) was found to be the most satisfactory. As a final result of this research, a mixture containing phosphorus, carbon disulfide, crude benzene, fuel oil, gas-tar oil, and trinitrotoluene was developed. This was found to be satisfactory from the standpoints of simplicity of preparation, safety, and effectiveness; also, by varying the proportions of the ingredients, the ignition could be regulated to occur either almost instantly upon exposure to the air, or after a considerable delay.

The speed and spread of combustion of the mixture are secured by its readily volatile constituents, and the duration and intensity of the flame, by its heavier combustibles. With proper precautions, the preparation and handling of the mixture can be done without danger of accidental ignition. Also, it is not subject to detonation by shock, and its low coefficient of expansion (0.0174 per degree centigrade) and low vapor pressure (58 cm. at 50°C.) will not cause undue pressure in the container. The mixture may be used alone or with an absorbent, (*e.g.*, cotton waste) in any sort of device designed to carry liquid material, such as 8-in. Livens projectiles.

In the course of the research on spontaneously inflammable liquids, many substances, such as zinc ethyl, phosphine, silicine, chromyl chloride, fuming nitric acid, permanganates, and phosphorus, were fully investigated. In the end, it was found that phosphorus–carbon disulfide solution was the best material to initiate the fire, and the fuel and tar oils were the best materials to propagate and sustain the flames. While the problem of spontaneously inflammable liquids was considered reasonably solved during the World War, the solution was not effected in time for use on the field of battle, at least insofar as American munitions were concerned. There is, however, no reason to believe that the solution indicated above would not be satisfactory in war.

A satisfactory spontaneously inflammable liquid has a great field of application from aircraft, for not only should drop bombs filled with such a liquid prove very effective on targets, and even on cities of light wooden construction, but by regulating the ignition to occur after the lapse of sufficient time for the liquid to reach the target, such a liquid could also be sprayed at night from low-flying attack planes over relatively large areas with tremendous effectiveness.

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Group II. Metallic Oxides

Thermite

For several years prior to the late war, a mixture of iron oxide and finely divided aluminum, known under the proprietary name of "Thermite," was used in industry for welding iron and steel. When ignited, this mixture reacts as follows:

$$8Al + 3Fe_3O_4 = 4Al_2O_3 + 9Fe$$

and produces an enormous heat (758,000 calories per gram molecule). This heat is sufficient to raise the temperature of the reaction to about 3,000°C., and the resulting molten slag prolongs the heating effect after the reaction ceases. However, when thermite is used alone, it has the disadvantage that its incendiary action is confined to a small area, and a very large percentage of its heat energy is wasted because of the fact that it is set free so rapidly. Against readily ignitable material which allows the conflagration to spread easily, thermite is very effective, but as such material is not often present in a target, the method of placing it with the thermite in the incendiary device was early adopted.

For igniting and starting the conflagration, thermite proved to be by far the most effective material used in the war; for a secondary incendiary material to continue the conflagration, thermite was found to be inferior to an inflammable liquid, either used as such or incorporated in a suitable absorbent carrier, and to specially prepared combustible materials, such as *solid oil*, which burned with a large flame and effectively set fire to a difficultly ignitable target. By using thermite as a primary igniting incendiary agent, the large amount of heat suddenly released is utilized and the secondary material begins its action with a tremendous burst of flame which is most effective. The proper secondary incendiary material is capable of not only burning with a large hot flame, but actually renders the target inflammable.

The thermite used in industry is generally composed of three parts by weight of aluminum powder to ten parts of magnetic iron oxide, but for military purposes a mixture consisting of 24 per cent aluminum and 76 per cent by weight of magnetic iron oxide was found to be most suitable. Ordinary granulation produced the best results, but special limits had to be placed on purity of materials, presence of moisture, and foreign substances.

As commercial thermite is simply a loose mixture of aluminum dust and coarse particles of iron oxide—materials of quite different densities—it could not be used in military devices that must withstand severe jarring, without some means of preventing segregation. To prevent segregation, the mixture may be either consolidated by pressure or bound

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together in a hard mass by such binding substances as sodium silicate, sulfur, and celluloid.

Segregation may be successfully prevented by compressing ordinary thermite under a pressure of 12,000 lb. per square inch, which doubles its density and holds the compressed mass together even when subject to severe jarring. However, this increase in density causes the ignition to become more difficult, makes the propagation of the reaction uncertain and increases the time of burning. Moreover, since the compressed thermite does not materially increase the incendiary effect over the same volume of thermite bound together with sodium silicate, the cost of obtaining the same results with compressed thermite is greater. For these reasons we did not adopt it for general military use and the British employed it only in their special flame mixture which contains barium nitrate.

On the other hand, the use of sodium silicate as a binder was found to give several advantages. Besides preventing segregation, it caused the thermite blocks to react completely regardless of the point of ignition, and the material so bound is insensitive to shock and shot and may, therefore, be utilized in high velocity projectiles and bombs. The optimum amount of sodium silicate (of 40°Bé.) was found to be 15 per cent by weight of thermite. The liquid silicate is simply mixed with the thermite which is then molded and baked until thoroughly dry. Because of its advantages, sodium (or potassium) silicate was generally used as a thermite binder by most of the nations in the World War.

In binding thermite with sodium silicate, it is very essential that all the water be driven out, and, because of the difficulty of completely drying the silicate-bound thermite, a number of other binders were tried. Sulfur was highly recommended as a binder, since a unit of weight of mixture made up according to the equation

$$8Al + 3Fe_3O_4 + 9S = 4Al_2O_3 + 9FeS$$

theoretically generates the same amount of heat as an equal weight of thermite containing no sulfur so that the binder does not reduce the heat efficiency of the mixture. However, in actual tests of incendiary value the sulfur-bound thermite did not show up well, owing to the fact that it burned with explosive violence and spattered as small drops over a considerable area, thus lessening its incendiary effect. Also, the molten products from the silicate-bound thermite were more effective in penetrating metal and prolonging incendiary action upon inflammable materials. Notwithstanding these drawbacks, the French used sulfur-bound thermite, which they called "Daisite," in an incendiary drop bomb in which the explosive property of the thermite was utilized to scatter the other incendiary materials in the bomb.

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Celluloid, dissolved in a suitable solvent, proved to be fairly successful as a binder, particularly where it was desired to get a long flame and uniform burn of the thermite. It was also used as an envelope for the incendiary units of scatter-type drop bombs, chiefly by the Germans. Various organic materials, such as resin, paraffin, and hard pitch, were also investigated as binders, but did not give satisfactory results.

For the ignition of thermite used in devices where it is not desired to scatter the contents, the commercial igniter, consisting of finely divided aluminum and barium peroxide mixed with a certain amount of coarse aluminum and black iron oxide, was found to be most satisfactory. This igniter has no explosive reaction and can be ignited by a black powder flash, although better results are obtained by the use of a "booster" charge composed of reduced iron and potassium nitrate pressed on top of it.

For the ignition of thermite in devices where it is desired to scatter the contents, an entirely different type of igniter is required. For this purpose, an igniter should react with such rapidity and explosive violence as to simultaneously ignite and scatter the reaction products and, at the same time, should be as safe as the slow igniter. The best World War solution of the quick igniter was the British "Ophorite" which consisted of an intimate mixture of 9 parts of magnesium powder to 13 parts of potassium perchlorate. Ophorite was much easier to ignite than the commercial igniter and was extensively used by the British and ourselves as an igniting and bursting charge for incendiary projectiles and also as an explosive in certain types of gas shell. Ophorite was, however, not altogether safe to manufacture and the British had several very serious explosions and fires in their manufacturing and loading plants during the war.

Modified Thermite

Since the general military requirements of a thermite mixture are that it should function properly under all conditions of use and that the reaction should produce the desired effects, and since it matters little what the reaction products are, it is obvious that the composition of the mixture may be varied greatly. A number of mixtures, in which copper, nickel, manganese, and lead oxides were used in place of iron oxide, were tested but were found to be no better for military purposes than the ordinary thermite mixture, although the Germans used, in certain early incendiary bombs, a mixture containing manganese dioxide and magnesium.

Later in the war, alumino-thermite mixtures, in which oxidizing agents other than the oxides were incorporated, were investigated, and a special flaming thermite was developed by the British and used in their "baby incendiary" bombs. This mixture consisted of:

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aluminum, powdered, 3 parts; barium nitrate, 6 parts; hammerscale (Fe_3O_4) 8 parts; and was compressed to half its original volume in the bombs.

Thermite mixtures containing oxidizing agents other than those necessary for the thermite reaction were also investigated but none were found to possess special merit for military purposes, and it was concluded after many tests that a simple mixture of magnetic iron oxide and aluminum was the most satisfactory for general military uses. Of all the incendiary materials adopted by the Allies, thermite was probably the most widely used. On the other hand, the Germans did not use thermite very extensively, although many German incendiary drop bombs and artillery shell contained thermite or an alumino-thermite mixture.

Group III. Oxidizing Combustible Mixtures

Incendiary mixtures which contain an *inorganic oxidizing agent*, such as potassium or barium nitrate, barium or lead oxide, or potassium perchlorate, together with such *combustible substances* as carbon, sulfur, magnesium, aluminum, or organic combustibles, are designated by the generic name of *oxidizing combustible mixtures*. Such mixtures have been used successfully in two widely different types of incendiary munitions, *viz.*: (1) small-arms incendiary bullets, and (2) drop bombs and other special devices.

For devices as different as bullets and drop bombs, it is evident that very different types of mixtures are required for most effective results. Thus, a mixture for use in bullets must meet very rigid requirements as to weight per unit volume, time of reaction, change of weight during reaction, and character of incendiary effect.

For bullets, the ballistic requirements are even more important than the incendiary requirements since the bullet must be capable of accurate flight in order to reach the desired target and have any effect at all. On the other hand, the type of mixture desired for drop bombs must react to give considerable heat and flame when the bomb bursts.

In both types of munitions, it is, of course, important that the mixtures do not segregate, and this is accomplished either by compression or by binding the mass with some substance, such as sulfur, shellac, resin, pitch, paraffin, gum, etc., and then heating or compressing.

The following typical mixtures have been used with success in small-arms incendiary ammunition:

	Parts, by Weight
Barium peroxide	17
Magnesium (powder)	2

The magnesium powder mixed with alcohol is pressed into the bullets under a pressure of 2,500 lb., and is ignited by the propellant.

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Red lead	9
Magnesium	1

or

Red lead	15
Aluminum	1

Compressed into the shell under a pressure of 15 tons per sq. in. and ignited by a primer consisting of

Potassium nitrate	65
Sulfur	13.5
Antimony (powder)	19
Shellac (powder)	2.5

Another typical mixture comprising a different type of oxidizing agent, is

Barium nitrate	64
Magnesium	28
Linseed oil	8

The linseed oil acts as a binder and deterrent.

For use in projectiles where the tracing effect is important, a considerable number of the so-called *pyrotechnic mixtures* have been used. These give upon ignition a large amount of smoke and a very brilliant light, but have little or no real incendiary effect. These mixtures should, therefore, not be registered as true incendiaries.

The use of oxidizing combustible mixtures in drop bombs and other relatively large incendiary devices was less successful than in small-arms ammunition. Such mixtures were used early in the war in incendiary artillery shell and in drop bombs, but in many cases were later discarded for the thermite-type mixtures. As a primary incendiary material whose chief function was to ignite other materials in drop bombs, the following mixture was used:

	Parts, by Weight
Potassium perchlorate	80
Paraffin	20

For use in a small unit drop bomb designed to set fire to very inflammable targets, we developed a successful mixture consisting of the following ingredients:

Barium chlorate	54
Resin	16
Aluminum	14
Asphaltum varnish	16

This mixture was ignited by a mixture comprising reduced iron and potassium permanganate bound with paraffin.

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Another celebrated World War mixture of the oxidizing-combustible type was the so-called "Scheelite" consisting of one part hexamethylenetetramine and two parts of sodium peroxide. It was named for its inventor, a Dr. Scheele, who claimed he had destroyed the cargoes of 32 vessels by its use. Our experiments with this formula showed that when ignited by sulfuric acid it reacts very rapidly in the open and generates great heat and flames, but, if confined, it explodes. On the whole, it was found unsatisfactory for use in the larger incendiary devices, but a modified form has possibilities for use in certain small drop bombs.

Group IV. Flammable Materials (Used as such)

This group comprises those incendiary materials that are used as such without admixture of oxidizing agents and includes the following substances: petroleum oils, carbon disulfide, wood distillation products, resins, pitch, celluloid, and various sorts of flammable oils and liquids not spontaneously inflammable.

The two principal uses of this class of substances are: (1) as secondary incendiary materials to propagate and prolong the incendiary action of the primary material in the larger size drop bombs and projectiles; and (2) as liquids used in flame projectors.

In the development of the intensive-type incendiary drop bomb, intended to set fire to heavy wooden structures and other targets relatively difficult to ignite, it was early found that such devices should contain some quick-acting great-heat-producing material, such as thermite, and a larger amount of flammable material which, when ignited by the thermite, would burn with a large hot flame for a considerable time and actually render the target more inflammable.

For this purpose, various oxidizing combustible mixtures, resins and pitches, and heavy oils were tried and found unsatisfactory. Then flammable oils, absorbed in cotton or jute waste, were experimented with in the hope that the absorbents would prevent too rapid volatilization and burning of the oil, but were found to possess many disadvantages. Thus, if the mass were scattered by an explosion, the intensive incendiary action is lost; if it is allowed to burn without scattering, the absorbent material protects the target to a considerable extent. Mixtures of paraffin and light oils were also tested and found to have objectionable hydrostatic effects when used in drop bombs and projectiles.

Systematic research was then undertaken to find and develop a more nearly ideal incendiary material for drop bombs and projectiles that would meet the following requirements:

1. Burn for a considerable time with a very large hot flame.
2. Actually render very inflammable not only the combustible material upon which it rests, but the material around it for a considerable area.

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3. Contain practically no material which is not extremely inflammable or which would not aid in the combustion.
4. Present no great problems of manufacture, cost, transportation, or use.

Solid Oil

As a result of an extensive investigation of materials which would meet the foregoing requirements, it was found that the oils possessed the most desirable incendiary properties and their only drawback was their liquid state. To correct this defect, experiments were made to solidify satisfactory oil mixtures by the use of colloidal substances, and after considerable investigation a process was developed whereby a permanent solidified oil mixture, meeting all requirements, could be prepared simply and cheaply. This solidified mixture—called *solid oil*—contained a small percentage of liquid, having a relatively low fire point and a large percentage of a liquid having a moderately high fire point. Such a mixture burns readily, owing to the liquid of low fire point, and the burning of this liquid generates the necessary heat to melt and ignite the material of higher fire point which spreads over a large area, penetrates contacting material, and actually renders it inflammable. Best results were obtained from distillate fuel oils with a range of fire points of from 170° to 225°C.

The raw materials entering into the manufacture of solid oil were readily obtainable and its preparation and filling into 50 drops bombs presented no difficulties.

Solid oil is also suitable for use in other large incendiary devices, such as Livens projector drums, artillery shell, and trench-mortar bombs.

Flame-projector Liquids

For use in flame projectors, the principal requirements of a liquid mixture are: (1) it must be readily and easily ignited; (2) it must not have too low a specific gravity; and (3) combustion should not occur to any material extent until the stream has reached its objective, since the desired object is to throw upon the target an *ignited liquid* and not merely a flame.

After an extended investigation of liquid mixtures for use in American flame projectors, it was found that the most satisfactory mixture consisted of a heavy viscuous oil or tar and a more fluid and flammable liquid. For the heavy component, water-gas tar (sp. gr. 1.044 and flash point 122°C.) proved to be the most satisfactory. For the light component, benzene heads (sp. gr. 0.756 and flash point 26°C.) or crude benzene were best. The optimum proportions were found to be 70 per cent water-gas tar and 30 per cent benzene heads, resulting in a liquid of 1.02 specific gravity, which gave an excellent trajectory, good range, and fierce flame. Ignition was effected by means of a hydrogen pilot lamp at the

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nozzle which has the advantage of being nonluminous when not in action and positive ignition when needed. Approximately 30 per cent of this mixture remains unburned at the end of the trajectory, and a jet shooting 0.5 gal. can be thrown approximately 100 ft.

Other nations in the World War used various combinations of the most readily available heavy and light liquids, mostly petroleum distillates and coal-tar fractions, having an average specific gravity of about 0.90 at 15°C. They also used many methods of ignition, such as cartridges of slow-burning oxidizing combustible mixtures attached to the nozzle and ignited by electricity or friction.

INCENDIARY WEAPONS

A description of the construction and use of the various devices in which incendiary agents were employed in the World War is given in subsequent chapters in connection with the material pertaining to the several combat arms.

FUTURE OF INCENDIARIES

Modern warfare has left little on the field of battle that is combustible; hence suitable targets and opportunities for the use of incendiaries in the Combat Zone are very limited and will become increasingly so as armies are mechanized. On the other hand, the military airplane has opened up a vastly larger field of application for incendiaries in the areas behind the battle front and in the hinterlands of the belligerents. To an ever-increasing degree the successful waging of modern war depends upon the industrial organization of a nation to meet the enormous demands for military material. It is, therefore, not at all unlikely that in wars of the future military operations will be carried far into the interior territory of each belligerent in an effort to cripple and destroy the industries upon which modern armies depend. In the attack upon industrial centers and upon military concentration areas in the rear of armies, incendiaries will play a large and useful role.

The vast amount of research and development work on incendiaries in the World War went far toward solving the many and formidable technical problems created by the adverse conditions of modern warfare, and it may be said that, insofar as concerns the technical efficiency of the agents themselves, incendiary armament had reached a generally satisfactory state of performance. On the other hand, the tactical results from use of incendiaries in the late war were disappointing. This was chiefly due to two factors. First, the conditions on the Western Front and, to a somewhat less extent, on the Russian Front, were naturally very unfavorable to the use of incendiaries. Not only was the weather and much of the terrain wet and adverse to application of incendiaries,

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but also the greater part of the possible targets were of masonry and other combustibly inert construction that afforded little or no chance for the successful use of incendiary agents.

In addition to these adverse conditions, many of the most effective incendiary devices were not perfected in time to be used in the war, and hence there was no opportunity to determine their real military value in that great conflict.

Since the World War, there has been little published concerning the development of incendiary armament. There is little doubt, however, that the use of those types of incendiary munitions which proved effective in the last war will be resumed in future wars. In fact it is not unlikely that with more efficient incendiary materials and devices these munitions will assume increased importance.

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CHAPTER XIV

CHEMICAL TECHNIQUE AND TACTICS OF INFANTRY

TECHNIQUE

In considering the chemical technique and tactics of the several arms, we shall follow the organization of the Theater of Operations for chemical warfare, as presented in Chap. III, Diagram I, and discuss the chemical technique and tactics of each arm in the order of its proximity to the battle front of an army.

In connection with the normal chemical-warfare zones of operation, shown in Diagram I of Chap. III, it should be borne in mind that these zones are not rigidly delimited, nor are they even mutually exclusive. They are merely the zones in which the chemical-warfare activities of each arm may be most effectively and efficiently carried on, under average conditions. It will also be noted that some of the zones overlap. This indicates that chemical operations may be carried on conjointly by one arm to cover a zone normally assigned another arm, as for example, when no chemical troops are available the artillery carries out chemical missions in the zone usually covered by chemical troops.

Since infantry normally constitutes the front-line elements of an army, it is the arm chiefly concerned with chemical operations along the *immediate* battle front, particularly where such operations are for its own protection. We shall, accordingly, begin our consideration of the chemical technique and tactics of the several arms with a discussion of the chemical technique and tactics of infantry.

Chemical Armament of Infantry

Chemicals are used by infantry in the following munitions:

1. Chemical grenades { Gas grenades. / Smoke grenades. / Incendiary grenades.
2. Smoke candles and pots.
3. Infantry-mortar smoke shells.
4. Smoke generators on tanks.
5. Miscellaneous smoke devices.

Chemical Grenades—Gas

The grenade is a form of ammunition which came into extensive use during the late war, largely as a result of the requirements of trench warfare. Within certain limitations, the grenade is a convenient type of

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ammunition to enable infantry to augment their primary weapons with a small missile similar, in general, to a shell or bomb. Grenades are classified according to the method of their projection, as:

1. Hand grenades.
2. Rifle grenades.
3. Combination hand-and-rifle grenades.

A chemical grenade is a grenade that is filled with a chemical agent, *i.e.*, a gas, smoke, or incendiary, dispersed by an igniting or exploding device, and thrown by hand or fired from a rifle.

Chemical warfare first made its appearance in the World War through the use of gas grenades. According to Hanslian, these earliest chemical weapons were in the form of 26-mm. rifle grenades, containing 19 cc. of tear gas (bromacetone), while Haber states that apparently at the same time (August, 1914), gas *hand* grenades, with the same kind of filling, were also used. These grenades were stated to be for use in attacking enfilading works, casemates, and passages of permanent field fortifications into which they could be shot through the narrow slits of the embrasures. As these grenades held such a small amount of gas, they were effective only in closed places and, since the first few months' fighting in the World War was almost altogether open warfare, they were not effective and were soon discarded.

In the second year of the war, after gas had been used on a large scale in cloud attacks and from artillery and trench-mortar projectiles, gas grenades, filled with more powerful gases, again made their appearance and continued to be used on both sides intermittently throughout the remainder of the war. Even with more powerful gases, gas grenades were never effective in the open and were used chiefly for raids during the period of trench warfare.

The following are the principal gas grenades used during the war:

Nation	Type	Chemical filling
German	Ball, glass, hand	Bromine; later FS; later BA
	Ball, Red B, hand	Bromomethylethyl ketone
	Ball, Red C, hand	Methylsulfuryl chloride and 5 per cent dimethyl sulfate
	Stick, Blue C, hand	DA and HE
French	26-mm., rifle	BA and chloracetone
	6-cm., egg-shaped, hand	BA and chloracetone
	Suffocating and lacrimatory Mle. 1916, hand	Acrolein
British	Hand	Ethyliodoacetate
	No. 28, hand, Mk-I	Stannic chloride
	No. 26, hand, Mk-II	Stannic chloride and PS
United States	Gas, hand, Mk-II	Stannic chloride

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United States Gas Hand Grenade, M-II (Fig. 10).—This grenade, which is typical of all the World War gas grenades, consisted of a sheet-steel body, steel bushing, detonator thimble, detonator, and automatic firing mechanism (*bouchon*), as shown in Fig. 10.

In throwing the grenade, it was first held firmly in the right hand with the firing mechanism up, in such a manner as to secure the lever. The safety pin was then pulled with the index finger of the left hand. The grenade was then armed. After it was thrown, the lever, which was no longer held by the safety pin, was thrown off and the striker pin, impelled by a strong spring, rotated around its hinge pin and struck the primer, first perforating the tinfoil disk which was sealed over the top of the cap to waterproof the primer. The end of the fuse was tipped by a priming

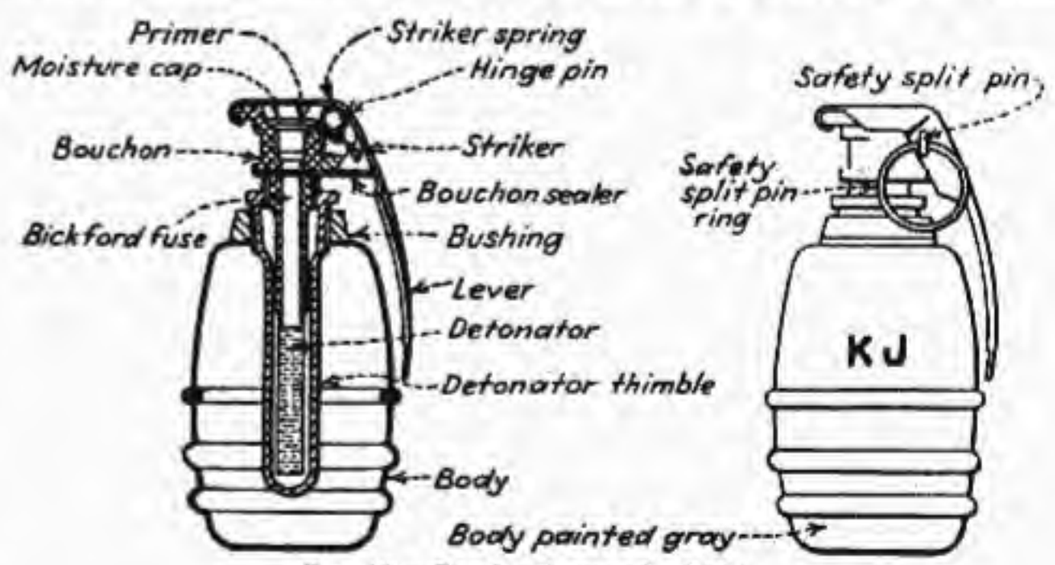

FIG. 10.—Gas hand grenade, M-II.

powder composition which ignited the primer and in turn the fuse. In 5 seconds the flame from the fuse exploded the detonator, which burst the grenade with sufficient force to scatter the chemical filling in fine droplets. The gas cloud produced was intensely irritating to the eyes and respiratory passages and caused lacrimation and violent coughing.

Postwar Development.—Since the late war several types of gas grenades have been developed in this country. The early postwar types utilized the grenade bodies manufactured during the war and were filled with CN, the American standard lacrimatory filling. These grenades were found to be unsatisfactory because of the small amount of chemical

filling that could be loaded into the grenade body. To overcome this defect, the grenade body was redesigned to increase its capacity without making it too large or heavy to be thrown by hand. As a result of postwar development, two types of gas grenades have been developed and adopted as standard for the United States Army. These are known as:

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1. Grenade, hand, tear (CN), M-7.
2. Grenade, hand, irritant (CN-DM), M-6.

United States Standard Tear-gas Grenade.—The standard *tear-gas* grenade (CN), M-7, consists of the container, igniting fuse, and filling (see Fig. 11). The container is a tin cylinder 2⅜ in. in diameter and 4½ in. high. Two thin disks are crimped and soldered to the wall forming the top and bottom of the container. The top has a ¾-in. hole punched in its center into which is inserted and soldered an adapter. The latter is internally threaded to take the igniting fuse. Small holes are punched

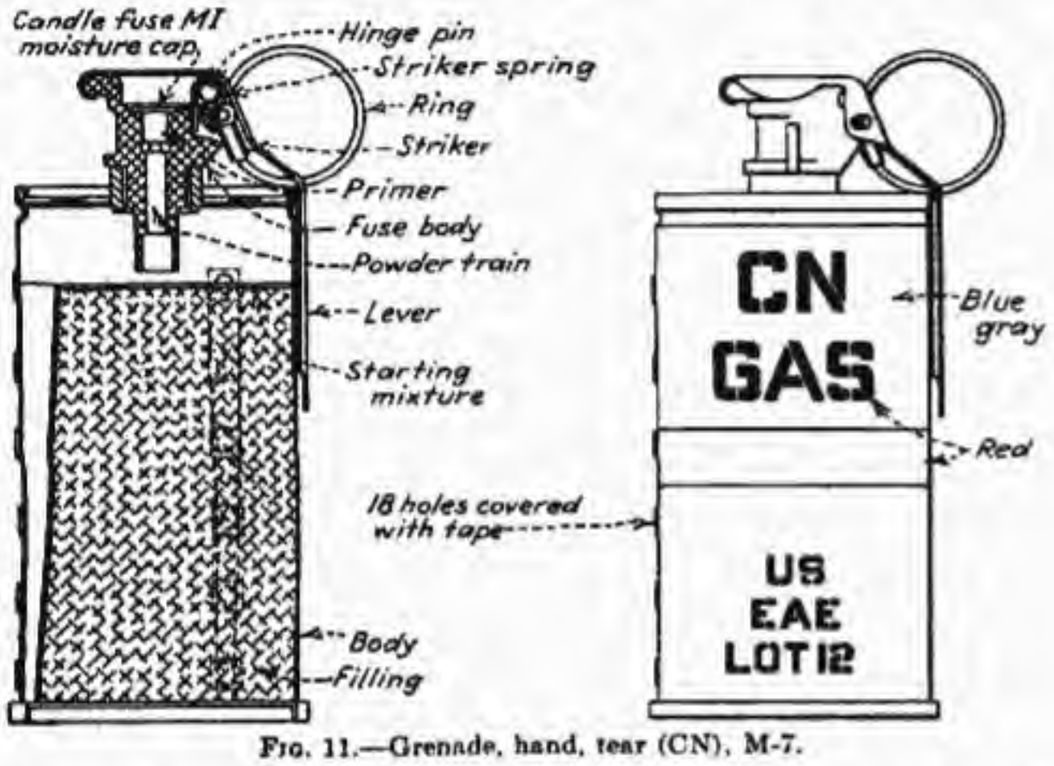

FIG. 11.—Grenade, hand, tear (CN), M-7.

in the top of the body around the adapter and, in the fast-burning type, in the wall of the container body. These are normally covered by small squares of adhesive tape.

The *fuse* consists of a fuse body which carries the firing mechanism and a 2-second fuse. The firing mechanism consists of a steel striker horizontally hinged on a steel hinge pin in a recess between the two wings of the fuse body and actuated by a steel-coil spring. A firing pin is attached to the striker. The striker is normally held away from the primer, against the tension of the spring, by a lever which forms a cover for the firing mechanism and extends downward over the top of the container. The lever hooks under a protruding lip of the fuse body and has two wings through which a split pin of annealed steel passes securing it to the body. This pin forms the safety device for the firing mechanism. The fuse assembly consists of a primer of fulminate of mercury and a

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2-second-delay powder train in a lightly sealed lead container projecting downward from the fuse body.

The *filling* is a solid or solidified mixture. A starting mixture of potassium nitrate, antimony trisulfide ferrous sulfide, and dextrine is placed on top of the agent.

Operation. *Throwing by Hand.*—When the safety pin has been pulled, the lever, held in the palm of the hand, acts as a deterrent to prevent contact between the striker and the primer. As the grenade leaves the hand, the striker, actuated by its spring, throws the lever clear and strikes the primer. The primer flashes the fuse which in 2 seconds' time ignites the starting mixture. The starting mixture generates the heat required to start the chemical reaction of the agent. The pressure, resulting from the combustion, forces the adhesive tape from the small emission holes and the agent from the container.

To Fire from a Stationary Point of Release.—Place grenade on ground and hold the lever firmly in position while withdrawing the safety pin. When ready to fire, release lever and move rapidly upwind for a distance of 5 yd. The functioning is the same as indicated above.

The following are the principal characteristics of the standard tear-gas grenade:

Weight filled	1 lb. (approximately)
Shape	Cylindrical
Color	Blue-gray
Safety device	Safety pin
Igniter	Fuse, igniting M-1 (a 2-second delay)
Filling	CN—10 oz. (mixture of chloracetophenone, oxide); a thin layer of starting mixture is placed on top of the filling
Identification	Red letters—CN Red word—Gas One red band
Characteristics of cloud	White to blue-gray to colorless vapor having a fruitlike pungent odor; an immediate lacrimatory effect on unprotected personnel; nontoxic except in extreme concentrations; practically no obscuring effect
Time of burning	25 to 40 seconds (comes to full volume within 5 seconds after firing); a small stream of vapor continues some 10 or 15 seconds longer.

United States Standard Irritant-gas Grenade.—The standard *irritant-gas* grenade (CN-DM), M-6, is identical with the standard tear-gas grenade (CN), M-7, except as to chemical filling. The irritant grenade contains a 50-50 mixture of CN and DM, instead of pure CN, as in the

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tear-gas grenade. It therefore has both the lacrimatory effect of CN and the irritant (sternutatory) effect of DM. The following are the principal characteristics of the irritant grenade:

Weight filled	1 lb. (approximately)
Shape	Cylindrical
Color	Blue-gray
Safety device	Safety pin
Igniter	Fuse, igniting M-I (a 2-second delay)
Filling	CN-DM, approximately 10 oz. (a mixture of chloracetophenone and diphenylaminechlorarsine and smokeless powder and magnesium iodide); a thin layer of starter mixture is placed on top of the filling
Identification	Red letters—CN/DM Red word—Gas One red band
Characteristics of cloud	Blue-gray to yellow in color, with a pungent fruitlike odor; the smell of smokeless powder is also apparent; the vapor has an immediate lacrimatory and nauseating effect on unprotected personnel and may cause sneezing and vomiting
Time of burning	25 to 40 seconds (candle comes to full volume in about 5 seconds after ignition)

CHEMICAL GRENADES—SMOKE

The principal smoke grenades used during the war were the following:

Nation	Type	Chemical filling
German	Ball (*Nebel*), hand	Chlorsulfonic acid
French	Incendiaire et Fumigène, Mle. 1916—Automatique, hand	Phosphorus (WP)
British	No. 27 Combination hand and rifle, M-I	Phosphorus (WP)
United States	Combination hand and rifle, M-I	Phosphorus (WP)
	Smoke, hand, M-II	Phosphorus (WP)

With the exception of the German, all the principal World War smoke grenades were filled with phosphorus. The American combination hand and rifle smoke grenade was identical with the British No. 27 smoke grenade, and these two were the only smoke grenades which could be projected with a rifle. The American hand smoke grenade was very similar to the combination hand-and-rifle smoke grenade, except that it had no base plate and rod.

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United States Combination Hand-and-rifle Grenade, M-II (Fig. 12.) This grenade consisted chiefly of the following parts: the body (and rod), the gaine, and the firing mechanism.

The body of the grenade, cylindrical in form, was about 3¾ in. long and 2¼ in. in diameter. It was made of tinned plate and was capped on either end with dished tinned-plate stampings somewhat heavier than the metal forming the body. To the lower cap, forming the base, was soldered a steel base plate approximately ¼ in. thick. This steel plate was tapped to receive a rod 15 in. long and of the proper diameter to fit the bore of the service rifle. The rod was used only when the grenade was projected with a rifle. The rods were issued detached from the grenades in the ratio of 60 per cent of the grenades.

FIG. 12.—Grenade, combination hand and rifle, W.P., line, complete, showing assembly.

To the upper cap, forming the cover of the body, was soldered a striker chamber, externally threaded to hold the firing mechanism. The gaine was inserted through the striker-chamber cover and was soldered to the former.

The primer rested on top of, and was held in place by, the striker chamber. The primer was crimped to the fuse, on the other end of which was crimped the detonator, the fuse and detonator extending into the gaine. The striker was held by a shear wire. Over the entire firing mechanism was placed a metal cover to prevent accidental discharge, the cover being held in place by means of a retaining pin and ring. A small hole was provided in the cover cap for filling. This was sealed with a disc of tin. The filling charge was about 0.90 lb. of white phosphorus.

When used as a *hand grenade*, the cap over the firing mechanism was removed after withdrawing the retaining pin. The striker was then struck against any solid object, as the heel of the boot, the butt of the gun, a rock, etc., and the grenade was thrown immediately after striking. The shock sheared the small restraining wire and the striker point fired the primer and started the fuse burning.

When used as a *rifle grenade*, the stem was attached by screwing it into the base plate of the grenade as far as it would go. The protecting cap was then removed, exposing the striker. A blank cartridge furnished for this purpose was next loaded into the rifle, after which the grenade

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rod was inserted into the muzzle of the rifle and pushed down as far as it would go. The butt of the gun was set against some solid object, such as the bottom of the trench, a sandbag, etc., and the elevation adjusted according to the range desired. Upon the discharge of the rifle, the setback sheared the small restraining wire, permitting the striker pin to impinge upon the primer and thus ignited the fuse which in 5 seconds fired the detonator.

The maximum range was obtained with the rifle held at 45 degrees. Shorter ranges could be had by either raising or lowering this elevation. Under favorable conditions, ranges up to 230 yd. were obtained.

Postwar Development of Smoke Grenades.—The phosphorus combination hand-and-rifle grenade was a very successful munition and was by far the most effective and useful chemical grenade in the late war. Because it was so satisfactory in the war, nothing has been done since to develop a more effective smoke grenade, and the World War type of combination hand-and-rifle smoke grenade remains today the most effective device of its kind.

Chemical Grenades—Incendiary

In addition to the phosphorus grenades mentioned above which, although primarily smoke devices, had considerable incendiary effect, there was also used in the war a special incendiary grenade which was called by the French, "Grenade-Incendiaire A Main, Mle. 1916—Cylindrique," and by the Americans, "Thermite Hand Grenade, MK-I." These two grenades were identical, the American grenade being copied directly from the French as the most successful device of its kind.

United States Thermite Hand Grenade, M-I (Fig. 13).—This grenade consisted of the following parts:

1. A cylindrical shell of tin plate to which the top and bottom were attached by crimping and soldering. In the cover was a hole into which was soldered a metallic ring, tapped to receive the firing mechanism.
2. A percussion cap provided with a Bickford fuse.
3. A charge of thermite.
4. A mixture of special ignition material.

The grenade body was approximately 5⅞ in. long and 2½ in. in diameter. The total weight of the charged grenade was about 1.65 lb.

To use the grenade, it was grasped firmly in one hand, and the cover cap was removed with the other hand. The striker was then forced in sharply by striking it a keen blow against a hard body such as the heel, a rock, the butt of the gun, etc., and the grenade was then immediately thrown or placed against the object to be burned. The percussion of the primer ignited the Bickford fuse. Its combustion required 5 seconds, after which the quick match was lighted. This, in turn, ignited the

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special igniting mixture. By reason of the delay and absence of explosion, the grenade could be placed by hand or thrown to a distance.

The thermite incendiary grenade was effective because of the intense heat of the molten material. It was placed by hand above the object to be burned and used principally for the destruction of noncombustible

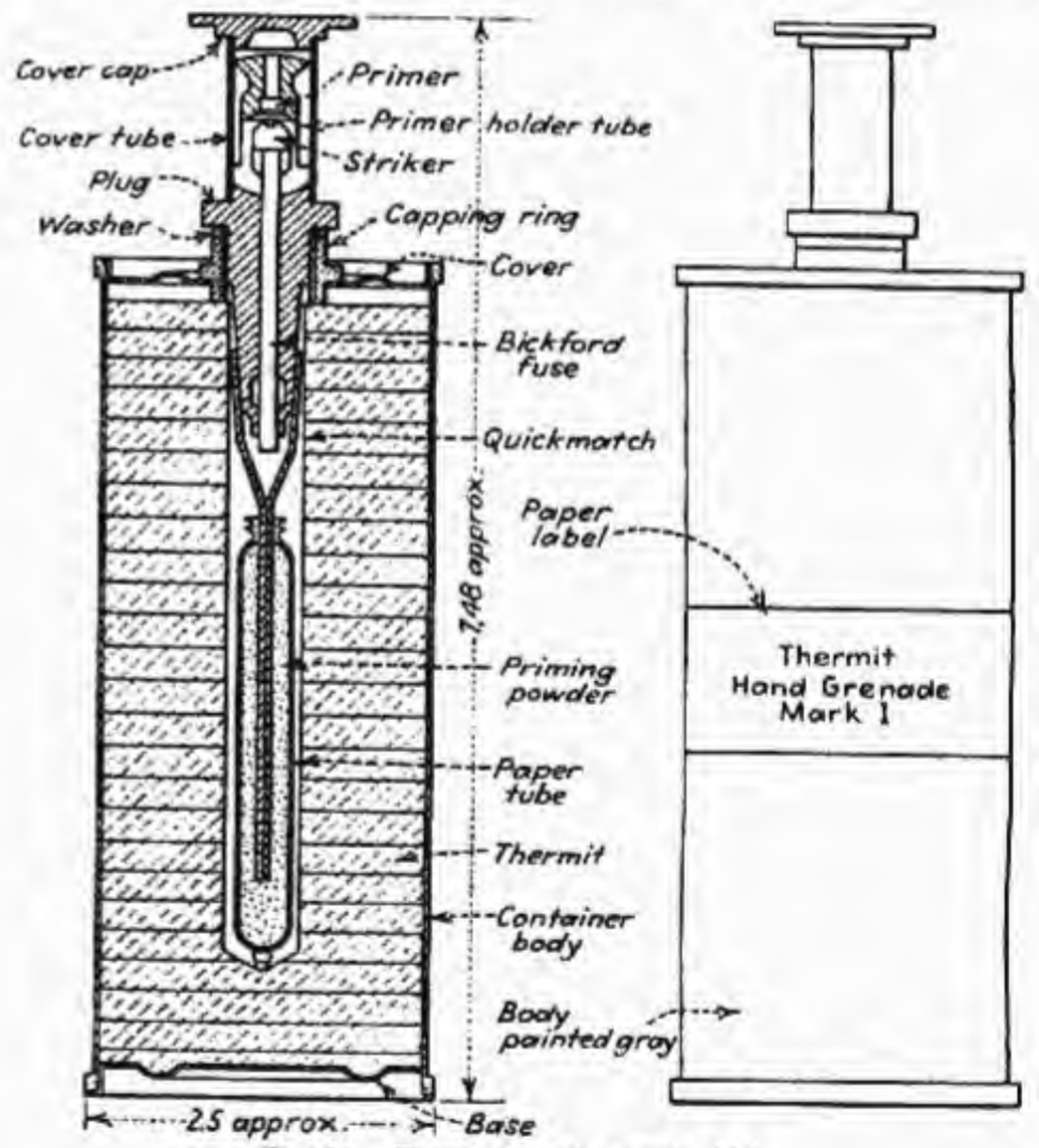

FIG. 13.—Thermite hand grenade, M-1.

material. It contained a thermite mixture which produced an exceedingly high temperature, the contents becoming a mass of white-hot molten metal.

Smoke Candles and Pots

Small portable nonmissile devices which produced smoke by progressive burning of a chemical filling were in the late war called *smoke candles*. If the device were of a larger size, not so readily portable, but producing a more enduring smoke cloud by longer burning, it was called a *smoke pot*.

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These devices were among the first smoke producers used in the war. They proved very effective for supplementing the gas operations of chemical troops and were later more extensively employed in screening

infantry operations.

Smoke candles were introduced by the British at the battle of Loos in September, 1915, being used by the British special gas companies in

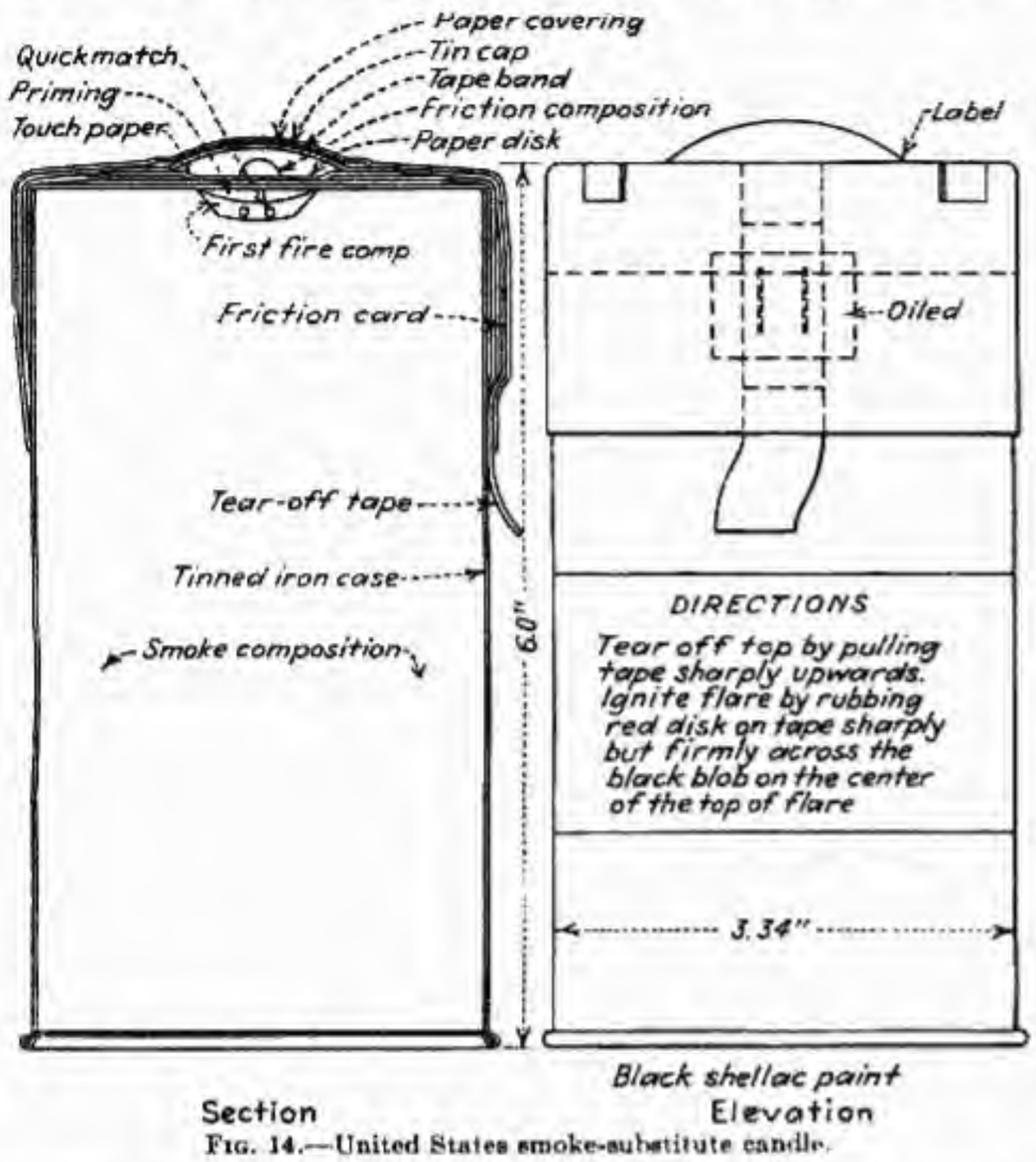

Fig. 14.—United States smoke-substitute candle.

conjunction with their gas operations at that time (12, page 56). These candles were known as "Smoke Candle, Mark I/L/Type S."

When the United States entered the war, it adopted a smoke candle, which was very similar to the British Type S Smoke Candle, and was known as "Candle, Smoke Substitute."

United States Candle, Smoke Substitute.—This candle consisted of a tin case, cylindrical in shape, 5⅞ in. high and 3⅜ in. in diameter, and filled with a solid smoke mixture, as shown in Fig. 14. To the top of the

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case was fitted a case cover, containing a central circular hole 1 in. in diameter, through which the match head was inserted and from which the smoke escaped when the candle was fired. A cardboard disk containing the match head was placed on top of the case cover. The match head extended down through the hole in the case cover and acted as the igniter for the smoke mixture. A scratch block for igniting the match head was taped to the cardboard disk on one side of the match head and a small strip of wood, the same size as the scratch block, was placed on the other side of the match head in such a manner that they were easily removable. The strip of wood, together with the scratch block, formed a protection for the match head. A metal cover was fitted over the top of the candle and sealed with adhesive tape.

Fig. 15.—Candle, smoke substitute, in operation.

The smoke mixture consisted of potassium nitrate, coal dust, sulfur, borax, and hard pitch, while the match head consisted of a mixture of potassium chlorate, antimony sulfide, and dextrine.

The candle completely assembled was 6½ in. high and 3⅜ in. in diameter, weighed 3½ lb., was painted black, and was not marked or stenciled in any way.

By drawing the scratch block quickly across the match head, the latter was ignited and flashed into the candle, igniting the smoke mixture. A delay of about 3 seconds occurred between the scratching of the match head and the evolution of smoke. The cardboard disk holding the match head burned off.

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Smoke of a yellowish brown color was generated in considerable volume for a period of 4 minutes. A small cloud of vapor at the finish usually lasted for another half minute. Figure 15 shows the candle, smoke substitute, in operation.

These candles could be fired either singly with the scratch block or as a group with electric squibs. When fired individually, the adhesive tape from the cover of the candle was removed and the candle was placed in an upright position on the ground.

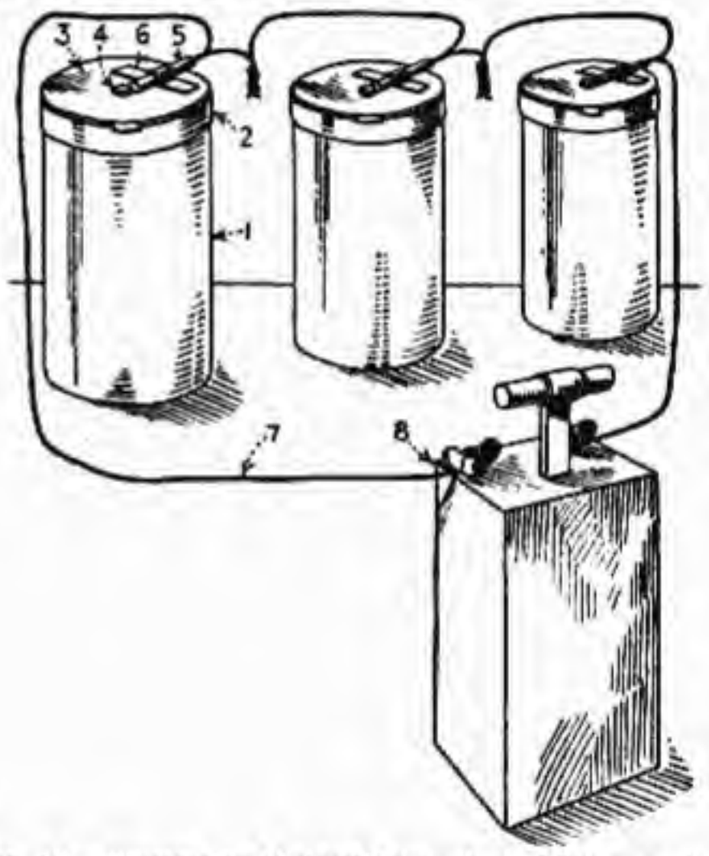

Fig. 16.—Illustration of electrical method of firing candles.

1. Candle.
2. Inner cover.
3. Cardboard disk.
4. Match head.
5. Squib.
6. Adhesive tape.
7. Lead wire.
8. Exploder

After the tape was removed from the match head; the scratch block was drawn across the match head. When fired as a group, the adhesive tape from the cover of the candle and the cover were removed, also the scratch block and tape, exposing the match head. The plug from the base of an electric squib was removed and the squib with base (open end) was securely taped against the match head.

The candles were then connected in a series and attached to a blasting machine (see Fig. 16). The number of candles that may be fired electrically is limited only by the capacity of the exploder or blasting machine used.

The candle, smoke substitute, was painted black. Paint was applied by dipping the candle in asphaltum paint for the purpose of protecting

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the container and preventing the access of moisture to the contents. No marking was placed on the candle, smoke substitute.

Postwar Development of Smoke Candles.—The postwar development of smoke candles has closely paralleled that of tear-gas candles. The first step was to substitute HC smoke mixture* for the British Type S smoke mixture. The next step was to standardize the size of the smoke candle so as to make it the same as the tear-gas candle and thus utilize the same container for both types. The result of this step in the develop-

* See Chap. XI, p. 245.

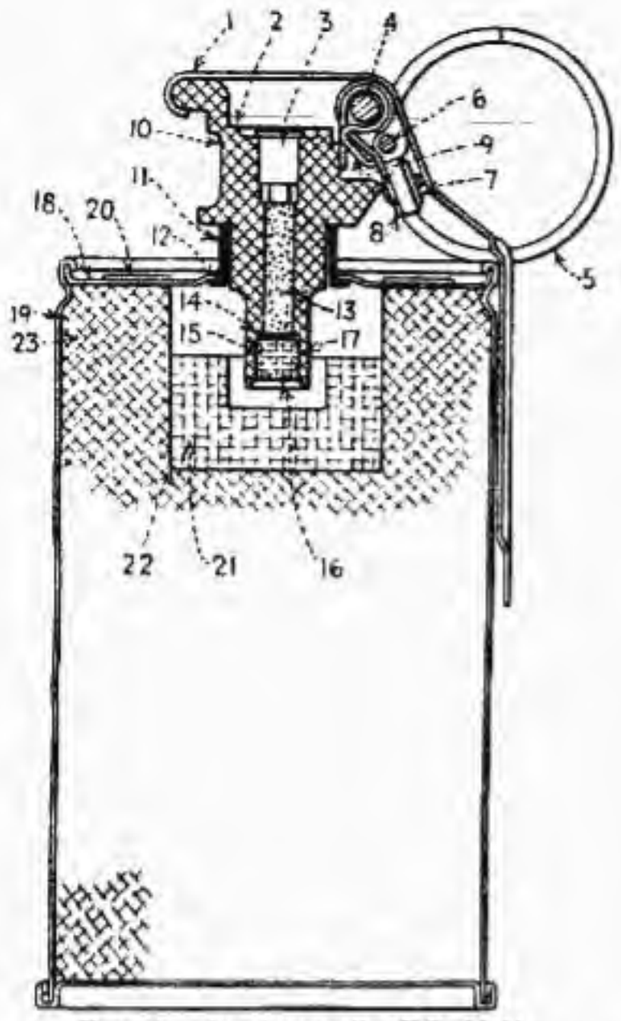

FIG. 17.—Smoke candle, HC, M-II.

1. Lever.
2. Disk.
3. New No. 4 primer.
4. Hinge pin.
5. Ring.
6. $\frac{1}{16}$-in. cotter pin.
7. Striker point.
8. Striker.
9. Spring.
10. Fuse body.
11. Adapter.
12. Solder.
13. Delay element.
14. 0.06-gram Army black powder.
15. 0.12-gram Army black powder.
16. Cup disk.
17. Cup.
18. Top.
19. Container body.
20. Zinc oxide adhesive tape.
21. Starter mixture.
22. Starter-mixture cup.
23. Smoke mixture.

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ment was known as "Smoke Candle, HC, M-II," (later called "Smoke Grenade, HC, M8").

Smoke Candle, HC, M-II, consisted of a cylindrical tin container $2\frac{5}{16}$ in. in diameter and $4\frac{1}{2}$ in. high, filled with a solid smoke mixture and a starting mixture and had a fuse mechanism for firing. With the fuse attached, the height of the candle is $5\frac{3}{4}$ in. For details see Fig. 17.

A zinc cup, circular in shape, $1\frac{1}{8}$ in. in diameter, and $\frac{3}{4}$ in. deep, was placed in a depression left in the top of the smoke mixture. The top of the cup was flanged outward, the flange being $\frac{9}{16}$ in. wide. The flange of the starter cup covered the entire surface of the mixture.

The container top, in which there were four $\frac{1}{4}$ in. holes covered by squares of adhesive tape and to which a brass adapter was riveted, was fitted to the can on top of the zinc starter cup. Into the brass adapter was assembled a fuse, M-1.

The smoke mixture was composed of hexachlorethane, powdered zinc, ammonium perchlorate, and ammonium chloride, and the starting mixture consisted of potassium nitrate, antimony trisulfide, and dextrine.

The candle, with fuse attached, weighed approximately $1\frac{3}{4}$ lb.

When the safety pin of the fuse was pulled and the lever released, the striker fired the primer. This ignited the delay element which in turn ignited the starting mixture. The starting mixture burned through the zinc cup and started a chemical reaction of the smoke mixture, generating considerable heat with the formation of zinc chloride.

The zinc chloride escaped into the air as a dense white smoke, composed of finely divided solid particles, which readily absorbed moisture and became highly obscuring liquid particles.

The candle burned from $2\frac{1}{2}$ to $3\frac{1}{4}$ minutes in full volume. A small stream of vapor lasted for possibly $\frac{1}{4}$ minute longer. Figure 18 shows Smoke Candle, HC, M-II, in operation.

To fire, the candle was grasped with lever held firmly against the candle body and the safety pin was withdrawn, keeping a firm grasp around the candle and lever. The candle was thrown with a full swing of the arm, like a grenade, or placed on the ground. As the candle was released from the hand, the lever dropped away, allowing the striker to fire the primer.

The candle could not be thrown into or placed within 5 ft. of dry grass or other readily inflammable material if a fire was to be avoided. After the candle was ignited, personnel remained at least 5 ft. away from the burning candle. While the candle was practically harmless, the smoke was evolved with great vigor, and there was a tendency to throw out hot particles of residue.

Smoke candle, HC, M-II, was painted gray. A yellow band $1\frac{1}{2}$ in. wide was painted around the can, 2 in. from the top. Stenciled in yellow

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in $\frac{1}{2}$-in. letters was the symbol "HC," $\frac{1}{2}$ in. from the top of the container, and the word "SMOKE" $1\frac{1}{4}$ in. from the top of the container. Below the yellow band, stenciled in yellow were the letters "U.S.," the manufacturer's identification mark, and the lot number.

HC Smoke Pot, M-I.—After several years' use of Smoke Candle, HC, M-II, it was found to be too small for the most economical generation of smoke, and a larger size device was developed. This device, known as "Smoke Pot, HC, M-I," uses HC smoke mixture as a filling and the scratch-block type of firing mechanism employed in the smoke-substitute candle. Smoke Pot, HC, M-1, is now the standard portable field screening smoke generator for the United States Army.

FIG. 18.—Smoke Candle, HC, M-II, in operation.

The present standard smoke pot (Smoke Pot, HC, M-1) is greatly superior to the World War types of smoke candles, both as regards quality and quantity of smoke generated. As indicated in Chap. XI (page 246), HC smoke mixture has a T.O.P. of 2,100, as compared to a T.O.P. of 460 for the World War Type S smoke mixture. Also the standard smoke pot contains 12.5 lb. of HC filling as against 3 lb. for the smoke-substitute candle. One standard pot, therefore, is equivalent to 20 smoke-substitute (Type S) smoke candles in obscuring capacity.

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CHAPTER XIX

INDIVIDUAL PROTECTION

WORLD WAR DEVELOPMENT

To accomplish its mission in war, an army must protect itself; it must seek to keep itself intact and avoid an excessive drain in casualties upon its resources and fighting power. Hence there is both an individual and a collective demand for protection in war regardless of what means or weapons are employed. In consequence of this, the history of war might well be viewed as an age-long and continuing struggle between weapon development as a means of taking life, on the one hand, and protection as a measure for safeguarding life, on the other.

Broadly speaking, gas is used as a war weapon to contaminate the atmosphere about the enemy's position, rendering it dangerous to breathe. Certain chemical agents are so toxic that but a few breaths of them in high concentration will cause death by asphyxiation. Other gases attack the surface of the body and produce casualties by burns. It is therefore imperative that each individual be provided with a protective device to remove the noxious substances from the air before they are breathed or before they come in contact with the body. This is the problem of *individual protection*.

War gases are heavier than air. Hence they tend to hug the ground and flow more or less like water into ground depressions, such as ravines, hollows, and valleys, remaining effective in such places much longer than on high ground exposed to the wind. Gas seeps into trenches and dugouts and penetrates ordinary buildings just as does pure air. Woods contribute to their persistency. Hence it is that ordinary cover from gun fire is not only ineffective against gas but, to the extent that it causes "gas pockets," actually contributes to the effectiveness of chemical agents. The continuing action of gas after its release has also to be reckoned with for, unlike an H.E. shell, the effect of which is complete when the shell explodes and each of its fragments has come to rest, the action of a chemical shell merely begins upon its explosion.

These factors greatly complicate the problem of gas protection, for not only is it necessary to have special protective equipment, but there must be some means of giving warning in time for this equipment to be adjusted. Moreover, men cannot wear masks continuously. They can neither eat nor obtain much rest while wearing masks. Hence means
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must be provided to enable soldiers to eat and sleep without masks and to enable staffs and special-duty men whose work requires freedom from the restrictions imposed by the gas mask to carry on their functions unmasked and yet protected from the all-pervading clutches of toxic gases. This is the problem of group or *collective protection*.

Finally, measures must always be taken to protect tactical units against chemical attack and to assist them in accomplishing their missions without excessive gas casualties. This is the problem of *tactical protection*.

From the foregoing it will be seen that defense against chemical attack presents three classes of problems: (1) individual, (2) collective, and (3) tactical protections. The first two of these involve protective measures of a generally passive nature, *i.e.*, principally the provision and use of individual protective equipment, discussed in this chapter, and installations for group protection, treated in Chap. XX. The third problem—tactical protection—concerns modes of action and troop leading, with the view to avoiding gas casualties in the conduct of military operations.

When the Germans launched the first chlorine cloud against the British and French in April, 1915, it caught them without any form of protection, and hence caused a tremendous number of casualties (15,000) and a high percentage of fatalities (33 per cent). So staggering was this blow that all the energies of the British and French Governments were concentrated during the next few weeks on improvising means of protection against gas, and the results achieved were nothing short of miraculous. Within the short space of two weeks, every British soldier at the front was issued a cotton pad soaked in a solution of sodium carbonate and thiosulfate, which could be tied over his face and which afforded protection against chlorine—the only gas then in use.

Concerning this early effort on the part of the British, General Foulkes says:

> Immediately after the first German gas attack . . . Lord Kitchener had sent two eminent scientists, Dr. Haldane and Professor Baker, to France to investigate the problem of protection on the spot; he had also appealed to the British public to supply pad respirators, such as were being improvised in the field, and in a very few days, thanks to the devoted efforts of British women and the organization of the Red Cross, every man in the B.E.F. had been supplied with some sort of protection against gas.

From the first big gas attack in April, 1915, to the end of the war, the resources of both sides, and particularly of the Allies, were strained almost to the limit to keep gas protection abreast of the rapid development in the offensive use of gas. It was truly a modern version (vastly accelerated) of the age-old race between armor and armor-piercing projectiles. During the three and a half years of the gas war the British Government alone issued 50,000,000 gas masks of seven different kinds to protect an
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army of 2,000,000 men in France—an average of 25 masks per man. This was not waste; it was dire necessity, forced by the following sequence of events:

The Germans used:

1. *Chlorine*, on Apr. 21, 1915, against unprotected troops. By May 3, 1915, British troops were issued cotton cloth pads soaked in a solution of sodium carbonate, sodium thiosulfate, and water. These were supplemented with boxes of cotton waste from which each soldier took a handful to stuff in his mouth and nostrils before fastening the pad over his face. The pads required frequent soaking. This form of protection was never regarded as more than a temporary expedient.

Fig. 108.—First British gas mask, Black Veil Respirator.

By May 10, 1915, British troops in the Ypres sector were provided with the *Black Veil Respirator* (see Fig. 108). This consisted of a fourfold piece of black veiling about 1 yd. long and 8 in. wide. The center portion was padded with cotton and saturated with sodium carbonate, glycerine, and water, the glycerine having been added to keep the pad moist. Tied about the face, this respirator, however, did not insure a gastight fit and was soon replaced with a new design.

Fig. 109.—British Hypo, P., or P.H. Helmet, showing skirt effect.

2. *Tear gas* (T-Stoff), in shell beginning in January, 1915, but increasing to serious proportions in May and June. These tear gases caused very serious lacrimation (an unprotected man was helpless) when present in a concentration only one six-thousandth of the lethal concentration of chlorine. To meet this threat the British issued the *Hypo Helmet* (see Figs. 109 and 110). This helmet was made of flannel in the form of a sack which could be put over the head with the open ends tucked inside the blouse. The cloth was dipped in hypo (sodium thiosulfate), washing soda, and glycerine. A rectangular piece of
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celluloid was inserted in the helmet for vision. This was easily cracked and the mask was otherwise defective in having no outlet valve to prevent the harmful accumulation of carbon dioxide inside the helmet. This mask was issued to all troops in the field by July 6, 1915.

3. *Phosgene*, on Dec. 11, 1915. Phosgene was ten times more poisonous than chlorine. By July, 1915, it was learned that phosgene would be employed by the Germans during the following December. The British Intelligence Service ascertained not only this important fact but also the exact area within which the attack would take place. With five months to prepare, the British developed the *P. Helmet*. This was similar in shape to the Hypo Helmet but was made of flannelette and was provided with two glass eyepieces. It also had an expiratory valve made of rubber, very similar to the outlet valve on present-day masks (see Figs. 109 and 110). The helmet was dipped in a solution of caustic soda, phenol, and glycerine. The first two of these substances react to form sodium phenolate which neutralized phosgene, hence the name *P.* or *Phenolate Helmet*. It was used by the British during the large phosgene attack near Pilckum on Dec. 19, 1915. It saved many lives though it was not fully satisfactory against high concentrations.

Fig. 110.—British Hypo, P., or P.H. Helmet in use, skirt buttoned under tunic.

Meanwhile the Russians had discovered that a substance known as urotropine or hexamethylenetetramine readily neutralized phosgene. With this information, the British now discarded the P. Helmet for the *P.H.* (phenate-hexamine) *Helmet*, similar except for the protective solution in which it was dipped (see Figs. 109 and 110). The new solution was urotropine, caustic soda, phenol, and glycerine. The P.H. Helmet

gave much better protection than the P. Helmet, was effective for about 24 hours' continuous use, and would withstand a high concentration of phosgene.

By the latter part of 1915, the Germans had commenced the extensive employment of lacrimators either alone or in conjunction with lethal gas. The P.H. Helmet offered little protection against lacrimators. Accordingly in September, 1915, goggles made of rubber with mica eyepieces were issued for use in connection with the P.H. Helmet. This involved difficulties of adjustment which led to the development of the *P.H.G. Helmet*, having tight-fitting goggles attached to the mask. This helmet, however, was also difficult to adjust and was soon discarded. With the

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subsequent invention and issuance of the box respirator, the P.H. Helmet was continued in service use for some little time as a substitute in case the respirator was lost or damaged.

4. *Increasing concentration of gas* early in 1916. The protection provided was inadequate. Having reached what they believed was the limit of protection with the helmet-type of mask, still not fully satisfactory, the British now turned to an entirely different principle, with the invention of the *Large Box* or *Tarbox Respirator*. This was the first British Army mask which included a canister of neutralizing chemicals. The canister contained granules of charcoal, soda lime, and potassium permanganate. It was connected by a rubber tube to the facepiece which covered only the chin, mouth, and nose. The facepiece was made of 24 thicknesses of muslin soaked in sodium zincate and urotropine. The facepiece included a nose clip to prevent breathing through the nose and a rubber mouthpiece for breathing with the mouth through the canister. Goggles were used for protection against lacrimators.

Fig. 111.—British Small Box Respirator.

5. *Chlorpicrin and similar (Green Cross) gases*, about Mar. 26, 1916. Chlorpicrin was about four times as poisonous as chlorine. It was also chemically very inert and was not efficiently absorbed by any respirator to this date.

The Large Box Respirator was cumbersome and deficient in protection against lacrimators. It, in turn, was supplanted by a mask of improved design called the *Small Box Respirator* (see Fig. 111). This was first issued to troops in April, 1916, and served the British, as well as many of the United States troops, to the end of the War. The Small Box Respirator consisted of a small canister containing layers of charcoal, soda lime, and potassium permanganate; a corrugated tube and a facepiece covered the entire face. The facepiece was made of rubber cloth and while a tight fit was depended upon for protection against lacrimators, the rubber mouthpiece and nose clip, to insure that only air from the canister was breathed, were retained.

6. *Mustard gas (Yellow Cross)*, in July, 1917. Mustard gas is 36 times as poisonous as chlorine. The Small Box Respirator sufficiently protected the eyes and nose against mustard gas. The mustard gas

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persisted for days in any locality where used and had very little odor and was not unpleasant at the time. The masks were very uncomfortable when worn for long periods. Also, the mustard gas affected all parts of the body, easily permeating the clothing. Hence tremendous casualties were caused by its use. Adequate protection never was devised. *Difficulties of manufacture fortunately limited the German supply.*

7. *Toxic smoke (Blue Cross)*, in July 1917. Some of these toxic smokes produce intense and intolerable (an unprotected man could not fight) irritation of the nose and throat in concentrations only one twenty-thousandth of the lethal concentration of chlorine. All the masks previously mentioned permitted the penetration of smokes. The Germans discovered smokes terribly irritating to the nose and throat and commenced their use on a very large scale. The Germans manufactured 14,000,000 Blue Cross shell and expected extremely important results, hoping to force the removal of the mask and permit casualties to be readily produced by other gases.

The British had forseen this possibility and had provided a partial protection in the shape of an extension to the Small Box Respirator. Subsequently other changes were introduced. Really adequate protection never was devised. Fortunately the German shells were not effective. (Penetration of the mask is effective only when the particles are approximately of a certain size.)

The above facts illustrate grimly the strenuous race that took place between offensive and defensive gas warfare in the late war.

Mask Development

The evolution of the *British* wartime gas mask, as outlined above, is of special interest since it was the British type which was adopted by the American Army upon entry of the United States into the war.

The earliest *German* respirators consisted of pads of cloth soaked in a sodium thiosulfate—sodium carbonate solution. These were followed by masks of absorbent cloth made in the shape of a snout which fitted over the mouth and nose.

During the fall of 1915, the Germans turned to a canister-type respirator (see Fig. 112). The facepiece of this mask was made of leather treated with tar oil and tallow to render it gastight and watertight. The facepiece covered the entire face including the eyes. Eyepieces, consisting of an outer layer of glass and an inner layer of chemically treated celluloid which prevented dimming, were inserted. Screwed to a socket in the facepiece was a small cylindrical canister containing absorbent chemicals. The air was inhaled and expired directly through this canister. Originally the canister filling consisted of a layer of kieselguhr or granules of earth soaked in potassium carbonate covered with

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powdered charcoal, a layer of charcoal granules, and a layer of pumice mixed with urotropine. In April, 1918, a layer of charcoal and zinc oxide was substituted for the layer of earth granules.

To protect against irritant smokes, a paper disk filter in a perforated metal container, which was fitted over the canister, was later issued.

This mask had the advantage of compactness, but as there was no outlet valve the wearer had to continually breathe a certain amount of his own expired air. Also the entire weight of the German mask and canister was carried by the head and produced fatigue of the neck muscles after a short period of wear.

Fig. 112.—Early German gas mask.

The *French* developed three masks, the M2, the Tissot and the A.R.S. (*Appareil Respiratoire Spécial*).

The M2 Mask (see Fig. 113) was in the form of a snout covering the face. It was made of 32 layers of muslin impregnated with neutralizing chemicals. Celluloid eyepieces were provided for vision. There was no outlet valve. Air was inhaled and exhaled through the fabric.

The facepiece of the Tissot Mask (see Fig. 114) was made of pure rubber and was connected by a tube to a canister of absorbent chemicals carried on the back. The mask is noteworthy as being the first to provide for drawing the incoming air across the eyepieces to prevent them from dimming. It was used extensively by artillerymen and special observers in both the French and American armies. It was clumsy, however, and difficult to adjust and was hence unsuitable for front-line troops.

The French now turned to the German type of snout canister mask, developing the A.R.S. Mask, experimentation with which began in September, 1917. This mask was an improvement on the German in that it incorporated the Tissot principle of preventing dimming of the eye-

pieces by drawing the dry inspired air across them and it also included an outlet valve which the German type lacked. The French snout canister, however, gave somewhat less protection than the German. Moreover, the French did not furnish each soldier with an extra canister to carry with his mask as did the Germans.

The original *Italian* mask was somewhat similar to the French M2 type. This was soon discarded for the British Small Box Respirator which the Italians adopted for their troops during the war

Fig. 113.—French M2 gas mask.

Fig. 114.—French Tissot gas mask.

The *Russian* wartime gas mask (see Fig. 115) consisted of a headpiece which covered the head including the ears. It was connected directly to a canister box supported on the chest. The canister contained charcoal only. This mask had neither mouthpiece nor nose clip, but was still uncomfortable to wear.

Fig. 115.—Russian gas mask.

Upon entry of the *United States* in the war, the War Department adopted the British Small Box Respirator (see Fig. 111), considering it the best of European masks which had been developed. However, in view of the then extensive use of mustard gas which necessitated the wearing of the mask for long periods of time, it was early realized by the American Gas Service that the uncomfortable mouthpiece and nose clip of the British type of mask should

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be eliminated. Accordingly experimentation was immediately begun leading to development of a number of improved designs. None of these fully met requirements, and it was not until the close of the war that a satisfactory American mask of improved design was produced. All told a total of 5,692,499 masks were made in this country during the war. Of this number 4,210,586 were shipped to France.

The first American effort in gas-mask production was a lot of 25,000 masks of British type intended for use of the 1st Division. These were made without sufficient knowledge of British specifications and fabrication methods. They were shipped to France in 1917 but proved faulty and were never issued to troops.

Following receipt of more definite information, production of *masks for training* purposes, practically in exact duplication of the British type, was begun in this country in July, 1917. The facepiece of this type was made of rubberized cloth and included celluloid eyepieces. It had a rubber mouthpiece and nose clip similar to the British.

The Training Mask was followed in October, 1917, with the *C.E.* or *Corrected English Mask.* This included an improvement in the facepiece fabric, protecting against all gases, the previous type having been permeable to chlorpicrin. Other improvements were the addition of the flutter valve guard, use of coiled spring to hold the eyepieces in place, change in the angle tube giving lower breathing resistance, and the substitution of activated cocoanut charcoal in the canister, for the unactivated wood charcoal in the original British type. Before the Armistice, 1,864,000 of the C.E. Masks were turned out.

The *R.F.K. Mask* was a somewhat improved type designed by three men connected with the American Gas service, Richardson, Flory, and Kops. Noteworthy improvements of the C.E. mask were the use of spun-in aluminum eyepieces and a change in the shape and the facepiece binder frame to increase the comfort. From February, 1918, until the Armistice, 3,050,000 of these masks were produced.

To meet the demand for increased comfort and lower breathing resistance, there followed several types noteworthy as the forerunners of the present-day American Army mask. In all of these the mouthpiece and nose clip were dispensed with, and the Tissot principle of deflecting the incoming dry air across the eyepieces was incorporated. The A.T. (Akron Tissot) Mask, was designed by the Akron Rubber Company (see Fig. 116). The facepiece of this mask was made of molded rubber covered with stockinette. Inside the facepiece was a Y-shaped tube to deflect the incoming air across the eyepieces and a sponge-rubber chin rest was also provided. Production of this type started in June, 1917, a total of 197,000 being made before the Armistice.

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Another improved type was designed by Kops and known as the *K.T.* or *Kops-Tissot Mask.* This mask contained a semiflexible facepiece binder frame and was provided with a butterfly shaped air deflector made of rubber. It had no angle tube, separate tubes for inlet and outlet of air being used. In place of the rubber chin rest of the A.T., it had an elastic chin rest strap. The self-centering adjustable head harness provided in the A.T. was incorporated in this mask. A total of 337,000 were made before the Armistice.

Fig. 116.—American A.T. (Akron-Tissot) gas mask.

The principal objection to the A.T. and K.T. Masks was that they were difficult to manufacture.

By October, 1919, production had begun on a further improved type known as the 1919 *Model* or *K.T.M. Mask.* About 2,000 of these were turned out before the Armistice, by which time preparations had been made for their manufacture at the rate of one million a month.

The facepiece of this mask was made of a special rubber compound. The outside surface was covered by a layer of thin cotton fabric called stockinette which was vulcanized to the rubber. The facepiece material with stockinette covering was manufactured in the form of sheets from which the facepieces were cut out by means of a special die. The die cutting was so shaped that when folded and two short edges were sewn together to form a chin seam, a properly fitting mask was obtained. This method of manufacture greatly facilitated mass production. Holes for the eyepieces were eliptical so that an uneven tension was produced around the eypieces causing the eyepieces to bulge forward as desired and insuring a proper fit about the temples. The mask had an angle tube similar to that of the A.T. and a deflector almost identical with that used in the K.T., but neither a chin rest nor a chin strap, the facepiece being so shaped that these were unnecessary. A head harness pad of canvas-covered felt and buckles for adjustment of the head harness straps were provided.

Canister Development (American)

The canisters of the early American type masks were filled with charcoal and soda lime in the proportion of 60 to 40 and were painted *black.*

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They were about one-fourth larger than the British type, it having been feared that our charcoal was inferior and that hence a larger amount was

needed. It was later learned that American-made charcoal was in fact superior and the canister was accordingly reduced to the same size as the British.

The canisters of the C.E. Masks were of the reduced size and were painted *yellow*. By January, 1918, two cotton pads were inserted in the canister to protect against irritant smokes. These canisters were also painted *yellow*.

When the R.F.K. masks were being manufactured, it was found that the canister could be reduced still further in size and also that breathing resistance could be lowered. Canisters of this improved type were painted *green*.

Various sorts of irritant smoke filters were used during the World War, including paper, cellulose, and cotton. Felt was found to be the most efficient material, though it offered considerable resistance to breathing and was expensive. Accordingly, the next American improvement in canisters was the incorporation of a felt filter. This canister was painted *blue* and was used in the 1919 mask.

Carrier Development

For the early American types of gas masks, a square-shaped canvas *satchel*, carried slung over the shoulder, was provided. The sling or carrying strap for these carriers was so made that the satchel could be quickly transferred to the *alert position* across the chest, a cord being used to tie around the body and hold the satchel in place. This *two-position* carrier was not satisfactory in this respect and, moreover, when lying prone it was difficult to adjust the mask from the alert position of the carrier without undue exposure of the body. The side satchel was hence developed. Using a longer corrugated tube it was unnecessary, with the side satchel, to change its position before adjusting the mask.

POSTWAR DEVELOPMENT

The Gas Mask

Since the war, development work on gas masks has been mainly directed toward further improving the "1919 Model" Army service gas mask, brought out at the end of the war, and toward providing additional types of special masks needed for certain troops who have special duties to perform, such as communicating messages over telephones (the diaphragm mask), observing through optical instruments (optical mask), and piloting airplanes (aviation mask).

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Our postwar mask-development work has been based upon certain practical requirements which control the design of the mask. These requirements may be summarized as follows:

1. The mask must protect against all chemical-warfare agents.
2. It must have a low breathing resistance.
3. It must be light in weight.
4. It must be comfortable.
5. It must be simple in design, easy to operate, and repair.
6. It must not interfere greatly with vision.
7. It must be rugged enough to withstand field conditions.
8. It must be reasonably easy to manufacture in quantity.
9. It must not deteriorate appreciably in storage for at least several years.
10. It must have a service life in the field for at least several months.

The ideal gas mask is one which affords complete protection against all known toxic gases. Theoretically such a mask is possible but it can not at the same time satisfy all of the practical requirements listed above. Thus, the requirements of maximum protection, low breathing resistance, and light weight, are essentially opposed, for protection varies directly with the amount of chemicals used and the capacity of the mechanical filter. But the more chemicals used and the larger the filter, the heavier the canister. Similarly, low breathing resistance requires a large superficial area for the filter which in turn increases the size and weight of the canister.

Again, if the canister is made small, the chemical filling must be reduced, which lowers protection, and the filter must be made smaller, which increases breathing resistance. Hence the military mask is a compromise, embodying an optimum balance among the ten requirements indicated above, particularly the first three.

In addition, the Army service gas mask is designed to protect only against substances suitable for war use as chemical agents. This should be thoroughly understood and the military mask should not be relied upon for any purposes other than those for which it is intended.

The Canister

The canister of the military gas mask is the means by which chemical agents present in the atmosphere are removed from air before it is breathed (see Fig. 117). It consists of three principal parts, *viz.*, a chemical container, usually made of sheet metal and provided with air inlet and outlet openings; a filter for the removal of solid and liquid particles by mechanical filtration; the chemical filling for the disposal of gases by physical adsorption, chemical neutralization, or by a combination of these processes.

As an integral part of the mask the canister itself must conform to the general requirements listed above. These requirements impose

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decided limitations upon the number of materials or substances which may be used as components. The material used for the *mechanical filter* must be sufficiently dense to hold out the extremely minute solid or liquid particles of which the irritant gases and smokes are constituted. These particles, it may be said, are so small that they cannot be seen with an ordinary high-powered microscope while even with the ultramicroscope they are only visible as points of reflected light. On the other hand, the filter material must not be so dense as to impede unduly the flow of air through it. The chemical or chemicals used for the removal of gases must be highly porous in order to provide within small space a relatively enormous absorbent surface. They must not react with each other or corrode their metal container. Their effectiveness must not be appreciably lowered by exposure to air of high humidity. They must remove the gas very rapidly since any given portion of inspired air is in contact with the canister filling for but a fractional part of a second. They must have the capacity to dispose of large amounts of gas since the canister cannot be frequently replaced. They must be fairly cheap and available in great quantity. In turn, they, as well as the filter, must not cause high breathing resistance.

Fig. 117.—Gas-mask canister (sectionalized).

The only single substance which approximately fulfills all the requirements of a chemical filling for gas-mask canisters is activated charcoal in the form of small granules. Generally speaking the best charcoals for this purpose are made from very dense raw materials. The most satisfactory material found during the World War for canister charcoal was cocoanut shell. Various nut shells, fruit stones, and other substances, however, were also used. Since the war, improved methods of manufacture have made possible the use of more readily available materials. Charcoal is a highly porous substance consisting principally of carbon which is made by the carbonization of organic matter. As such, it is called *primary charcoal*. By subjecting primary charcoal to a certain process of heat and steam, called *activation*, the property of adsorption of gases, which primary charcoal possesses, is greatly increased.

When gas-laden air is passed through activated charcoal, the molecules of gas are attracted and held physically on the surface of the pores in the

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charcoal granules, the purified air passing on through. This process of removal of the gas is called *adsorption*. It may roughly be compared to the action of a magnet in attracting and holding iron fillings on its surface. Activated charcoal which will adsorb half its own weight of toxic gas has been made on a large scale, while charcoals have been made in the laboratory which will adsorb more than their own weight of gas. The principal deficiency of charcoal as a canister filling is that it does not hold tena-

ciously certain highly volatile acid gases, notably phosgene, but gradually releases them to the passing air current. This deficiency is compensated for by the use of another substance mixed with the charcoal, *viz.*, soda lime.

Soda lime is a mixture consisting of hydrated lime, cement, kieselguhr, sodium hydroxide, and water in various proportions according to the formula used; there are several. Gases, which the charcoal does not hold firmly by adsorption and which are gradually given off by it, are caught by the soda lime, with which they enter into chemical combination. After continued exposure to certain gases, such as phosgene, a gradual transfer of the gas to the soda lime takes place, thus leaving the charcoal free to pick up more gas. It may therefore be said that the principal function of the soda lime is to act as a reservoir of large capacity for the permanent fixation of the more volatile acid and oxidizable gases, while the charcoal furnishes the required degree of activity for all gases as well as storage capacity for less volatile ones.

Another reason for the combination absorbent is that, while a rise in either temperature or humidity causes a decrease in the adsorptive capacity of charcoal, such conditions increase the reactivity of the soda lime.

The canister of the present military mask contains a mixture of soda lime and specially prepared charcoal as well as a highly efficient mechanical filter. It can thus be relied upon to give full protection against any gas likely to be encountered in the field. The function of the different components of the canister as regards the principal war gases is set forth below.

Gas	Neutralizing Agency
Brombenzyl cyanide	Charcoal
Chlorpicrin	Charcoal
Cyanogen chloride	Charcoal
Mustard gas	Charcoal
Chloracetophenone	Charcoal and filter
Chlorine	Charcoal–soda-lime mixture
Phosgene	Charcoal–soda-lime mixture
Diphosgene	Charcoal–soda-lime mixture
Hydrocyanic acid	Charcoal–soda-lime mixture
Lewisite	Charcoal–soda-lime mixture
Diphenylchlorarsine	Filter
Diphenylaminechlorarsine, etc	Filter

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It should be impressed upon all concerned that the canister provided with the military gas mask is for protection against chemical warfare agents only. There are certain toxic gases unadapted for war use which may otherwise be encountered, especially in industry. The principal ones are carbon monoxide and ammonia. The Army canister does not protect against these gases and should never be relied upon for such purpose.

Carbon monoxide has neither odor nor color and a person subjected to a sufficient concentration of it loses consciousness without warning. Being lighter than air, high concentrations of this gas are generally limited to enclosed spaces. As it is one of the products of combustion of wood it is invariably present in burning buildings. Hence the military gas-mask canister should never be used in fire fighting. Carbon Monoxide is also present in automobile exhaust gas, in natural gas, artificial illuminating gas, blast-furnace gases, mine-explosion gases and in the gases resulting from the burning of smokeless powder in artillery.

Repair or rescue work about refrigeration plants and other places where there is leakage of ammonia gas should be undertaken with the military gas mask.

It should also be realized that the military gas mask does not supply or make air or oxygen and hence should never be used in an atmosphere deficient in oxygen. Tunnels and shafts of mines following an explosion, the holds of ships, and tanks and tank cars containing volatile liquids are places likely to be dangerous in this respect.

It should further be understood that *the Army service gas-mask canister is not designed to protect against concentrations of war gas greater than 1 per cent by volume.* It is most unlikely that concentrations as high as this will be encountered in the field. However, such concentrations may be found in the immediate vicinity of the explosion of the gas shell, for instance in a dugout when a shell bursts in the entrance to it. As additional precaution men, even though wearing masks, should move quickly from the immediate vicinity of the explosion holding their breath while so doing. Dangerously high concentrations may also be encountered through leakage in changing the valve on a cylinder containing a chemical agent liquefied by pressure, or in a tank containing a volatile solvent such as gasoline.

The Army Service Gas Mask

The gas mask now provided for the Army is known as the *Service Gas Mask* (see Fig. 118).

The principle upon which the gas mask functions is the purification of inspired air by removal of the gas or smoke. Perfect fit of the facepiece is depended upon to insure that only air which passes through the canister is drawn into the lungs. The mask consists of three main parts:

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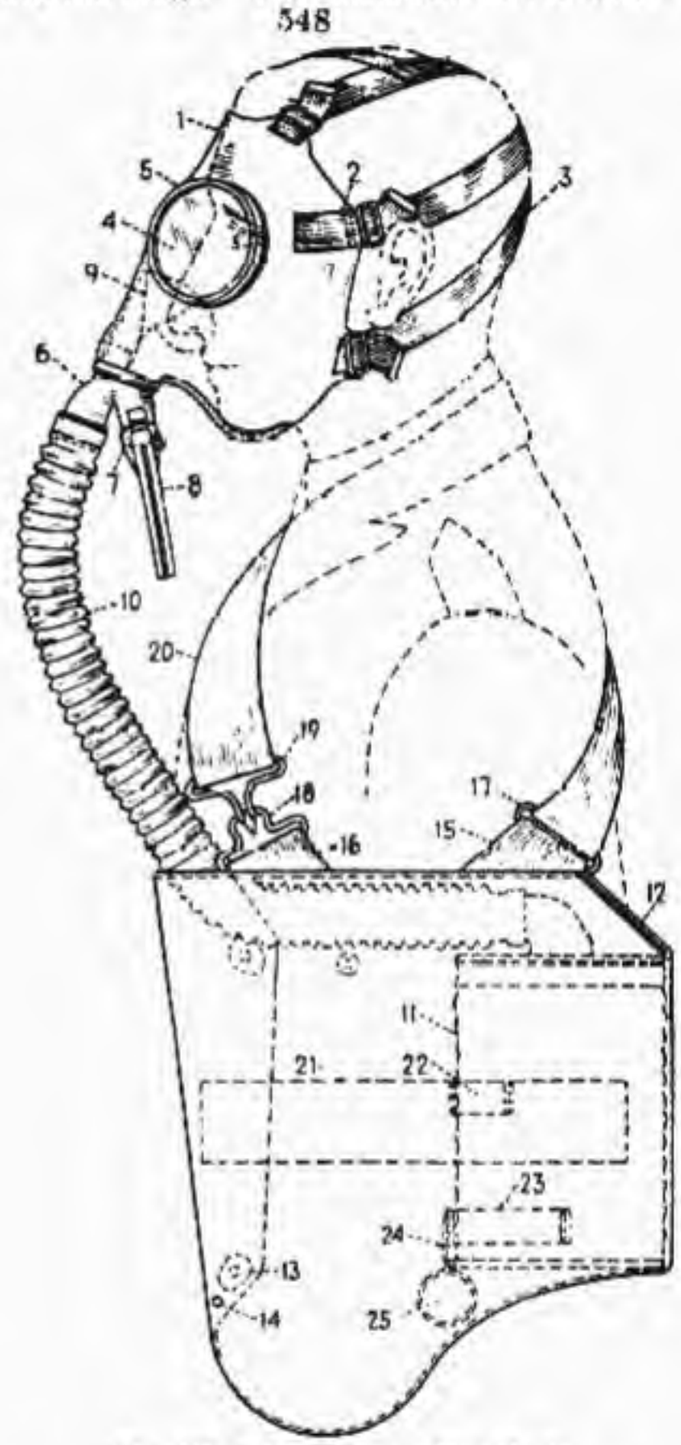

Fig. 118.—Army Service Gas Mask.

1. Rubber mask.	10. Hose.	19. Hook clasp.
2. Harness attachment.	11. Canister.	20. Shoulder strap.
3. Head harness.	12. Carrier body.	21. Body strap.
4. Lens.	13. Lift-the-dot fastener.	22. Upper can strap.
5. Eyepiece.	14. Rivet.	23. Lower can strap.
6. Angle tube.	15. Chape 30°.	24. Antidim set strap.
7. Outlet valve.	16. Chape 45°.	25. Antidim set.
8. Outlet valve guard.	17. Strap loop.	
9. Deflector.	18. Eye clasp.	

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the facepiece, the canister, and the hose tube. The mask with the carrier weighs 5 lb.

The facepiece is made from molded-rubber blanks of approximately the correct size covered on the outside by a thin layer of cotton fabric called *stockinette* vulcanized to the rubber. The facepieces are cut out from the face blanks to exact size and shape by means of a die. These die cuttings are then folded, and two short edges are sewn together by a special zigzag stitch and taped with adhesive tape, thus forming a gastight seam at that portion of the mask which fits under the chin.

The eyepieces are made of two layers of glass separated by a thin layer of celluloid. Even if struck a sharp blow and badly cracked they will remain gastight and will not splinter. The lens are held in the facepiece by detachable screw-on type retaining rims, so that they may easily be replaced.

When adjusted, the facepiece is held in place by an elastic head harness. The harness is made of strips of elastic tape held together in the center by a thin oblong piece of felt called the *head harness pad*. When

the head harness is worn out a new harness can quickly be attached to the retaining buckles which are sewn to the facepiece itself.

Attached to the facepiece just above the chin seam is a metal casting called the *angle tube*. This tube has two passages, one connected with the hose tube for the passage of inhaled air, the other attached to the outlet valve is for the passage of exhaled air.

The outlet valve, protected by a metal guard, is made of rubber. It is a simple but effective device which allows the exhaled air to pass out of the facepiece but otherwise remains closed, preventing any air from being drawn into the mask through the outlet portion of the angle tube.

Inside the facepiece and connected to the air-inlet portion of the angle tube is a butterfly-shaped tube made of rubber. It is known as the *deflector*, its purpose being to deflect the incoming dry air across the eyepieces. This prevents the condensation of moisture from the breath on the glass surfaces. Without this device the eyepieces would soon become so fogged or dimmed that it would be impossible for a man wearing the mask to see.

To insure proper fit for any size or shape of face, facepieces until recently were furnished in a range of four sizes. A universal facepiece designed to fit any face has now been developed and is being supplied. This greatly simplifies the problem of fitting and also of supply.

The canister (see Fig. 117) is an oblong-shaped metal box, painted olive-drab color, and containing a combination gas and smoke filter. The filter consists of an oval-shaped perforated sheet-metal container filled with a mixture of 80 per cent activated charcoal and 20 per cent soda lime. The outer surface of the chemical container is covered with a material

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which filters out irritant-smoke particles. Inspired air enters the canister through a one-way valve in the bottom called the *inlet valve*. From there it is drawn first through the smoke filter where solid and liquid particles, if present, are separated out. The air then passes to the interior of the chemical container where the toxic vapors are adsorbed by the charcoal or neutralized by the soda lime. The purified air passes out of the canister through a metal-elbow fitting at the top connected to the hose tube.

FIG. 119.—Army diaphragm gas mask.

The hose tube (see Fig. 118) is a corrugated tube of rubber covered with stockinette. It serves to conduct the purified air from the canister to the facepiece. The corrugations of the tube prevent it from collapsing or kinking and thus shutting off the flow of air.

The carrier (see Fig. 118) is a somewhat irregular-shaped satchel made of olive-drab canvas provided with adjustable shoulder and waist straps. It is carried at the left side, under the arm, the shoulder strap fitting over the right shoulder. The opening covered by a flap held in place by snap fasteners is at the front. The carrier not only serves for convenient carriage of the mask but protects it, especially the canister, from moisture and other harm. The mask is adjusted to the face from the carrier without change of the position of the carrier as was necessary with the wartime type.

Inside the carrier is a small cylindrical tin box containing a stick of soaplike substance, called *the antidim compound*, and a piece of cloth. When applied to the inner surfaces of the eyepieces and rubbed to a thin layer with a cloth this compound forms a transparent film over the glass surfaces which aids in preventing them from becoming fogged. The antidim container is held in place by a loop of fabric from which it can readily be detached when needed.

Special Masks

The Diaphragm Mask (Fig. 119) is especially designed to meet the requirements of personnel of the Army whose duties make ease in talking essential. The mask is identical with the service mask except for the facepiece which includes a diaphragm to facilitate the transmission of the sound of the voice. Instead of the angle tube as used in the Army service

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facepiece, a metal part containing inlet and outlet air passages and also a seating for a diaphragm is employed. This metal piece, in addition, has two air-deflector tubes leading to the eyepieces which serve in lieu of the rubber deflector in the Army service mask. The voice transmission diaphragm consists of a thin disk of fabric treated with bakelite. It is held in place and protected by a perforated metal disk. For Army use, this type of mask is applicable for officers and for telephone operators.

The Diaphragm-optical Mask is designed for use by men whose duties require them to use optical instruments, such as range finders, telescopes, etc. For this purpose, the eye of the observer must be brought up into close and definite relationship to the observing optical instrument so the eyepieces of the mask are made small and are held in rigid though adjustable relation to each other and to the eyes of the wearer.

As observers requiring optical masks have also to transmit observed data by telephone, the optical mask is equipped with a special sound-transmitting diaphragm, similar to the Diaphragm Mask, and, since it embodies two special features, it is designated as the *Diaphragm-optical Mask*. The hose tube, canister, and carrier are the same as the Army service gas mask.

FIG. 120.—Oxygen-breathing apparatus (commercial type).

Oxygen-breathing Apparatus

Since air-purifying canisters on Army gas masks are effective only in atmospheres containing not over 1 per cent of toxic gases, they do not furnish adequate protection for certain personnel whose duties require them to enter or remain in closed places where higher toxic concentrations may accumulate. To protect such special personnel (only a very small fraction of combat troops), oxygen-breathing apparatus is required. Such apparatus is currently used in mine rescue work and in other hazardous occupations in industry where high toxic concentrations are encountered. For military use, the most suitable types of commercial oxygen-breathing apparatus are adapted to meet the special service requirements. The principal military characteristics are: (1) minimum weight; (2) maximum time of protection; (3) simplicity of operation; and (4) ruggedness of construction. Usually it is advantageous to combine

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the service mask with an oxygen-breathing apparatus and provide a two-way valve so that either the service canister or oxygen may be used as the situation requires (see Fig. 120).

The Horse Mask

The horse mask (Fig. 121) is a device to protect the respiratory tract

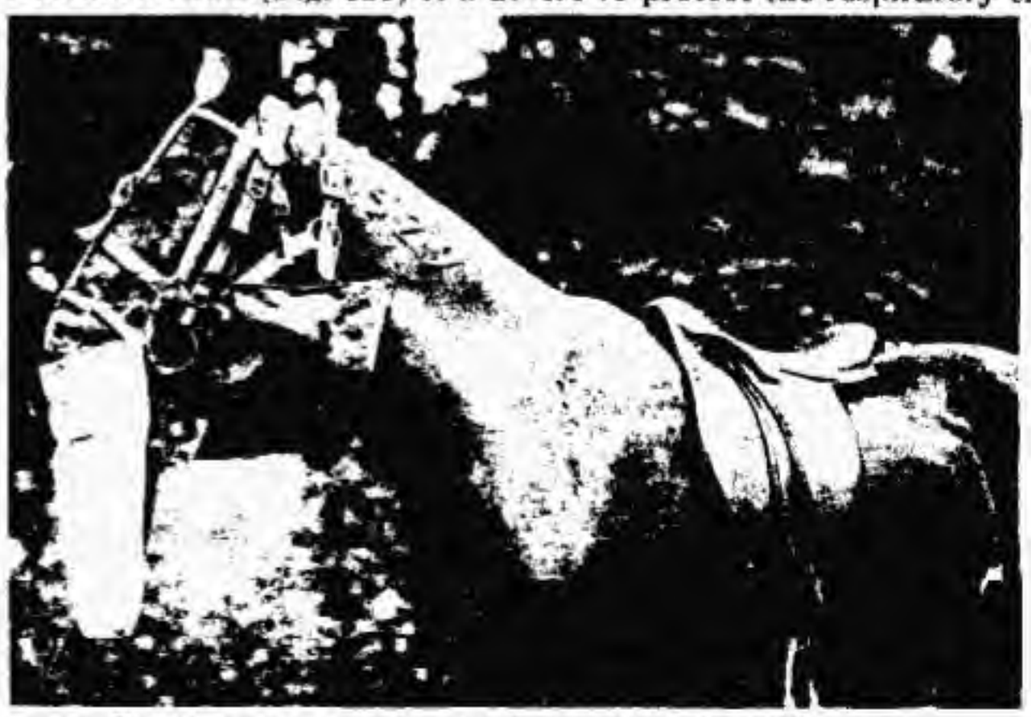

FIG. 121.—American horse mask in position (World War type).

of a horse or mule from lung injurants. It is a bag made of layers of cheese cloth treated with chemical which neutralize the gas when air is breathed through it.

As horses and mules never breathe through the mouth and as their eyes are not seriously affected by lacrimators, the mask covers the nostrils and upper jaw of the animal only.

The mask is provided with a canvas or leather pad which fits into the animal's mouth preventing him from biting through the mask; a drawstring to insure tight fit of the bag over the upper jaw; a simple head harness which fits over the head and ears and is retained in place by a throat latch. When not in use, the mask is carried in a waterproof burlap bag, which hangs under the lower jaw, attached to the halter.

To adjust the mask slip the mouthpiece pad well into the mouth, the open end of the bag covering the nostrils; adjust the head harness over the head; fasten the throat latch. The drawstring should be tightened so that the edge of the bag fits tightly over the upper jaw several inches above the nostrils.

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Horse masks are primarily for protection of draft animals required for work through gas-contaminated areas. The mask greatly impedes the flow of air to the horse's lungs. As horses doing heavy work or running require a large volume of air, they should be given frequent rests while at work wearing masks and should not be required to run.

The Dog Mask

The dog mask is somewhat similar to the horse mask, except that it covers both jaws as well as the nostrils, since a dog breathes through both nose and mouth. As dogs are not used in the American Army, dog masks are not authorized.

The Pigeon Mask

Impregnated flannelette bags are provided for gas protection of pigeons used in war. The dimensions of the bag are 15 by 15 by 24 in. and it is designed to fit over the pigeon cage, the open end being drawn together tightly at the top by means of a drawstring. When for any reason pigeons cannot be protected they should be released at once.

Use of the Gas Mask

Gas masks are now made in but one (universal) size which has been specially designed to fit any type of face. The facepiece is made big enough to fit the largest face, on the principle of a flexible conical cap. It can be adjusted to fit smaller faces by entering the face further into the mask. The universal facepiece has been extensively tested and has been found to fit all sizes and types of faces to date. If subsequent experience should show that certain unusually variant types of faces, especially very small-sized faces, cannot be fitted with the universal facepiece, an additional small-size mask will also be supplied for such cases.

The World War type of mask with its uncomfortable nose clip and mouthpiece had a double line of protection. Proper fit of the facepiece was hence not vital as it is with the present mask. As the integrity of the present mask depends upon proper fitting, its importance cannot be too strongly emphasized.

There are two tests for *testing the fit* of a mask.

The *suction test* gives a good indication of the fit of the mask and should invariably be applied during the fitting procedure. It consists of three steps as follows:

1. Adjust the mask to the face.
2. Exhale fully.
3. Pinch the corrugated tube tightly and inhale.

The facepiece should now collapse tending to cling to the face and the wearer should be unable to breathe. If the vacuum thus formed inside

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the facepiece breaks and air is felt to stream into the mask the fit is defective.

The only conclusive test of the fit of a gas mask is to test it in a gas atmosphere. This test is best carried out in a *gas chamber*.

The gas chamber is any room or other enclosed space in which a gas concentration may be set up and maintained by introducing a chemical agent readily detected at low concentrations (lacrimators are most frequently used). After fitting with masks and testing them by the

(1) (2) (3)

Fig. 122.—To sling the mask. (1) Position at the command "Sling." (2) Passing the shoulder sling behind the head and over the right shoulder at the command "Mask." (3) Fastening the hook and clasp together.

suction test described above, the masked men are marched into the gas chamber in small groups of from ten to twenty and remain in the gas concentration for a few minutes. If the facepiece does not fit correctly, or is adjusted improperly, warning is given in the gas chamber without any more serious effect than a momentary irritation.

Gas-mask Drill (17)

Preliminary drill is conducted "by the numbers" in order to develop proficiency in proper adjustment of the mask. Proficiency *in this drill* is then followed by practice without the numbers to insure as quick an adjustment as possible, and also to give practice in holding the breath. As a rule, careful adjustment is more essential than great speed.

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Mask Drill. (1) *To Sling the Mask.*—1. Sling, 2. MASK. At the command "Sling," grasp with the left hand the metal hook, which is near the flap of the carrier, above the two snap fasteners, at the same time grasping with the right hand the metal clasp at the extremity of the shoulder sling. Hold the carrier waist high in front of the body with side containing snap fasteners next to the body (Fig. 122-1). At the command "Mask," extend the left arm sideways to full length. At the same time pass the shoulder sling behind the head and over the right shoulder with the right hand (Fig. 122-2); then bring the two hands together across the chest and fasten the hook and clasp together (Fig. 122-3). Adjust the carrier snugly under the left arm pit. Pass the waist strap around the waist and

Fig. 123.—Mask in slung position. (The pack is put on after the mask is slung. The left front strap of pack is snapped to cartridge belt over the gas mask.)

fasten together in front (Fig. 123).

(2) *To Adjust the Mask. a. Dismounted.*—The headpiece adjusted with strap under the chin. 1. By the numbers, 2. GAS. Stop breathing. Place rifle (if unslung) between knees so that butt is off the ground; with left hand open flap of carrier; place fingers of left hand on chin above the chin strap; with the right hand knock off headpiece from behind (the headpiece being caught on the left arm by the chin strap) and continue the downward movement of the right hand until the latter is on a level with the opening of the carrier. Thrust the right hand into the carrier, grasping facepiece between the thumb and fingers just above the angle tube. Grasp the flap of the carrier with the left hand (Fig. 124-1).

TWO. Bring facepiece smartly out of carrier to height of chin, holding it firmly in both hands with the fingers of each extended and joined outside of the facepiece, the thumbs inside, midway between the two lower straps of the head harness. Thrust out the chin (Fig. 124-2).

THREE. Bring the facepiece toward the face, digging the chin into it. With the same motion guide straps of the harness over the head with the thumbs (Fig. 124-3).

FOUR. Feel around the edge to make sure the facepiece is well seated (Fig. 124-4). See that head harness is correctly adjusted.

FIVE. Close outlet valve by pinching between thumb and fingers of right hand to prevent passage of air through it and blow vigorously into

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(1) (2)

(3) (4) (5)

FIG. 124.—To adjust the facepiece by the numbers. (1) Position at the command GAS. (2) Position at the command TWO. (3) Position at the command THREE. (4) Position at the command FOUR. (5) Position at the command FIVE.

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the mask, completely emptying the lungs, thus clearing the facepiece of gas (Fig. 124-5).

SIX. Replace headpiece, adjusting the chin strap to the back of the head. Pass the flap of the carrier around the hose and fasten on the outer snap fastener. Take the position of "Trail arms" (Fig. 125).

b. Mounted.—1. By the numbers, 2. GAS. Stop breathing. Drop the reins behind the pommel of the saddle. Continue as prescribed for the dismounted drill. Having fastened the flap of the carrier around the hose as prescribed, take the reins.

FIG. 125.—The mask adjusted to the face. (During the drill no equipment should touch the ground, which might be contaminated by a liquid agent.)

FIG. 126.—Position in testing for gas. (Knee or equipment should not touch the ground.)

(3) *To Test for Gas.*—Mask being adjusted, the command is: TEST FOR GAS. Dismount if mounted. Take a moderately full breath. Stoop down so as to bring the face close to the ground but do not kneel, care being taken that the rifle does not touch the ground. Insert two fingers of right hand under facepiece at right cheek. Pull the facepiece slightly away from right cheek and sniff gently (Fig. 126). If gas is smelled, readjust the facepiece and resume the erect position. Close outlet valve by pinching between thumb and fingers of right hand and blow out hard, thus clearing the facepiece of gas. Release hold on outlet valve.

(4) *To Remove the Mask.*—1. Remove, 2. MASK. At the command "Remove," drop the reins behind the pommel of the saddle if mounted; if

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dismounted place rifle, if unslung, between knees so that the butt is off the ground; bend forward smartly and insert the left thumb under the pad of the head harness; grasp the headpiece with right hand (Fig. 127-1).

(1) (2)

FIG. 127.—To remove the mask. (1) Position at the command "Remove." (2) Position at the command "Mask."

At the command "Mask," lift the headpiece with right hand sufficiently to remove head harness, which is carried over the head with a forward circular motion of the left hand stretching the elastic fabric only enough to allow the head harness to pass over the head. The mask is retained by the thumb and forefinger of the left hand and held in front of the body. At the same time replace headpiece with right hand (Fig. 127-2).

(5) *To Replace the Mask.*—1. Replace, 2. MASK. At the command "Replace," grasp the facepiece in right hand, palm up, and hold with edges of facepiece turned upward, the fingers under the left eyepiece and thumb under the right eyepiece. With the left hand, place head-harness pad inside the facepiece just above the eyepieces. With left hand, open flap of carrier (Fig. 128). At the command "Mask," feed and slide the corrugated tube into the bottom of the carrier with the left hand until the angle tube has passed the carrier entrance, then, with the right hand, turn the edges of the facepiece toward the back of the carrier and push the facepiece into the upper empty part of the carrier about the hose. With both hands, fasten the flap of the carrier on both snap fasteners,

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the top of the flap on the inner or rear snap fastener. If mounted, take the reins. If dismounted, take position of "Train arms."

(6) *To Unsling the Mask.*—1. Unsling, 2. MASK. At the command "Mask," unfasten the body straps with both hands and then the shoulder strap with both hands. The mask is retained in the left hand by grasping the metal hook of the carrier just above the flap.

(7) *To Prepare for Mask Inspection.*—The mask being in the sling position, the command is: PREPARE FOR MASK INSPECTION.

FIG. 128.—To replace the mask. Position at the command "Replace."

FIG. 129.—To prepare the mask for inspection. Position at the command "Prepare for mask inspection."

Place rifle (if unslung) between knees so that butt is off the ground. Unsling mask. Open flap of carrier and take out complete mask, including canister. Hold carrier in left hand and canister, with facepiece hanging downward, in right hand (Fig. 129).

(8) *Mask Inspection by the Numbers.*—Being prepared for mask inspection: 1. By the numbers, 2. Inspect, 3. MASK. Free right hand by holding canister in left arm pit, the hose and facepiece hanging over upper left arm (Fig. 130-1). Examine the sling and the exterior and interior of the carrier in turn to insure that there are no defective or missing parts; that all parts are securely fastened in place; that the body of the carrier contains an antidim tube and is free from holes, tears, and rips.

TWO. Fasten the hook and clasp of the shoulder sling together. Slip the left arm through the sling and allow the carrier to hang from over the left shoulder, at the same time removing the mask therefrom by

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grasping the canister with the right hand (Fig. 130-2). Examine the canister for rust spots and weak places by pressing lightly with the fingers, beginning at the bottom and working toward the top; see that its contents do not rattle on shaking; see that rain shield is not loose and that the inlet valves are present.

THREE. Adjust the mask to the face. Then pinch together the walls of the hose just above the canister nozzle and inhale (Fig. 130-3).

(1) (2) (3)

FIG. 130.—Mask inspection by the numbers. (1) Position at the command MASK. (2) Inspecting the canister at the command TWO. (3) Testing for leaks at the command THREE.

If air can be drawn in, a leak is present, and its approximate location may be determined as follows: Pinch the walls of the hose together at the angle tube. If a leak is no longer detected on inspiration, the leak is in the hose; otherwise it is elsewhere. This inspection is not conclusive as to the absence of a leak in the hose, and such a leak will be determined by the minute inspection indicated below. If the leak is found not to be in the hose, then pinch together the outlet valve at the angle tube and also the hose. If the leak is no longer detected on inspiration, the leak is in the outlet valve below where it was pinched; otherwise it must be above this point or in the facepiece. Having determined the approximate location of the leak, or its absence, next examine the hose for obvious

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tears, punctures, or other defects. See that it is properly connected to the canister nozzle and to the angle tube and that the adhesive tape over the binding wires is present and in good condition.

FOUR. Examine the outlet valve for tears and pinholes by distending the rubber between the fingers (Fig. 130-4). Look especially for pinholes,

(4) (5) (6)

FIG. 130.—Mask inspection by the numbers (*Continued*). (4) Inspecting the outlet valve and guard at the command FOUR. (5) Inspecting the facepiece at the command FIVE. (6) Inspecting the head harness at the command SIX.

just below where the outlet valve is joined to angle tube, and for tears around valve opening. See that valve has no dirt or sand in it and that it is properly connected to the angle tube. See that the binding wire is

properly taped. See that outlet-valve guard is not loose.

FIVE. Examine outside of facepiece for tears or other damage to stockinette. See that angle tube is properly connected to facepiece, with rubber band surrounding the binding. See that the fabric has not torn or pulled loose around the eyepiece frames. Examine the chin seam and see that it is in good condition and properly taped inside and outside. Examine the inside of the facepiece for pinholes (Fig. 130-5). See that the deflector is in good condition, properly connected to the angle tube, and properly cemented to the sides of the facepiece. Test the entire facepiece fabric for softness and pliability.

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SIX. Examine the head harness (Fig. 130-6). Make sure that it is complete, that all its parts are properly attached, and that they are in a serviceable condition.

SEVEN. All men with defective masks step forward one pace. Others replace mask in the carrier, taking care to replace canister and facepiece in proper position (Fig. 131).

Care of the Mask

The importance of care of the mask, guarding it especially against moisture and rough handling, should be impressed upon troops. They should be made to understand the causes of deterioration of gas masks and realize that a defective mask affords no protection.

Fig. 131.—Replacing the canister in the carrier.

Excessive and prolonged *moisture* causes general deterioration of a gas mask finally rendering it useless altogether. Moisture in the canister materially reduces the adsorptive power of charcoal and is likely to result in caking with the opening up of large air passages through which the gas will freely flow owing to lack of sufficient contact with the absorbents.

Moisture causes rotting of the stockinette and deterioration of the rubber itself. The corrugated tube, flutter valve, and head harness are likewise affected. When the facepiece of a mask becomes wet and the mask is put away *without* careful drying the rubber tends to crease or take a *permanent set* so that it will no longer fit closely to the face. Other effects of moisture are deterioration of the adhesive tape, rusting of binder wires, and separation and mildew of the eyepiece.

If a mask has been used in the rain or has otherwise become wet, it should be slowly dried in a warm room. In no case should it be placed on a stove or near a fire as the rubber will be damaged.

Rubber parts of the mask gradually *deteriorate* with *age* though the use of antioxidents in the manufacture of rubber tends to prolong its life. If exposed to sunlight or heat the deterioration is greatly accelerated. Oil is also a cause of deterioration and oil from the hands and face are likely to accumulate on masks in service use.

Masks *in storage* should be kept in a cool dry place away from contact with sunlight, oils, corrosive liquids, or solvents. Packing in airtight

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containers so as to leave a minimum amount of dead air space will retard oxidation. For long storage, masks should be kept in a neutral atmosphere. The method of storage of masks for war reserve is to pack each mask in a separate airtight metal container from which all air is removed and replaced by nitrogen.

When canisters are stored separately a cork should be placed in the nozzle of each canister and they should be placed in watertight boxes. Canisters so stored have shown no deterioration after eight years. It is probable that they can be preserved in this manner indefinitely.

Canisters of masks used *in training deteriorate slowly*, principally owing to absorption of carbon dioxide from the air. Tests, however, have shown that even after several years use many canisters are still in good condition. As a rule, in training use, other parts of the mask become unserviceable long before the canister begins to break down. The facepieces of masks which are frequently used, if properly cared for, last longer than those left in organization supply rooms. A training mask should give about five years' service.

It is probable that the average *life* of the gas mask *in field* service will be about six months. This is little more than a guess as it is impossible to say what concentrations masks may be exposed to in future war, and for how long a time. Frequent inspections should be made and new canisters obtained as required. The World War practice of attempting to have each soldier keep a record of exposures so as to determine the remaining service life of the canister is no longer considered practicable. Assuming new canisters are available there is no cause for apprehension in this respect since, when a canister begins to fail, gases penetrate it at first in most minute and harmless quantity. Their odor, however, can be detected thus giving warning that a new canister should be obtained.

From time to time, masks reported defective have been tested at Edgewood Arsenal with the result that in no case was a defective canister found among them. Failure of these masks to protect could be traced to one or several of the following causes: (1) poor fit of facepiece, (2) improper adjustment of facepiece, (3) leakage of valve or other facepiece defects. All such defects should have been detected in inspection.

The life of the facepiece of the mask will be prolonged if *talcum powder* is sprinkled frequently over the exposed rubber surfaces. The talcum tends to retard oxidation. Care should be exercised to prevent the powder from getting into the corrugated tube or the flutter valve.

There are two types of *repair kits*, the Mark II and Mark III. The Mark II kit is a small cardboard containing a tube of rubber cement and a roll of adhesive tape. It is designed for *company* use and is for minor repairs only. The Mark III kit contains materials, spare parts, and tools for all repairs which may be made outside the factory. The

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kit is packed in a wooden box 23 by 10½ by 7¼ in. and weighs 32 lb. It is designed for issue to *regiments*.

A gas mask not used exclusively by one person should be *disinfected* immediately after use. The disinfection may be carried out as follows:

Material required: Two per cent solution of cresol or cresol liquor compound; several small rags.

To insure that no moisture will get into the canister during the disinfection, it should be elevated above the facepiece by placing the carrier containing the canister on a table or shelf with the facepiece hanging down. After disinfection, the facepiece should be left hanging until thoroughly dry before it is replaced in the carrier.

Saturate a rag with the disinfectant and sponge the entire inner surface of the facepiece, including the outer and inner side of the deflector. Apply disinfectant similarly to the outside of the flutter valve.

Pour about a teaspoonful of the disinfectant into the exit passage of the angle tube. Press the sides of the flutter valve with the thumb and finger so as to let the disinfectant run out. Do not shake off the excess.

Allow all disinfected parts to remain moist for about 15 minutes and then wipe out the inside of facepiece with a dry rag. The mask should dry thoroughly in the air before it is replaced in the carrier.

Rules for the care of the masks in the hands of troops may be briefly summarized as follows:

1. Keep mask dry.
2. If exposed to moisture dry mask carefully before replacing in carrier.
3. After using, sponge out inside of facepiece with cold water to remove saliva, dry thoroughly, and sprinkle with talcum powder.
4. Carry nothing in carrier but the mask and antidim compound.
5. Do not throw mask about.
6. When not in use see that mask is guarded against a blow or heavy weight.
7. Always replace mask properly in carrier to avoid kinking or creasing of corrugated tube or facepiece.
8. Inspect thoroughly at frequent regular intervals.
9. Repair damages to mask immediately.

INDIVIDUAL PROTECTION OTHER THAN MASKS

Protective Clothing

The gas mask protects only the respiratory organs, the eyes, and face. For protection of the body generally against the blistering action of vesicant agents which either in liquid or vapor form will readily pene-

trate ordinary cloth, special protective clothing is required.

Protective clothing is made of the so called *linseed oil cloth*, or cotton fabric treated with vegetable drying oils. The garment is a coverall with elastics at the ankles and wrists to insure tight fit at these places and a

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zipper or other similar fastening in front. A hood is provided to be *drawn over the head and fit tightly about the gas mask*. Protective gloves and shoes complete the equipment (see Fig. 132).

Protective clothing is for protection against vesicants which may come in contact with the body. In the field it is suitable for decontamination work and for men detailed to clear passages through contaminated areas. It is also useful for men working in mustard-shell filling plants, etc. Once splashed with the liquid agent this clothing is very difficult to clean and generally must be discarded. Great care must be exercised in removing contaminated clothing to avoid touching the liquid agent. The wearer should be assisted by another man wearing both gas mask and protective gloves. Discarded contaminated clothing should be buried in a pit and covered with chloride of lime and earth.

FIG. 132.—Protective suit, impermeable.

Protective clothing which is impervious to vesicant agents, such as mustard gas in either liquid or vapor form, is also impervious to air. It becomes very uncomfortable after short periods of wear since it interferes with the normal respiration of the body through the pores of the skin. It, therefore, can only be worn for a brief period at a time without injury to health. This period will vary from 15 to 30 minutes, depending upon the temperature and the amount of exercise.

Protective Salve

The idea of covering the body with some kind of salve or ointment which would protect it from vesicants was considered and tried during the World War. A salve called *sag paste* was developed and issued for this purpose. It was not a success as it absorbed mustard gas without decomposing it. Thus mustard soon penetrated the salve and came in contact with the body. At the present time, little prospect is entertained for protection against vesicants by the use of body salves or ointments.

Identification of Gases

Through Sense of Smell.—Development of ability to recognize the different chemical agents by their characteristic odors forms an important

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part of training in individual protection. Characteristic odors of gases are covered in Chaps. V to X on chemical agents. They are also given in Table IV and hence need not be repeated here.

Through the odor, it is frequently possible to tell whether a gas is of the persistent or nonpersistent type, whether vesicant or nonvesicant. Quick perception of such facts is of paramount importance in the case of men detailed as gas sentries and on gas reconnaissance work. It is, however, important that each individual soldier be able to determine such facts himself. In war, many cases will arise in which an individual will have to rely upon his own knowledge. He should be able to distinguish *gas* from the odor of powder fumes; to know whether he should or should not wear a gas mask; to know whether the substance he smells is injurious or innocuous. Such knowledge is essential for the intelligent application of first-aid measures and for the elimination of fear and panic which arise from ignorance.

Chemical Detectors.—It is recognized that some men have a much more highly developed sense of smell than others and are hence able to detect gas in low concentrations that others fail to perceive at all. To eliminate the human equation in detection of the presence of gas, considerable effort has been made, both during the World War and since, to devise some sort of chemical detector. Such devices as have been produced, however, have not proved satisfactory. They have either been too complicated for use in the field by men with no technical training or else not sufficiently selective. The International Red Cross Society at Geneva has offered a reward of $25,000 to anyone who can produce a *satisfactory* war-gas detector, but so far no one has been able to claim the reward.

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CHAPTER XX

COLLECTIVE PROTECTION

GENERAL CONSIDERATIONS

Measures of protection against chemical agents which apply generally to a group of persons, as distinguished from those measures which pertain solely to an individual, are classed under the heading of *Collective Protection*, (38) and comprise the following:

1. Provision and use of gasproof shelters where personnel may work, sleep, rest, and eat their meals in a gas-free atmosphere during gas attacks.
2. Removal of gas from enclosed spaces.
3. Decontamination of ground, buildings, clothing, and equipment.
4. Protection of weapons and ammunition.
5. Precautions with reference to food and water.
6. Provision of a protective organization to supply and issue protective equipment, to give warning of gas attacks, and to supervise training of personnel and the conduct of protective measures.

It will be noted that the measures listed above are generally of a passive nature. In addition to these there remain certain protective activities of a tactical nature which are involved in the handling of troops in combat operations. While these are sometimes included under Collective Protection, they pertain primarily to the combat elements rather than to the military force as a whole. Such measures are therefore considered separately in this text under the heading of Tactical Protection.

Collective Protection applies to all personnel in the Theater of Operations whether combatant or noncombatant. Group protective *measures*, however, should be regarded as merely supplemental to individual protection. The fundamental basis of all gas protection is still the individual mask and protective clothing.

In the combat zone, group protection by the use of gasproof shelters can be provided, at best, for a limited number at a time. Such shelters will afford means of carrying on certain activities during gas attacks which cannot be carried out by personnel wearing masks. They will affords places of temporary relief from gas where troops may be sent to eat their meals and rest. In rear areas, more extensive gas-protective arrangements will be possible; probably entire buildings, such as offices and storehouses, may be rendered gastight and habitable without necessity for the occupants to wear masks. The gas mask, however, must

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always be close at hand for emergencies and for going to and from the sheltered enclosure.

GASPROOF SHELTERS

In war, especially in stabilized situations, large areas may be subjected to harassing or lethal concentrations of gas for long periods, possibly for several days at a time. Under such conditions, provision must be made for troops to eat, rest, and sleep without wearing gas masks. Places where work can be carried on without the encumbrance of the mask are also necessary, or at least most desirable, for headquarters, medical dressing stations, telephone and signal stations, observation posts, etc. In rear areas subject to shelling and bombing, offices and sleeping quarters for Lines of Communication personnel must likewise be made habitable under gas-attack conditions. The answer to these requirements is the gasproof shelter. Such a shelter is any enclosed space, dugout, part of a trench, a tent, building or room which is rendered gastight. It may be a simple nonventilated enclosure designed for only limited use or it may be an elaborate installation with a ventilating system enabling it to be occupied indefinitely.

Nonventilated shelters are for limited use only in the protection of personnel. Frequently they may be all that it is practicable to provide for front-line troops except in stabilized situations. Such shelters are merely enclosed spaces rendered as gastight as conditions and facilities

permit.

The primary principle involved in the location or construction of a nonventilated shelter is the elimination of drafts. Insofar as practicable, such shelters should be protected from the wind, thus the lee side of a hill is preferable to the top or the windward side. Such shelters should always be provided with air-lock doorways, as described below.

In nonventilated shelters no fires can be allowed, since fires quickly consume the oxygen of the enclosed air and cause air from the outside to be drawn in through cracks and crevices and even through ordinary walls. Chimneys and all openings should be plugged up to render them as airtight as possible. The shelter should be located as high up as practicable, considering also other safety requirements. In the field, ravines, valleys, and wooded patches, where the concentration and persistency of gas are likely to be greatest, should be avoided. In buildings, the upper floors will be safer as regards gas concentration than the lower floor and cellar.

The *air-lock doorway* is an enclosed passageway with a door at each end, the passage being deep enough so that a man on entering or leaving cannot handle both doors at once. For medical dressing stations the passage must be sufficiently deep to accommodate two men carrying a stretcher. The doors hang on slanting frames and consist of weighted

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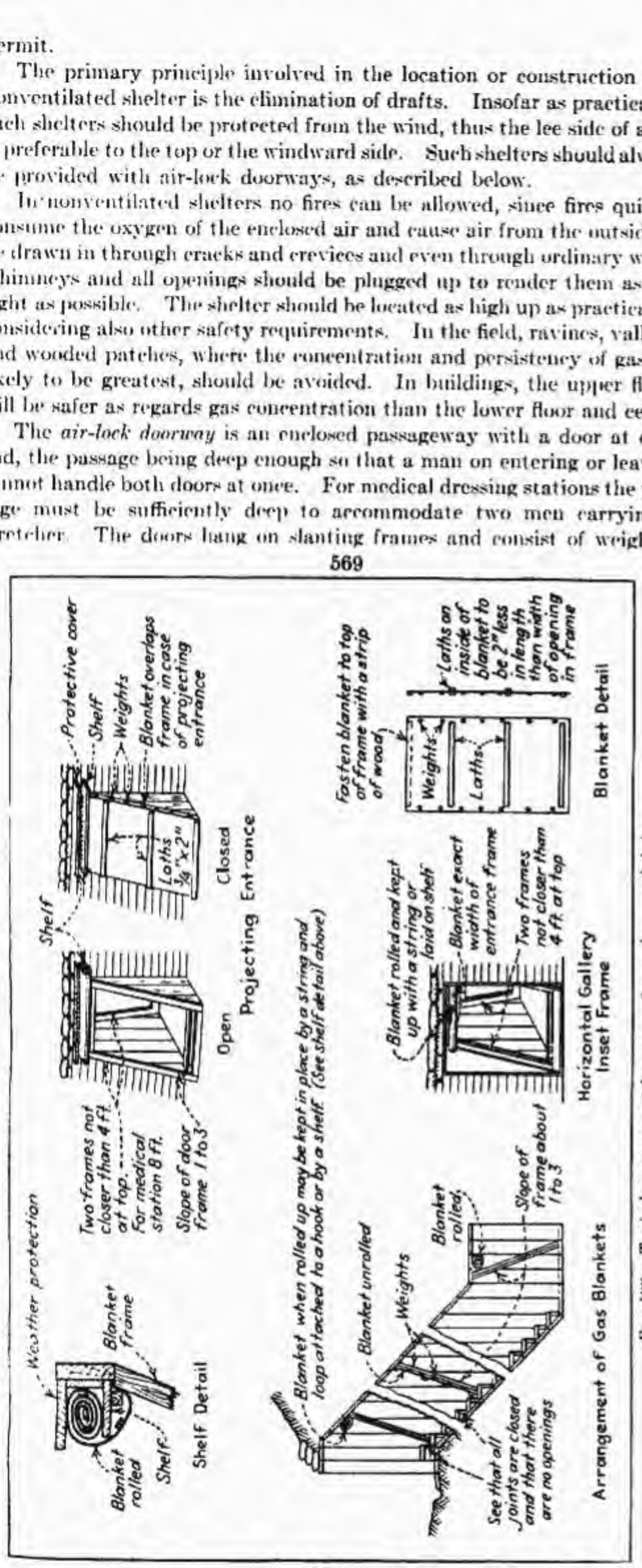

Fig. 133.—Typical arrangement for gasproofing underground shelters.

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blankets which are raised up from the bottom to enter, the weights causing them to fall shut when released (see Fig. 133). The outside blanket is always lifted against the wind, as otherwise a gust of air will be blown into the passageway and raise the inner door admitting gas to the shelter. A box of chloride of lime (bleach) is kept in the passageway and is sprinkled over the floor of the passage. In case men entering the shelter have mustard gas on their shoes, they should shuffle their feet in the bleach. This will tend to neutralize the mustard and prevent a concentration of mustard vapor being built up in the enclosure. Otherwise a dangerous concentration may develop, and so gradually that its odor may not be detected by those inside. When practicable, shelters may be provided with anterooms where men can remove contaminated clothing and equipment before entering the inmost enclosure.

Nonventilated shelters are for limited use only in the protection of personnel. They may frequently be all that it is practicable to provide for front-line troops except in stabilized situations. Such shelters are merely enclosed spaces rendered as gastight as conditions and facilities permit. They should at least be provided with air-lock doors.

As there is no fresh air entering such a shelter, when occupied by personnel, the atmosphere inside will gradually become fouled owing to replacement of the oxygen by carbon dioxide given off in exhalation. Thus the length of time that such a shelter may be used depends upon the amount of air it contains, or its cubic capacity, and the number of persons occupying it. In making use of such spaces, it should be understood that the *minimum* amount of *air* required *for a man* is 1 *cu. ft. per minute*. Persons inside the chamber should remain quiet and not move about because muscular activity increases the consumption of oxygen, thus shortening the time which the place may be used with safety.

In the World War, many shelters of this type actually proved to be *gas traps*. This can be attributed to several causes. They were frequently dugouts leading from trenches into which gas tended to flow and remain in high concentration. Doorways were often poorly made and improperly used. Again, men were constantly entering and leaving these places each bringing in a certain amount of gas on his clothing or shoes so that gradually a dangerous concentration was built up inside. This was particularly true as regards mustard gas.

Nonventilated shelters are suitable for storage of food supplies, munitions, and equipment. They should be opened and ventilated as soon as the outside air is free of gas.

A *ventilated shelter* is one provided with apparatus for drawing in fresh air from the outside and filtering out the gas or irritant smoke in the same manner as a gas-mask canister. Such a filtration device is called a *collective protector*. For permanent installations, a collective protector

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should consist of a large canister containing both chemical and mechanical filters, the air being drawn through the canister by a suction fan driven by an electric motor.

For use in the field, a collective protector should be portable on motor transportation and should be furnished in at least two sizes—one purifying sufficient air for small gasproof shelters in the forward part of the combat area, and one purifying sufficient air for larger shelters in the rear areas of the combat zone.

Coast-artillery plotting rooms, etc., can be rendered gasproof in this manner, though additional provisions are required in the way of blastproof doors and windows.

In all such shelters, the fact that the concentration of gas is invariably greater near the ground level should be remembered and, consequently, the air intake should be as high as it may be practicable to place it.

It is unnecessary to provide any special means of air outlet. It is necessary that a slightly higher air pressure be developed inside the shelter than outside. This will insure against seepage of gas through walls and crevices. As fresh air is drawn in through the filter and a positive pressure set up in the shelter, some air will be forced out through the walls and crevices so that there will be a gradual change of air in the enclosure.

Gas shelters in the forward part of the combat area will generally be bombproofed. In rear areas, when located near installations that are likely targets for air attack, bombproof shelters also probably will be required. Gas masks, of course, must be kept immediately at hand at all times.

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CHAPTER XXIV

THE EFFECTIVENESS OF CHEMICAL WARFARE

Many factors enter into an evaluation of the relative effectiveness of war weapons. Chief among these are: (1) the belligerent's philosophy of battle; (2) the tactical objectives sought, *i.e.*, casualties, destruction of material, the occupation of important strategic positions, denial to the enemy of the use of vital land or water areas, etc.; (3) the military

effort required to achieve the objectives sought; (4) the degree of preparation and training of the enemy's armed forces; and (5), last but not least, the morale and determination of the civil population. The strategical and tactical employment of chemicals in war and their effect upon the enemy's armed forces and civilian population has been discussed in preceding chapters. It is the purpose of this chapter to touch briefly on the other factors just mentioned, to discuss at some length the casualty value of chemicals in war, and to draw some comparisons between the results produced by the principal military agents used in the World War.

PHILOSOPHY OF BATTLE

Prior to the era of modern times, there do not seem to have been any generally recognized limits to the scope and character of warfare. On the contrary, in war, might made right, and those means which most expeditiously and utterly annihilated an enemy were preferred. Few if any checks or limitations appear to have been placed upon the powers of the commanders of armies in the field.

The first code of warfare which sought to define the limits within which armed conflict between civilized nations should be confined were the rules and instructions for the governance of the Union armies in the American Civil War (1861–1865). These were promulgated in the celebrated General Order 100 of the U.S. War Department in 1863, and eventually became the basis of what is now known as the Rules of Land Warfare. These "rules" are now accepted, at least in principle, by all civilized nations as the basis for the conduct of war.

There is, however, still a considerable divergence of viewpoint in the interpretation of many of the provisions in the Rules of Land Warfare. Perhaps the most fundamental of these differences is that concerning what might be termed the philosophy of battle. Here, there are two quite distinct schools of thought: One holds, in principle, that the ends

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of war justify the means and that there is no limit to the degree of force which may be employed in order to attain victory. This philosophy of battle is typically illustrated in the German doctrine of war set forth in the German War Book of 1910, as follows:

> In the matter of making an end of the enemy's forces by violence it is an incontestable and self-evident rule that the right of killing and annihilating, hostile combatants is inherent in the war power, and its organs, and that all means which modern inventions afford, including the fullest, most dangerous, and the most massive means of destruction, may be utilized.

The other school of thought holds that no greater degree of force should be employed in war than is necessary to achieve victory in battle and that ruthless destruction of life and property is not warranted in the conduct of warfare. The United States Government has consistently held to this second viewpoint, and has always sought to wage war within the limitations thus imposed. As will be shown in this chapter, no weapons yet devised measure up to chemical agents in effectiveness in waging war in accordance with this philosophy of battle.

The object of war is to bring about the complete submission of the enemy as soon as possible by means of *regulated* violence. Manifestly, those means and instrumentalities which enable a nation at war to achieve this object with the minimum military effort and the least dislocation of its normal national life are, in general, the most effective. The choice of such means is not unlimited, however, since among modern civilized states the scope of armed conflict is measured by the recognized limits of military necessity. These limits are stated in the Rules of Land Warfare as follows:

> Military necessity admits of all direct destruction of life or limb of *armed* enemies, and of other persons whose destruction is incidentally *unavoidable* in the armed contests of war; it allows of the capturing of every armed enemy, and of every enemy *of importance* to the hostile government, or of peculiar danger to the captor; it allows of all destruction of property, and obstruction of ways and channels of traffic, travel, or communication, and of all withholding of sustenance or means of life from the enemy; of the appropriation of whatever the enemy's country affords that is necessary for the subsistence and safety of the army, and of such deception as does not involve the breaking of good faith, either positively pledged, regarding agreements entered into during the war, or supposed by the modern law of war to exist.

Despite the fact that airplanes, long-range artillery, and other modern inventions have vastly extended the scope and character of armed conflict, so that war is now no longer confined to the battle front, but extends far into the home territory of the enemy which supports the battle front by furnishing the means of war in both men and materials, nevertheless, the hostile army in the field is still the primary objective in military operations.

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This being the case, it follows that the complete submission of an enemy will, in the future as in the past, be accomplished in the main by destroying the *combat strength* of his armed forces. How will this result be accomplished in future wars?

In ancient and medieval times, when wars were fought by professional armies small in comparison with the total population of a state, the most effective means of conquering an enemy was the more or less complete annihilation of his army. In modern times, however, wars are fought by enormous armies, raised by universal conscription, and composed of practically the entire able-bodied manhood of the nation. Also the vast quantities of munitions required in modern warfare tax the productive effort of the state as never before.

In the World War, not only were the armies of the various belligerents the largest ever raised, both in actual numbers and as percentages of the entire belligerent populations, but the effort to maintain these huge armies strained the economic life of each nation to the breaking point. Measures which increase this burden of maintenance will obviously contribute far more toward deciding the issues of future wars than the intrinsic loss of man power from battle deaths.

Based upon the mobilizations of the late war, military authorities variously estimate that modern war requires from three to six men behind the lines to keep one soldier at the front, and the difficulties of maintaining an army in the field are enormously increased by the task of caring for the sick and wounded.* Men put out of action by nonfatal battle wounds are (for the duration of their noneffective periods) military liabilities, instead of assets. The strategic value of battle deaths has thus greatly diminished, and modern military thought places chief emphasis upon *nonfatal* battle casualties. Those instrumentalities which enable an army to inflict upon the enemy the greatest number of *nonfatal* battle casualties, in proportion to the military effort expended, are accordingly regarded as the most effective military agents.

* In the A.E.F. in France in 1918, the average annual strength of the Medical Department was 76,606, equal to *one-eighth* of our average total *combat* strength in France.

In order to ascertain the relative effectiveness of modern military agents, we cannot do better than examine and evaluate the casualties of the World War. We will accordingly devote the next few pages to a brief survey and comparison of the casualties sustained by both sides in the late war.

CASUALTIES

Before examining these casualty records, it might be well to define what is meant by the expression *casualty*. The popular idea of a war

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casualty is a person who is either killed in action on the field of battle or who *died* from the effects of battle wounds. In a military sense, however, a casualty is any loss of personnel which reduces the effective fighting strength of a military unit. Military casualties are, therefore, those losses caused by death, wounds, sickness, capture, desertion, and discharge from the service. Casualties are usually divided into two general classes—battle casualties and nonbattle casualties. The former are those losses caused by enemy action in battle, while the latter include all other losses. Casualties may also be either permanent or temporary. Permanent casualties are those who are not returned to the army during the remainder of the war, while temporary casualties are those who are put out of action for temporary periods but are subsequently returned to the army during the war.

Very complete and accurate statistics have been compiled and published by the United States and British Governments concerning their World War casualties and many valuable military lessons have been learned as a result of the analytical study of these figures.

Unfortunately such excellent data have not been published by the other belligerents. Some have released partial statistics and have stated that they did not keep such detailed records of their casualties as to show

cause of casualty and the result thereof, while others have published no figures at all and have made no explanation of their silence on the subject. The author has made every effort to secure the most accurate and reliable figures available, and has cited his principal authorities in each case. However, it must be borne in mind that statistics are always somewhat imperfect, especially where they have not been compiled from uniform viewpoints, as in this case.

Records of battle injuries from the very nature of the case cannot be complete. In most cases military casualty statistics are based upon hospital admissions and thus include only those men who were treated in the field hospitals. This necessarily leaves out of the record a very large number of men who were rendered *hors de combat* by battle injuries for which they received local treatment. While such men nominally remained with their units, they were militarily noneffective for considerable periods of time. This was particularly true of a large number of men who were sufficiently gassed to be put out of action, but who were not at the time thought to be so seriously injured as to require evacuation to the field hospitals.

Table IX shows the number of men mobilized by countries during the World War, together with the total casualties sustained by each. It also shows the number killed or dying from all causes, the wounded, those taken prisoner or missing, and the percentages of casualties in the total mobilizations of each country.

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TABLE IX.—CASUALTIES IN THE WORLD WAR

	Total mobilized forces	Killed and died*	Wounded, excluding deaths	Prisoners and missing	Total casualties	Per cent
Allies:						
Russia	15,500,000	1,700,000	4,950,000	2,500,000	9,150,000	59.0
France	8,410,000	1,357,800	4,266,000	537,000	6,160,800	73.3
British Empire†	8,904,467	698,706	2,004,976	352,458	3,056,140	34.3
Italy	5,615,000	650,000	947,000	600,000	2,197,000	39.1
United States‡	4,137,828	116,902	219,296	4,500	340,698	8.2
Japan	800,000	300	907	3	1,210	0.2
Roumania	750,000	335,706	120,000	80,000	535,706	71.4
Serbia	707,343	45,000	133,148	152,958	331,106	46.9
Belgium	267,000	13,716	44,686	34,659	93,061	34.5
Greece	230,000	5,000	21,000	1,000	27,000	11.7
Portugal	100,000	7,222	13,751	12,318	33,291	33.3
Montenegro	50,000	3,000	10,000	7,000	20,000	40.0
Total	45,471,638	4,933,352	12,730,764	4,281,986	21,946,012	48.2
Central Powers:						
Germany	11,000,000	1,773,700	4,216,058	1,152,800	7,142,558	64.9
Austria-Hungary	7,800,000	1,200,000	3,620,000	2,200,000	7,020,000	90.0
Turkey	2,850,000	325,000	400,000	250,000	975,000	34.2
Bulgaria	1,200,000	87,500	152,390	27,029	266,919	22.2
Total	22,850,000	3,386,200	8,388,448	3,629,829	15,404,477	67.4
Grand total	68,321,638	8,319,552	21,119,212	7,911,725	37,350,489	54.7

* Killed and died includes deaths from *all* causes.

† British "Official Medical History of the War," H. M. Stationery Office, London, 1931.

‡ Figures for the United States include 80,727 United States Marines, but exclude United States Navy. Excluding United States Marines who served with the Army in France, the United States Army casualties were as follows: total mobilized forces, 4,057,101; killed and died, 114,095; wounded casualties, 210,398; excluding 13,691 who died of wounds; prisoners and missing, 4,423 (representing prisoners only, all missing cases cleared up; total casualties, 328,916; per cent, 8.1).

In order to arrive at the number of injuries inflicted by weapons ("battle injuries"), the "prisoners and missing" should be omitted, since obviously nothing definite is known as to their condition. In this connection, however, it should be pointed out the probabilities are that approximately the same percentages of "killed" and "wounded" would occur among the "prisoners and missing," as among the forces accounted for, so that, in arriving at the *total* "killed and wounded," it would be logical to extend the percentages of "killed and wounded" to apply also to the "prisoners and missing." On the other hand, in comparing casualties caused by various military agents, it is safer to exclude the "prisoners and missing," from the figures, in order to eliminate all conjecture, although it would not affect the relative percentages either way. Accord-

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ingly the "prisoners and missing" are excluded in the following casualty statistics, unless otherwise stated.

Another important point to be noted in connection with Table IX is the fact that the figures in Column 3, showing "killed and died," include men who died from nonbattle injuries (including disease), as well as those who died from battle injuries. Exact figures are not available from all the countries shown in Table IX to permit these two classes of deaths to be separated. We have, however, the official figures for the United States and the British Empire and the approximate estimates for the other belligerents.

Table X shows (by country) the number of battle deaths and nonbattle deaths, the total wounded (including deaths), and the percentages of battle deaths to the total numbers wounded.

TABLE X.—BATTLE DEATHS IN WORLD WAR

Country	Battle deaths	Nonbattle deaths	Total wounded, including battle deaths	Per cent of "battle deaths" to "total wounded" (including "battle deaths")
Allies:				
Russia	1,416,700	283,300	6,366,700	22.2
France	1,131,500	226,300	5,397,500	21.0
British Empire	585,533	113,173	2,590,509*	22.6
Italy	541,500	108,500	1,488,500	36.4
United States	52,842	64,060	272,138	19.4
Japan	250	50	1,157	21.6
Roumania	279,756	55,950	399,756	70.0
Serbia	37,500	7,500	170,648	21.9
Belgium	11,430	2,286	56,116	20.4
Greece	4,000	1,000	25,000	16.0
Portugal	6,000	1,222	19,751	30.4
Montenegro	2,500	500	12,500	20.0
Total	4,069,511	863,841	16,800,275	24.2
Central Powers:				
Germany	1,478,000	295,700	5,664,058	25.9
Austria-Hungary	1,000,000	200,000	4,620,000	21.6
Turkey	270,000	55,000	670,000	40.3
Bulgaria	73,000	14,500	225,390	32.4
Total	2,821,000	565,000	11,209,448	25.2
Grand total	6,890,511	1,429,041	28,009,723	24.6

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From Table X it is noted that the battle deaths were almost five-sixths of the total deaths, while less than one-fourth of the total wounded died.

While the figures in Tables IX and X show that the total casualties in the World War greatly exceeded, both in number and percentage of forces engaged, the casualties of all previous wars, and the ratio of *battle* injuries to *nonbattle* injuries was very much higher than ever before, the percentage of *deaths* due to battle injuries was much lower. The use of

TABLE XI.—GAS CASUALTIES IN THE WORLD WAR

Country	Battle casualties due to gas			Ratio of gas casualties to total wounded		Remarks
	Nonfatal injuries	Deaths	Totals	Including deaths	Excluding deaths	
				%	%	
Russia	419,340	56,000	475,340	7.5	8.5	1
France	182,000	8,000	190,000	3.5	4.3	1
British Empire	180,597	8,109	188,706	7.3	9.0	1
Italy	55,373	4,627	60,000	4.0	5.8	2
United States	71,345	1,462	72,807	26.8	32.5	4
Germany	191,000	9,000	200,000	3.5	4.5	5
Austria	97,000	3,000	100,000	2.2	2.7	6
Others	9,000	1,000	10,000	13.2	15.4	7
Total	1,205,655	91,198	1,296,853	4.6	5.7	

chemicals in the World War played a large part in reducing the percentage of deaths from battle injuries.

As gas was not used to any serious extent in the World War, except on the Western, Eastern, and Austro-Italian Fronts, only the countries which fought on those three fronts sustained any considerable number of gas casualties. It has been stated that Roumania and Bulgaria suffered a large number of gas casualties, but the author has been unable to verify this report or to ascertain any reliable figures concerning same. Accordingly, Table XI shows, for the countries engaged on the Western, Eastern, and Austro-Italian Fronts only, the number of *gas* casualties, the deaths resulting from battle gases, and the percentage of gas casualties to the total wounded, both including and excluding deaths.

[1] "A Comparative Study of World War Casualties," by Colonel (now Major General, Ret.) H. L. Gilchrist, U.S. Government Printing Office, Washington, 1928. (46)

[2] The final volume of the British "Official Medical History of the War," published by His Majesty's Stationery Office, London, 1931, which deals with the statistical aspect of casualties, gives (Table 9, p. 111) the approximate total gas casualties admitted to Medical Units in France, 1915-1918, as 185,706 casualties (admissions) of which 5,899 were deaths. The figures for the year 1915, however,

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include *British* troops only; the admissions and deaths among Dominion troops being unknown. Also since the casualties here reported are based upon hospital admissions, they do not include gas casualties who died on the battlefield. General Foulkes in his recent book, "Gas! The Story of the Special Brigade" (page 338), gives the total known British deaths from gas as 6,109, to which (he says) "must be added about 3,000 that were unrecorded, mostly dead, in April and May, 1915." These unrecorded casualties undoubtedly include the Dominion Troops (particularly Canadians) who were subjected to the first German gas-cloud attack at Ypres in April, 1915, and who were not included in the British official figures quoted above. The author has, accordingly, arrived at the total British gas casualties and deaths, given in Table XI above, by adding 3,000 casualties, including 2,000 deaths, to the British official casualty figures and to the total deaths stated by Foulkes.

[3] Gilchrist (46) gives the Italian gas casualties as 13,300, of which 4,627 (34.8 per cent) were deaths, but states that these figures are unreliable. From a study of the chemical attacks on the Italian Army and resulting gas casualties, it is believed that these figures are seriously in error. The author, after a careful estimate of the chemical-warfare situation on the Italian Front, is inclined to accept the stated deaths (4,627) as approximately correct, but believes the total number of Italian gas casualties were at least 60,000.

[4] "The Medical Department of the United States Army in the World War," Vol. XV, "Statistics," Part 2, Table 119, gives the complete casualty records of the United States Army during the World War. The figures, however, do not include the casualties of the United States Marines serving with the A.E.F. The figures, shown in Table III above, were arrived at by adding to the official Medical Department casualty records of the Army, the casualty figures for the Marine Corps, as follows: disabled by gas, 2,014; died of gas, 35; killed in action by gas, 6; total gassed, 2,055.

[5] Gilchrist (46) gives the German gas casualties as 78,663, of which only 2,280 died. Dr. Otto Muntsch, (48) quotes the same figures, but, in explanation of the relatively small number of German gas casualties, says:

"A great many of the gas casualties are to be found among those who were reported missing. In many cases, the casualty lists report as sick only the men who were treated in the field hospitals. The doubtless very great number of men who were only slightly affected by gas and who, although unfit for service, were able to remain with their units, receiving treatment in the ambulances, are thus left out of the statistics. Skin diseases caused by chemical substances are frequently classified in the statistics, not as gas injuries, but as skin affections."

It is also noted that Dr. Muntsch shows no gas casualties during the first year of the war (1915), although the British launched several very effective cloud-gas attacks against the Germans in the fall of 1915, and the French commenced the use of gas artillery shell against the Germans in September, 1915. Dr. Rudolph Hanslian (20) also quotes the same figures for the German gas casualties, thus: "The German casualties due to gas *are said* to have amounted to 78,663." He further states that 58,000 of these casualties occurred between Jan. 1 and Sept. 30, 1918! It has also been explained by other German writers that German battle casualties who were retained for treatment in regimental and corps areas (estimated at 30 per cent) were not included in the official casualty statistics. Even after making due allowances for all the various considerations mentioned above, the author is of the opinion that the published figures for the German gas casualties are far too low. Considering the great chemical activities of the British and French Armies and the known effectiveness of the British gas troops' attacks, it is impossible to believe that the German gas casualties could have been any less than either the British or French alone. After a careful estimate of the chemical-warfare situation on the Western Front, the author places the German gas casualties at 200,000, of which 9,000 were deaths.

[6] Considerable difficulty was encountered in obtaining reliable information concerning the Austrian gas casualties. A careful study was made of the Russian and Italian gas attacks against the Austrians and the conclusion was reached that the Austrian gas casualties approximated 100,000, including 3,000 deaths.

[7] In addition to the principal belligerents listed above, there were a number of troops of several smaller powers, such as Belgium and Portugal, which operated on the Western Front and sustained gas casualties. The gas casualties sustained by these troops are estimated collectively at 10,000, including 1,000 deaths.

From Tables IX, X, and XI, we extract the following significant figures. For the countries engaging in chemical warfare (*i.e.*, Russia, France, British Empire, Italy, United States, Belgium, Portugal, Germany and Austria-Hungary), the *total wounded* (including battle deaths) were 28,009,723, of which 1,296,853 (4.6 per cent) were due to gas, and 26,712,870 (95.4 per cent) were due to other military agents. Of the corresponding total of 21,119,212 *nonfatal* battle injuries, 1,205,655

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(5.7 per cent) were due to gas, and 19,913,557 (94.3 per cent) were due to other military agents. For the same countries, the *total battle deaths* were 6,890,511, of which 91,198 (1.32 per cent) were due to gas, while 6,790,313 (98.68 per cent) were due to other military agents.

Thus, while gas caused 4.6 per cent of all battle injuries and 5.7 per cent of all *nonfatal* battle injuries, it caused only 1.32 per cent of all battle *deaths*. Gas was, therefore, over four times as effective in securing nonfatal battle injuries as in causing battle deaths. The military importance of *nonfatal* battle injuries, as distinguished from deaths, has already been pointed out, so that we may logically draw the conclusion that gas, as a military agent, responds in an outstanding degree to one of the most important requirements of modern warfare.

MILITARY EFFORT EXPENDED FOR GAS CASUALTIES

Having determined the battle casualties caused by gas, our next inquiry logically concerns the military effort expended in securing these casualties, as compared to the military effort expended in securing the sum total of battle casualties.

In connection with this inquiry, it should be borne in mind that the military effort here referred to is only that part of the total *combat* effort which was expended in securing *personnel* losses (*i.e.*, battle injuries and deaths), and does not concern *material* and other tactical losses inflicted on the enemy, although these latter are frequently of great importance in modern war.

Battle injuries and deaths are inflicted by the so-called *combat arms of armies*. As organized in the World War, the armies of the principal belligerents consisted of five combat arms in order of relative strength as follows: (1) infantry; (2) artillery; (3) combat engineers; (4) air corps; and (5) cavalry. These combat arms in all of the principal armies constituted about two-thirds of all troops in the Theater of Operations, and the relative strengths of these arms, in percentages of the total combat strengths, averaged approximately as follows:

	Per Cent
1. Infantry (including machine-gun and tank units)	50.0
2. Artillery (including heavy trench-mortar units)	25.0
3. Combat Engineers (including chemical units)	8.0
4. Air Corps (including observation-balloon units)	6.0
5. Cavalry (including mechanized units)	1.0
Miscellaneous (including headquarters and headquarters troops, M.P.'s, train headquarters, staffs, executive services, antiaircraft machine-gun units, and miscellaneous auxiliary combat units	10.0
Total *combat* strength	100.0

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TABLE XII.—TOXIC GASES USED IN BATTLE DURING THE WORLD WAR*

(Tons)

Country	Arm	1914	1915	1916	1917	1918	Total used in battle	
Germany	A	0.5	1,500	6,500	15,000	30,000	53,000	5
	C	0	1,650	1,200	1,250	500	4,600	
France	A	0	350	3,000	7,000	15,650	26,000	
	C	0	0	800	1,200	850	2,850	
England	A	0	0	500	3,300	6,200	10,000	
	C	0	170	1,205	2,065	2,260	5,700	
United States	A	0	0	0	0	1,000	1,000	
	C	0	0	0	0	100	100	
Russia	A	0	200	1,500	2,000	0	3,700	
	C	0	0	500	1,000	0	1,500	
Austria	A	0	0	650	2,700	4,650	8,000	
	C	0	0	230	320	250	800	
Italy	A	0	0	350	2,500	3,500	6,350	
	C	0	0	100	300	200	600	
Total	A	0.5	2,050	12,500	32,500	61,000	108,050	5
Total	C	0	1,820	4,035	6,135	4,160	16,150	
Grand total†		0.5	3,870	16,535	38,635	65,160	124,200	5

* In addition, smokes and incendiaries constituted about 20 per cent and 5 per cent, respectively, of the toxic-gas expenditures.

A indicates artillery, including trench mortars.

C indicates special chemical (engineer) troops.

† In the British and United States Armies the only trench mortars firing gas ammunition were the 4-in. Stokes mortars, especially designed for projecting chemicals. These mortars were manned by chemical troops. In all other armies a part of the ammunition fired by trench mortars was gas, and as trench mortar batteries were generally included under the artillery arm, the gas fired by trench mortars (other than British and United States) is credited to the artillery.

As smoke agents and incendiaries were primarily employed for the protection of personnel and the destruction of enemy material, repectively, and caused only a negligible number of casualties, these two classes of chemical agents need not be further considered here.

Coming now to the war gases, we find two distinct classes—(1) the nonfatal lacrimators and irritants, which, while useful for many tactical purposes, caused no appreciable battle injuries, and (2), the lethal and

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vesicant gases, which caused practically all the gas casualties. Again we eliminate the effects of noncasualty gases and consider only results produced by the casualty gases.

During the World War gases were employed offensively by *three* combat arms only, *viz.*, (1) artillery, (2) chemical troops (included above as engineers), and (3) infantry. As the infantry used gas only to a very limited extent in grenades, and these were nearly all of the lacrimatory and less irritant types, practically no gas casualties were caused by infantry action. This then left casualty gas warfare in the hands of the artillery and chemical troops.

Table XII shows the quantities of toxic gases used in battle by the artillery and chemical troops of the principal belligerents during the war.

From Table XII it will be noted that the artillery (including trench mortars) put over about 85 per cent, and the chemical troops about 15 per cent, of the gas used in the World War.

No artillery units were exclusively employed in chemical shoots, but all the light and medium artillery and part of the heavy artillery, on both sides, fired gas shell. The artillery effort devoted to gas warfare is accordingly measured by the ratio of gas shell fired to the total artillery ammunition expended during the war. The quantities of gas shell used were not uniform, even as percentages of the total shell fired, but varied considerably during the progress of the war. However, as indicated in Table XII, there was a rapidly expanding increase in the use of gas shell as the war progressed. In order, therefore, to arrive at any estimate as to the amounts and percentages of gas shell used, we should consider each year of the war separately and then strike an average for the whole war period.

No casualty-producing gas shell were used until near the end of the first year of the war (June, 1915), when the Germans brought out their K shell; the Allies did not commence firing such shell until January, 1916. From the beginning of 1916 to the end of the war, the percentage of gas shell used on both sides steadily increased, both in actual numbers and as percentages of the total artillery-ammunition fired (see Chart XIX, page 681).

The percentage of gas shell fired also varied greatly on the different fronts and even on various parts of the same front. By far the greatest part of all the gas shell used in the World War was fired on the Western Front. Next in gas artillery activity came the Eastern Front and the Austro-Italian Fronts in the order named. As far as can be ascertained, relatively few gas shells were used on other fronts in the late war. It is said that the Rumanians and Bulgarians sustained a considerable number of gas casualties, but neither the means employed nor the actual numbers involved could be verified.

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Table XIII shows that 4.54 per cent of the artillery ammunition used in the war was gas. This means then that 4.54 per cent of the total artillery effort was devoted to gas warfare. As the strength of the artillery averaged about 25 per cent of the total combat strength of an army in the late war, we may say that artillery gas warfare constituted 4.54 per cent of 25 per cent, or 1.13 per cent of the total combat effort of each army engaged in gas warfare. To this figure for the artillery we must add the combat engineer (*chemical troops*) effort that was also devoted to gas warfare.

Table XIV shows the engineer troops that were organized and employed as special chemical troops during the war.

From Table XIV it is noted that the 23,765 engineers employed as gas (chemical) troops during the war constituted approximately 2.0 per cent of the total combat engineers, so we may say that 2.0 per cent of

Table XIII shows the estimated total artillery ammunition used during the war by the nations shown in Table XII.

TABLE XIII.—ESTIMATED TOTAL ARTILLERY AMMUNITION EXPENDED DURING THE WORLD WAR

Country	Gas shell		Other shell		Total	
	Number	Per cent	Number	Per cent	Number	Per cent*
Germany	33,000,000	6.37	485,000,000	93.63	518,000,000	35.6
France	16,000,000	4.57	334,000,000	95.43	350,000,000	24.05
England	4,000,000	2.2	178,000,000	97.8	182,000,000	12.51
United States	1,000,000	12.50	7,000,000	87.50	8,000,000	.55
Russia	3,000,000	4.17	69,000,000	95.83	72,000,000	4.95
Austria	5,000,000	2.86	170,000,000	97.14	175,000,000	12.03
Italy	4,000,000	2.67	146,000,000	97.33	150,000,000	10.31
Total	66,000,000	4.54	1,389,000,000	95.46	1,455,000,000	100.00

* Per cent of total shell fired by all the countries named.

the combat-engineer effort was devoted to chemical warfare, and that gas warfare by engineer (chemical) troops constituted 2 per cent of 8 per cent, or 0.16 per cent of the total combat effort of the armies. Adding the artillery effort (1.13 per cent) and engineer (0.16 per cent) together, we find that 1.29 per cent of the total combat effort of the armies was expended in gas-warfare operations from which were produced 4.6 per cent of the total battle injuries and 5.7 per cent of all the nonfatal battle injuries. We may, therefore, say that, on the basis of the ratio of casualties to military effort, *gas was from four to five times more effectiv* than the average of the military agents used in the war.

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These are very remarkable results when we remember that gas warfare was not introduced until near the end of the first year of the war; it then went through a period of experimentation for the next two years and was not developed to a stage even remotely approaching its possibilities until almost the last year of the war when mustard gas was introduced in

TABLE XIV.—SPECIAL CHEMICAL TROOPS IN THE WORLD WAR

Country	Chemical units		Total chemical strength	Total combat engineer strength	Chemical per cent of combat engineers	Organization of chemical units
	Battalions	Companies				
Germany	9	36	7,000	320,000	2.0	4 Regiments of 2 battalions of 4 companies plus 1 additional battalion
England	5	21	7,365	106,000	6.9	1 Brigade of 5 battalions of 4 companies and 1 special company
France	6	18	3,600	175,000	2.0	6 Battalions of 3 companies each
United States	2	6*	1,700	85,000	2.0	1 Regiment of 2 battalions of 3 companies each
Russia	7	14	2,800	250,000	1.1	7 Battalions of 2 companies each
Austria	1	4	800	75,000	1.1	1 Battalion of 4 companies
Italy	1	3	500	150,000	0.3	1 Battalion of 3 companies
Total	31	102	23,765	1,161,000	2.0	

* Only two battalions of the 1st Gas Regiment arrived in France and took part in the operations on the Western Front in 1918. In March, 1918, the 1st Gas Regiment was increased to six battalions (of three companies each) with a total strength of 5,083 officers and men. Early in September, 1918, two additional six-battalion regiments were authorized, making a total of 15,000 chemical troops that would have been employed by the American Army in France in 1919, had the war continued.

July, 1917. Unlike H.E. shell which had been fully developed and were standard munitions for thirty years before the World War, gas shell had to be hastily improvised and developed under stress of war conditions. Many of the gases used in artillery shell proved unsuitable for such use

or were not adapted to conditions met on the field of battle. Thus, out of a total of more than fifty chemical substances loaded into artillery shell, only four or five proved really effective under battle conditions.

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Each time a new gas was tried out much effort was involved in preparing and firing the shell and in ascertaining their battle effectiveness. Often the efficiency of such shell was a matter of dispute and their real value could only be definitely ascertained after a large number of rounds had been fired. Perhaps the most noteworthy example of this kind was the French Vincennite shell, filled with a mixture of hydrocyanic acid and arsenic trichloride. This mixture had a very marked toxicity in the laboratory and great results were expected to be obtained in the field from its use. The French filled no less than 4,000,000 artillery shell with this filling, yet the consensus of opinion was that, owing to its extreme volatility and peculiar physiological reaction, it was not an effective gas under battle conditions, and hence only a very small percentage of casualties were actually obtained from a very large expenditure of this ammunition.

In addition to inefficient toxic gases, there were also a large number of shell containing gases of the lacrimatory and irritant types which were not intended to produce casualties, but to harass the enemy, causing him to mask or to penetrate the mask and cause its removal in the presence of toxic gas. Thus, Germany filled 14,000,000 shell with DA, a substance which, while highly irritant, was virtually not lethal and did not produce more than 20,000 casualties all told. When the various non-casualty-producing gas shells are substracted from the total, it discloses a very high casualty power for the remaining successful types such as the phosgene and mustard shells.

This is strikingly illustrated by the following comparison: Considering the seven countries which engaged in chemical warfare during the World War (listed in Table XIII), we find (from Table X) that the total casualties were 28,009,723, of which 1,296,853 were due to gas (Table XI). Of the 26,712,870 nongas casualties, it is estimated that approximately one-half were due to H.E. shell and shrapnel, or a total of 13,356,435. Since the total artillery ammunition (other than gas) expended by these countries during the war was 1,389,000,000 rounds (Table XIII), it follows that approximately *one casualty was produced by each 100 rounds of nongas artillery ammunition fired.*

On the other hand approximately 85 per cent of the 1,296,853 gas casualties (1,102,325) were due to artillery gas shell (see Table XI). These casualties were caused by the *toxic-gas* shell which were approximately 75 per cent of the total gas shell fired, so that we have 1,102,325 casualties produced by 49,500,000 toxic-gas shell, or an average of *one casualty for each 45 of such shell fired.* From this it follows that toxic gas shell were more than twice as effective as nongas (H.E.) shell in producing battle casualties.

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RELATIVE CASUALTY VALUE OF GASES

In order to determine the relative casualty value of the principal battle gases, it is necessary to take into consideration the amounts of each that were used in battle during the World War. Table XV shows the amounts of battle gases of each class that were manufactured during the War.

Of the 150,000 tons of battle gases manufactured during the war, approximately 125,000 tons were used in battle and 25,000 tons were left on hand after the war in filled shell and in bulk storage, as indicated in Table XV.

Subtracting the stocks on hand at the end of the war from the totals manufactured during the war, we arrive at the tonnages of the various gases used in battle. Table XVI shows these tonnages and the corresponding number of casualties resulting from each.

From Table XVI, it is noted that all told about 125,000 tons of gas were used in the war and caused 1,296,853 casualties, or one casualty for each 192 lb. of gas. It must be remembered, however, that a large part of the early war gases were lacrimatory and irritant gases which caused no recorded casualties, so that the real casualty power of the later gases was considerably above this average.

Of all the casualty gases used in the war, mustard gas was by far the most effective. It was not introduced until July 12, 1917, and hence was used by Germany only during the last sixteen months of the war. Owing to production difficulties, France was unable to fire mustard gas-

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shell until June, 1918, and Great Britain not until September, 1918—less than two months before the Armistice. Notwithstanding the short period of use, 1,200 tons of mustard gas (in artillery shell) caused 400,000 casualties, or one casualty for each 60 lb. of gas.

TABLE XV.—BATTLE GASES MANUFACTURED DURING THE WORLD WAR
(Tons)

Country	Gases				Totals
	Lacrimators	Lung injurants	Vesicants	Sternutators	
Germany	2,900	48,000	10,000	7,200	68,100
France	800	34,000	2,140	15	36,955
England	1,800	23,335	500	100	25,735
United States	5	5,500	710	0	6,215
Austria	245	5,000	0	0	5,245
Italy	100	4,000	0	0	4,100
Russia	150	3,500	0	0	3,650
Totals	6,000	123,335	13,350	7,315	150,000
Left on hand unused	0	22,835	1,350	815	25,000

TABLE XVI.—BATTLE GASES USED IN WORLD WAR AND RESULTING CASUALTIES

Gases	Tons used in battle	Resulting casualties	Pounds of gas used per casualty
Lacrimators	6,000	0	0
Lung injurants	100,500	876,853	230
Vesicants	12,000	400,000	60
Sternutators	6,500	20,000	650
Totals	125,000	1,296,853	192 (average)

Altogether about 10,000,000 artillery shell were filled with mustard gas, and of these approximately 9,000,000 were fired in the late war. These 9,000,000 shell produced 400,000 casualties or one casualty for every 22.5 mustard shell fired. Thus, mustard gas shell proved to be twice as effective as the *average gas* shell and nearly five times as effective as shrapnel and high-explosive shell.

Contrast this record with high-explosive, rifle, and machine-gun casualty results. About 5,000,000,000 lb. of high explosives were used by all belligerents in the war, from which it is estimated 10,000,000 battle casualties resulted; thus each casualty required 500 lb. of high explosive. Again, a total of 50,000,000,000 rounds of rifle and machine-gun ammunition produced 10,000,000 casualties; thus each casualty required 5,000 rounds.

PRINCIPAL GAS ATTACKS IN WORLD WAR

Impressive as are the foregoing average results in the late war, many instances can be found where gas was used under favorable conditions and produced still more effective results. This was particularly true of the large-scale gas attacks put over by the chemical troops on both sides. These attacks comprised gas clouds released from cylinders or projected on the enemy by gas projectors.

Table XVII shows the principal gas attacks during the war, the approximate quantities of gas used, the means employed for putting over the gas, the casualties produced, and the average amount of gas casualty for each attack.

From the last column in Table XVII it will be noted that, in general, the early gas attacks were the most effective from the point of view of the

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Amount of gas per casualty, lb.	22	34	60	60 215 63	58	169	58	205	225	275 150 330 215	140	57 63 67	33

TABLE XVII.—PRINCIPAL GAS ATTACKS IN WORLD WAR.—(*Continued*)
Cloud-gas Operations

Date	Place	By	Against	Number of cylinders	Amount of gas, tons	Kind of gas	Casualties		Amount of gas per casualty, lb.
							Injuries	Deaths	
	1915								
	Western Front								
Apr. 22	*Ypres (Bixschoote-Langemarck)*	*Germans*	*French*	5,730	168	Cl	15,000	(5,000)	
24	Ypres (Bixschoote-Langemarck)	Germans	British						
25	Ypres (Bixschoote-Langemarck)	Germans	British						
May 1	Lens	Germans	British	15,000	330	Cl	7,000	(350)	
6	Hill 160	Germans	British						
10 to 24	South of Menin Road	Germans	British						
Sept. 25	Loos	British	Germans	2,400	70	Cl	2,400	(600)	
Oct. 13	Hohenzollern Redoubt	British	Germans	1,225	36	Cl	1,200	(300)	
19-20	*Rhiems at Fort Pompelle*	*Germans*	*French*	25,000	550	Cl	5,096	(815)	
27	Marquises	Germans	French	2,000	44	Cl	1,400	(100)	
Nov. 26	Forges-Bethincourt	Germans	French	500	11	Cl	387	(57)	
Dec. 19	Flanders-Wieltje	Germans	British	4,000	88	Cl/CG	1,009	(120)	
	Eastern Front								
May 2	*Bolimow*	*Germans*	*Russians*	12,000	264	Cl	9,100	(6,000)	
	1916								
	Western Front								
Feb. 21	Somme-(Fourges Bethincourt)	Germans	French	6,000	132	Cl/CG	1,289	(283)	
Apr. 27	Flanders (Bullsch)	Germans	British	3,200	71	Cl/CG			
29	Flanders (Bullsch)	Germans	British	3,200	71	Cl/CG	1,260	(338)	
30	Flanders (Wulverghem)	Germans	British	3,200	71	Cl/CG	512	(80)	
May 19	Navarin-Souain			2,000	44	Cl/CG	584	(140)	
21	Champagne-(Somme-Py)	Germans	French	4,500	100	Cl/CG	600	(155)	
June 17	Flanders (Wulverghem)	Germans	British	2,750	60	Cl/CG	562	(95)	
26	*Somme*	*British*	*Germans*	5,110	148	Cl/CG	5,000	(1,500)	
Aug. 3	Flanders (Wieltje)	Germans	British	1,500	35	Cl/CG	804	(371)	
Oct. 5	Flanders (Nieuport)	British	Germans	4,925	141	Cl/CG	4,500	(1,000)	
8	Flanders	British	Germans	3,400	100	Cl/CG	3,000	(600)	
	Italian Front								
June 29	Plateau of Doberdo	Austrians	Italians	3,000	100	Cl/CG	6,000	(5,000)	

TABLE XVII.—PRINCIPAL GAS ATTACKS IN WORLD WAR.—(*Continued*)
Cloud-gas Operations

By	Against	Number of cylinders	Amount of gas, tons	Kind of gas	Casualties		Amount of gas per casualty, lb.
					Injuries	Deaths	
Germans	Russians	10,000	220	Cl/CG	6,000	(3,000)	73
Germans	Russians	10,000	220	Cl/CG	4,000	(1,200)	110
Germans	Russians	2,500	55	Cl/CG	1,500	(400)	73
Russians	Germans	5,500	165	Cl/CG	1,100	(200)	300
Germans	*Russians*	12,000	264	Cl/CG	7,791	(1,100)	68
Russians	Germans	5,000	150	Cl/CG	1,500	(300)	200
Germans	*French*	18,500	407	Cl/PS	2,062	(531)	395
Germans	French	1,500	33	Cl/PS	458	(108)	144
Germans	French	1,000	22	Cl/PS	335	(52)	130
Germans	French	1,000	22	Cl/PS	375	(7)	60
Germans	French	2,000	44	Cl/CG	450	(136)	195
Germans	French	400	9	Cl/PS	60	(12)	300
Russians	Austrians	4,000	140	Cl/CG	800	(60)	350
Russians	Germans	5,000	150	Cl/CG	1,200	(700)	250
British	Germans	3,028	90	Cl/PS	1,500	(150)	120
British	Germans	3,788	110	Cl/PS	2,000	(200)	110
British	Germans	4,144	120	Cl/CG	3,000	(240)	80
British	Germans	5,110	148	Cl/CG	4,200	(350)	70
	Total.....	205,210	5,093	.....	105,094	31,749	95 (average)

TABLE XVII.—PRINCIPAL GAS ATTACKS IN WORLD WAR.—(*Continued*)
Projector Operations

Date	Place	By	Against	Number of projectors	Amount of gas, tons	Kind of gas	Casualties		Amount of gas per casualty, lb.
							Injuries	Deaths	
	1917								
	Western Front								
Apr. 4	*Arras*	*British*	*Germans*	3,827	48	CG	500	(100)	191
Dec. 5	Riechicourt	Germans	French	1,000	8	CG	100	(20)	160
11	Cambrai	Germans	British	1,000	8	CG	78	(21)	205
31	Givenchy	Germans	British	500	4	CG	34	(2)	235
	Italian Front								
Oct. 24	*Isonzo near Tolmein*	*Austrians*	*Italians*	1,000	8	CG	600	(500)	27
	1918								
	Western Front								
Jan. 31	Lens	*Germans*	*British*	250	2	CG	19	(3)	200
Feb. 14	Bullecourt	Germans	British	500	4	CG	60	(4)	121
26	Anauville (1st Division)	Germans	Americans	250	2	CG-PS	85	(8)	47
Mar. 6	Avion	Germans	British	500	4	CG	70	(13)	114
7	Gomiecu	Germans	British	500	4	CG	57	(13)	140
19	*St. Quentin*	*British*	*Germans*	5,649	85	CG	1,100	(250)	108
19	St. Elie	Germans	British	500	4	CG	75	(20)	107
21	*Lens*	*British*	*Germans*	3,728	57	CG	700	(150)	162
31	Hill 70	Germans	British	250	2	CG	17	(5)	235
Apr. 15	Pretre near Montauville	Germans	French	400	3	CG	26	(3)	230
17	Pretre near Montauville	Germans	French	750	6	CG	52	(24)	230
May 16	Apremont	Germans	French	1,000	8	CG	187	(20)	86
10	San Mihiel-Toul (26th Div)	Germans	Americans	500	4	CG	185	(23)	43
10	Rupes, north of Parroy	Germans	French	1,000	8	CG	120	(48)	133
26	N.E. of Badonviller	Germans	French	1,000	8	CG	247	(40)	65
28	N.E. of Badonvilles	Germans	French	500	4	CG	70	(5)	114
June 23	Ypres	British	Germans	1,337	20	CG	500	(80)	80
July 12	Lens-Avion	British	Germans	1,462	22	CG	600	(85)	73
August 18	Dormans	Germans	British	1,000	8	CG	300	(50)	53
	Metrallor near Barentat	Americans	Germans	800	12	CG	250	(30)	100
	Total.....			29,203	343	.....	6,038	1,517	114 (average)

Casualties		Amount of gas per casualty, lb.
Injuries	Deaths	
1,600	(90)	343
1,100	(95)	340
600	(50)	500
750	(65)	500
2,400	(87)	100
1,250	(75)	400
14,726	(500)	340
13,158	(143)	380
1,200	(110)	225
1,000	(100)	350
900	(85)	267
2,330	(600)	300
{4,800}	{(67)}	275
{2,423}	{(20)}	
{11,860}	{(66)}	680
{ 3,000}	{(45)}	
542	(0)	258
8,242	(30)	485
8,470	(43)	492
693	(4)	430
4,080	(71)	600
3,918	(32)	750
443	(0)	54
600	(1)	50
518	(0)	770
2,600	(47)	770
3,400	(68)	500
759	(47)	470
1,060	(0)	10
1,892	(0)	5
1,000	(50)	400
24,363	(540)	328
10,600	(278)	300
137,267	3,400	94 (average)

Date	Place
1916	Eastern Front
Sept. 7	Baranowitchi
Oct. 17	Witonize
18	Kieselin
24-25	Baronovichi
December	*Riga-Minsk*
1917	
Jan. 26	As on the Rigmitan Road
	Western Front
31	*Champagne (of the Pyrenees)*
Apr. 7	Remenauville
23	Nieuport
June 6	Nieuport
July 1	Seichprey
Sept. 26	Bethune Mines
	Eastern Front
Mar. 27	Kowel
Apr. 15	East of Kowel (Kichary)
1918	Western Front
May 13	La Bassee Canal-Searpe
24	La Bassee Canal-Searpe
June 10	La Bassee Canal-Searpe
July 13	La Bassee (Lens-Avion)

TABLE XVII.—PRINCIPAL GAS ATTACKS IN WORLD WAR.—(*Continued*)
Artillery Operations

Date	Place	By	Against	Number of rounds	Amount of gas, tons	Kind of gas
		Germans	*Russians*	18,000	93	T-Stoff
1915	Eastern Front					
Jan. 31	Bolimow on Bzura	Germans	French	110,000	225	CC
	Western Front	Germans	French	75,000	127	CC
1916						
June 22	*Fleury*	British	Germans	60,000	150	BX
July 11	Verdun	British	Germans	75,000	192	BX
1917		Germans	British	50,000	125	BX
Mar. 25-Apr. 9	Arras offensive	British	Germans	100,000	250	BX
May 26-June 7	Messines offensive	Germans	*British*	1,000,000	2,500	BX
July 12	Ypres	*French*	French	1,000,000	2,500	BX
17-31	Ypres (third battle)	French	French	60,000	145	CG
Aug. 14-Sept. 24	*Nieuport—Armentieres*	Germans	Russians	116,400	176	CG/DA
Oct. 15-22	*Meuse near Verdun*	Germans	Russians	80,000	120	CG/DA
	Allette Basin near Laffaux	Austrians	Italians	170,000	350	CG
	Eastern Front					
Sept. 1	Dvina River at Ikskull	*Germans*	*British & French & Portuguese*	500,000	1,000	BS/CC
Sept. 21	Jakobstadt	*Germans*	*British & French*	2,000,000	4,000	BS/DA/CG
	Italian Front	*Germans*	*Americans*	3,000	7	BS
June 15		*Germans*	*British-Portuguese*	1,000,000	2,000	BS, DA/CG
1918	Western Front	*Germans*	*British*	1,000,000	2,000	BS/DA/CG
	Somme offensive:	Germans	Americans	10,000	15	BS
	Preparation bombardment (Ypres-San Quentin)	Germans	*French*	1,000,000	1,200	DA/CG
Mar. 9-19		Germans	French	750,000	1,200	BS/DA/CG
	Attack bombardment (Gauche-la Fere)	Germans	Americans	8,000	12	BS/CG
Mar. 21-Apr. 6		Americans	Americans	7,500	15	BS/CG
	Haute de la Faut (42nd Division)	Americans	Americans	10,000	20	BS/CG
Mar. 21	*Lys offensive*	Germans	French	500,000	1,100	BS/DA/CG
Apr. 9-27	(Lens-Armentieres)	Germans	French	340,000	850	BS/DA
	(Kemmel-Ypres)	Germans	Americans	9,000	18	BS/DA
Apr. 20-25	Castigny (1st Division)	Americans	Americans	2,000	5	BS/DA
3-4	*Aisne offensive*	Americans	Americans	2,000	5	BS/DA/CG
May 27-June 6	Noyon-Montdidier offensive	Germans	Americans	2,000	5	CG
June 9-15	Berzy-le-Sec (3rd Division)	Germans	*British*	100,000	200	BS
18	Chateau-Thierry (26th Division)	Germans	*British*	2,000,000	4,000	CG/BS
July 14-15	Champagne-Marne offensive					
14-17	Neuilly-Mesgre					
16-18	Sergy (28th Division)					
31	Fismes (28th Division)					
Aug. 7-8	Soissons (26th Division)					
12-15	Ourcq (32nd Division)					
30-31	*Somme counteroffensive*					
Sept. 12-Nov. 11	*Meuse-Argonne*					
Sept. 26-Nov. 11			Total	12,086,000	26,630	

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number of pounds of gas required per casualty. This, of course, was due to the absence of any effective protection from the first gases used in the war. As the means of protection increased in efficiency, the number of pounds of gas required to secure a casualty increased proportionately, although the results of successive gas attacks were by no means uniform; local conditions often entering largely into the relative effectiveness of each gas attack.

Another noteworthy point brought out in Table XVII is that on an average the large gas attacks were not as effective, per pound of gas used, as the smaller attacks. This was due primarily to the fact that, in general, in the small operations the targets were more definitely defined, and also the smaller the attack the better the execution could be controlled.

In considering the relative effectiveness of the various types of gases it must, of course, be borne in mind that the infliction of casualties is not the sole criterion. For example, lacrimators, being effective in much smaller concentrations than the other types, are far more efficient in forcing the enemy to mask than are any of the other gases. Indeed, so decided is the economy of the lacrimators for such use, it would be a tactical error to employ any of the other gases for this purpose. Since gas masks, no matter how much they may be improved, will always involve a material reduction in the physical vigor and fighting ability of troops, it is believed that lacrimators will always be used in war, although they cause no casualties.

Similarly, the sternutators (sneeze gases) cause relatively few casualties, but are so effective in extremely low concentrations in causing nausea and general physical discomfort that they fill a distinct tactical need for counterbattery work and in general harrassment of troops. Moreover, gases of this type are generally in the form of toxic smokes and have a marked mask-penetrative power. So penetrative are these gases that special mechanical filters are required to be added to gas-mask canisters in order to protect against them. Gas masks so equipped necessarily have a higher breathing resistance and thus tend still further to lower the physical vigor and combat ability of masked troops.

From what has just been said, it is apparent that while the infliction of casualties is the primary object of modern battle, it by no means follows that because a chemical agent does not possess a high casualty-producing power, it is of no tactical value in war. This point will be more fully appreciated when the tactical employment of chemical agents is taken into consideration.

AMERICAN GAS CASUALTIES

In the foregoing discussion we have considered the gas casualties of the late war from the general viewpoint of the total casualties of the

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principal belligerents engaged in the war. While such a survey has the advantage of a broad point of view, it has the limitation that complete and accurate statistics concerning many aspects of the gas casualties of the principal belligerents are not available. We are, therefore, not able to draw definite conclusions as to the value of gas as compared with other military agents, or as to the relative values of the different gases. Fortunately, the excellent casualty records of the A.E.F. in France, compiled by our own medical department, are so accurate and complete that they afford ample material from which these omissions may be supplied and many valuable lessons may be learned from a careful analysis of these records.

While our battle experience was limited to the last nine months of the war, it embraced the period of greatest development in chemical attack, and hence most accurately reflects the real powers and limitations of this mode of warfare. The casualty records of the United States Army are for the year 1918 only, hence they indicate the results of chemical warfare after it had passed through its period of incubation and had reached a stage approximating its full effectiveness. We will, therefore, conclude our study of World War casualties by considering a few of the salient points indicated by our own casualties in the war.

A reference to Table XI will show that the United States had a far higher percentage of gas casualties than any other belligerent in the war. This has already been accounted for in the preceding paragraph and, if the casualty records of the other belligerents on the Western Front are considered for the year 1918 only, it will be found that the gas casualties of the other armies were about the same as our own. Thus the French sustained the following percentages of gas casualties during the great offensives of 1918,

	Per Cent
Mar. 1 to Apr. 6 (Somme offensive)	39.72
May 27 to June 5 (Aisne offensive)	11.17
June 9 to June 15 (Noyon-Montdidier offensive)	17.15
June 15 to July 31 (Aisne-Marne counteroffensive)	30.14
Aug. 1 to Sept. 20 (Somme counteroffensive)	23.39
Average	24.3

These figures are very significant, as they clearly show the rapidly increasing casualty power of chemical agents as the war progressed. Thus, while the average gas casualties for the whole war period were only about 5 per cent of the total casualties, during the last year of the war, gas casualties had increased to approximately 25 per cent of the total casualties, including deaths, and an even greater percentage when deaths are excluded. This strikingly illustrates the point referred to above,

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namely, that the experience of 1918 is far more indicative of the real and future power of chemicals than figures based upon the whole war period when chemical warfare was largely in the experimental stage.

The figures in Table XVIII show that gas ranked first among all the military agents in the production of nonfatal casualties, and second in production of total casualties. Table XVIII further shows that, with the single exception of *gunshot missiles* (a very generic and comprehensive class), *gas caused a far greater percentage of our casualties than any other military agent used in the war*, even including H.E. shells and shrapnel which were employed on a vastly larger scale.

This is a very impressive showing for any military agent, and is even more so for one which was hastily developed under stress of war and did not emerge from an experimental stage until the war was nearly half over.

It is noted that Table XVIII does not include those that died on the battlefields nor any casualties among the marines who served with the A.E.F. Supplying these omissions, we have the total battle casualties for the A.E.F. in Table XIX:

The official casualty reports of our medical department give the hospital admissions and deaths from battle injuries in the A.E.F. caused by the various military agents. These data have been extracted and consolidated in the following table:

TABLE XVIII.—BATTLE CASUALTIES AND DEATHS IN A.E.F. FROM VARIOUS MILITARY AGENTS*
(Based on Hospital Admissions)

Military agents	Battle casualties			Per cent of hospitalized casualties
	Nonfatal	Deaths	Totals	
Gunshot missiles	67,409	7,474	74,883	33.42
Gas	69,331	1,221	70,552	31.49
Shrapnel	31,802	1,985	33,787	15.08
Rifle ball	19,459	961	20,420	9.12
Shell	18,261	1,778	20,039	8.94
Hand grenade	824	56	880	0.40
Bayonet (cutting instruments)	369	5	374	0.16
Pistol ball	229	13	242	0.10
Airplane attacks	170	28	198	0.08
Saber	9	3	12	0.005
Miscellaneous, including agents not stated, crushing, falling objects indirect result	2,535	167	2,702	1.205
Totals	210,398	13,691	224,089	

* Excluding marines serving with the A.E.F.

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TABLE XIX.—TOTAL BATTLE CASUALTIES IN A.E.F. FROM GAS AND NONGAS AGENTS*

Military agent	U. S. Army casualties			U. S. marine casualties			Total casualties		
	Killed in action	Died in hospital	Wounded nonfatal	Killed in action	Died in hospital	Wounded nonfatal	Total deaths	Wounded nonfatal	Total casualties
Nongas	36,494	12,470	141,067	1,837	579	6,884	51,380	147,951	199,331
Gas	200	1,221	69,331	6	35	2,014	1,462	71,345	72,807
Totals	36,694	13,691	210,398	1,843	614	8,898	52,842	219,296	272,138

It will be seen from Table XIX that, while gas caused 26.75 per cent of all our casualties and 32.53 per cent of nonfatal casualties, only 2.00 per cent of the gas casualties died, whereas 25.78 per cent of the nongas casualties died. We may say from this that men wounded by gas had over twelve times the chance to escape with their lives than men wounded by other weapons.

This very low death rate from gas, as compared to other weapons, was also experienced by the other principal armies engaged in the gas war. Thus, British casualty records* show only 1.3 per cent deaths from gas as compared to 24.0 per cent deaths from nongas weapons; the French had 4.2 per cent deaths from gas as against 32.0 per cent deaths from nongas weapons; while the Germans had 4.5 per cent deaths from gas as against 36.5 per cent deaths from nongas weapons (see Plate I).

Not only were the deaths from gas comparatively low, but the percentage of those permanently put out of action by gas was equally low. This is indicated by the number of discharges for disability from battle injuries by various military agents, as shown in Table XX.

From Table XX it will be seen that gas caused only 11.3 per cent of the total discharges for disability, while it was responsible for 26.75 per cent of all casualties, and 32.55 per cent of all nonfatal casualties (see Table XIX). Dividing the number discharged for disability from each military agent, as indicated in Table XX, by the number of nonfatal casualties from each agent, as given in Table XVIII, we find the per cent of discharges among the casualties from the principal agents as follows:

25.4 per cent of those wounded by shell were discharged for disability.
21.9 per cent of those wounded by rifle balls were discharged for disability.
17.3 per cent of those wounded by shrapnel were discharged for disability.
10.8 per cent of those wounded by gunshot missiles were discharged for disability.
7.9 per cent of those wounded by gas were discharged for disability.

* France and Flanders only.

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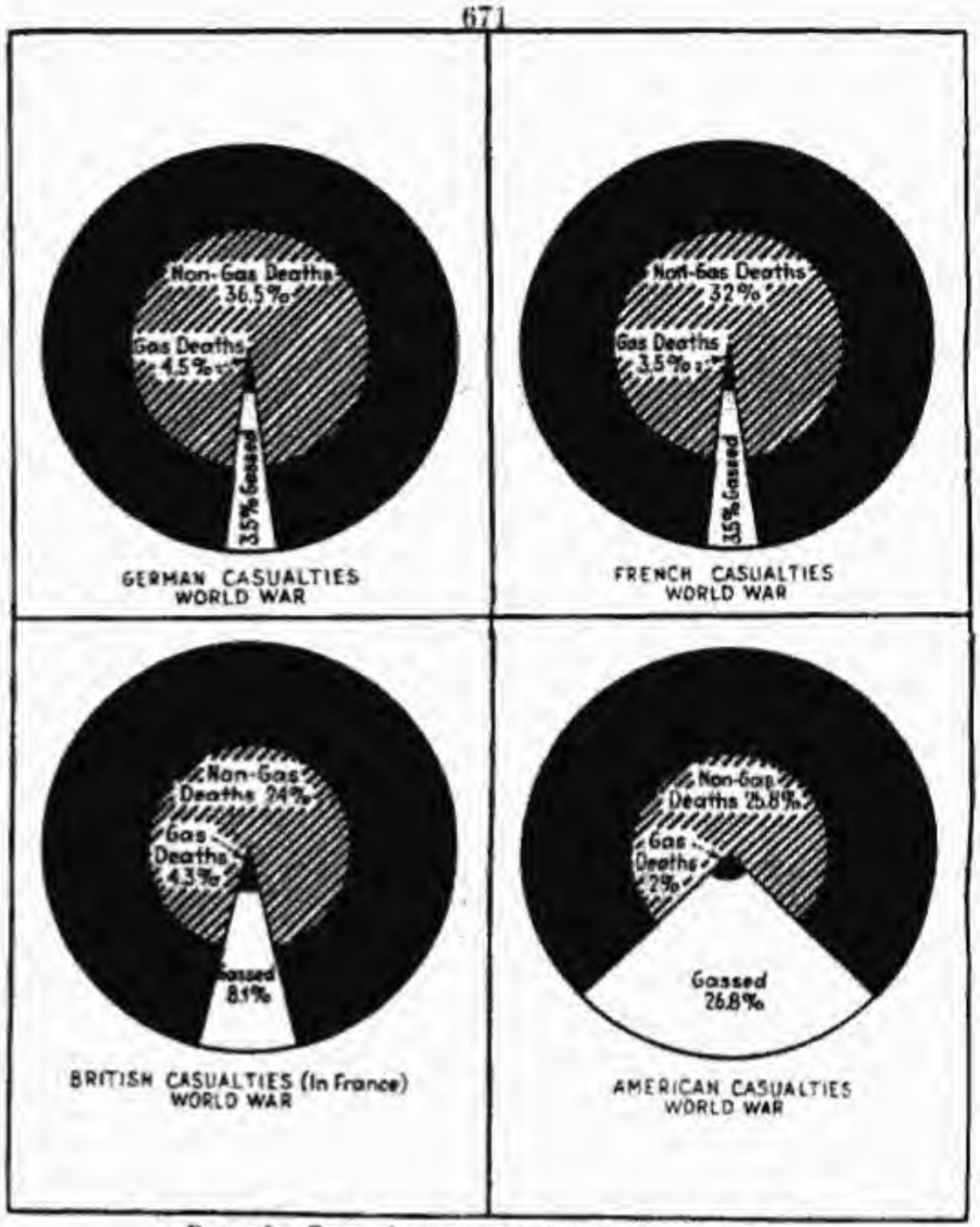

PLATE I.—Gas and nongas casualties in the World War.

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TABLE XX.—DISCHARGES FOR DISABILITY AND DAYS LOST IN HOSPITAL IN A.E.F. FROM VARIOUS MILITARY AGENTS*

Military agent	Discharges for disability		Days lost in hospital	
	Number	Per cent	Number	Per cent
Gunshot missiles	7,280	29.0	6,157,451	35.2
Shrapnel	5,488	21.8	3,423,040	19.8
Shell	4,638	18.4	2,158,629	12.3
Rifle ball	4,264	16.9	2,373,692	13.5
Gas	2,857	11.3	2,947,308	16.8
Hand grenade	198	0.78	81,911	0.42
Airplane attacks	50	0.186	23,962	0.14
Pistol ball	26	0.1	23,153	0.13
Bayonet (cutting instruments)	14	0.056	16,151	0.1
Saber	2	0.008	1,577	0.01
Miscellaneous, including agents not stated, crushing, falling objects, indirect results, and others	370	1.47	284,937	1.6
Totals*	25,187	100.00	17,491,844	100.00

* Excluding marines serving with the A.E.F.

Stated in another way, we may say that as a casualty producer gas ranked first among all the weapons of war, but as regards eliminations through discharges for disability, it ranked *fifth* among the causative agents, being exceeded by gunshot missiles, shrapnel, shell, and pistol balls.

In view of the above, it might be inferred that, since such a small percentage of gas casualties were permanently put out of action, men gassed one day would return to their organizations the next day, and thus gas is too humane an agent to be a really effective war weapon. Such, however, is far from the fact, as is attested by the comparative number of days lost in hospital from the various military agents including gas. Referring again to Table XX, it will be noted that gas was responsible for

16.8 per cent of the total days lost in hospital, while it caused only 11.3 per cent permanent eliminations (discharges for disability) and 2.00 per cent deaths (Table XIX).

Stated in another way, we may say that gas ranked *third* among the causative agents as regards days lost in hospital, being exceeded only by gunshot missiles and shrapnel, while it ranked *fifth* as regards discharges for disability, and *fourth* as regards death (Table XVIII) (see Plate II).

What has just been said applies to all war gases as a group, but there is considerable variation among the several types of gases as regards the length of hospitalization from gas wounds. Thus the lethal or deadly

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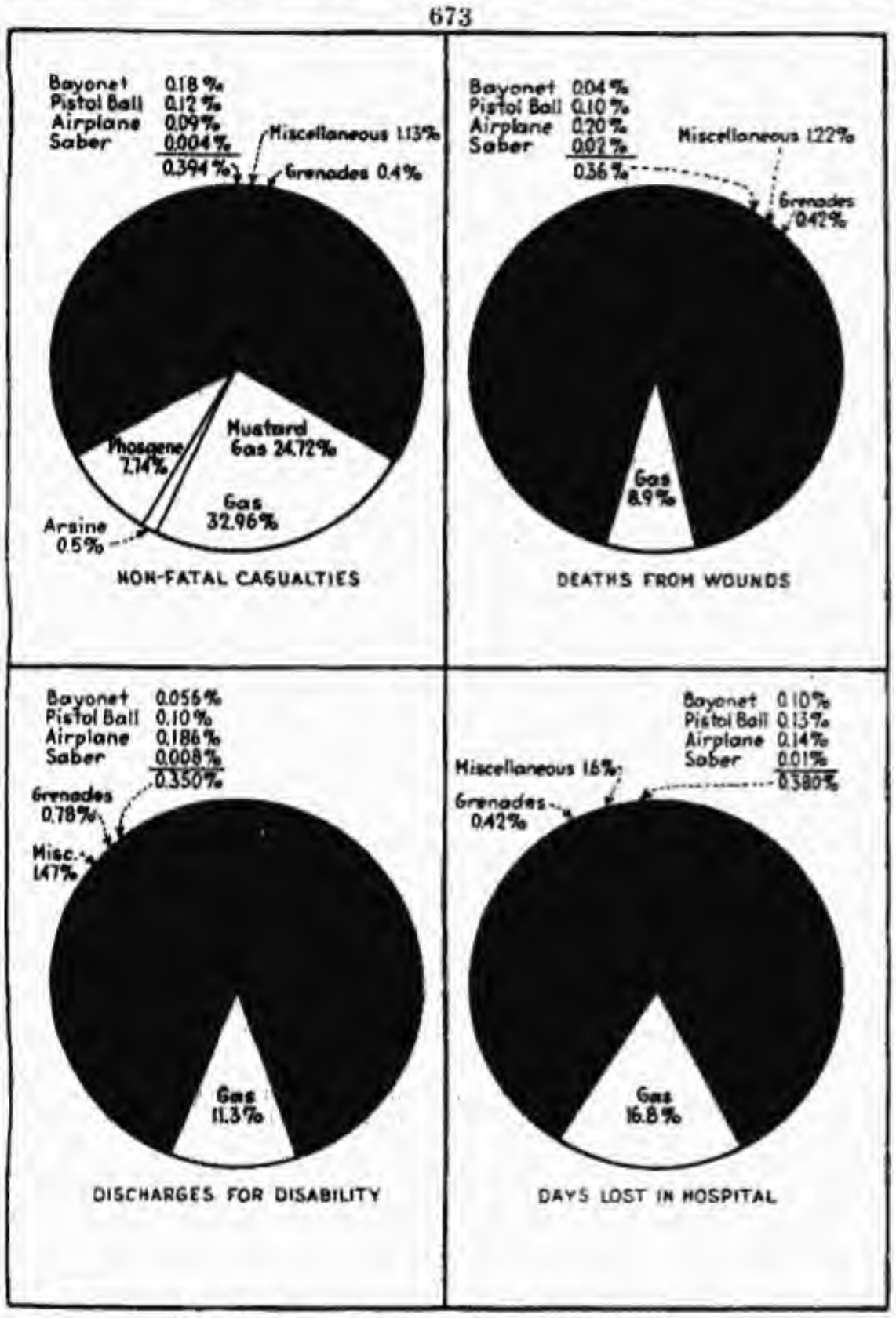

PLATE II.—American battle casualties by military agent.

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gases, as a group, cause less loss of days in hospital than the vesicant-type gases, such as mustard gas. British statistics show that over 80 per cent of men fatally gassed with phosgene died on the first day in the hospital, whereas only 1 per cent of men fatally gassed with mustard died on the first day. On the other hand, among men nonfatally gassed with mustard, French statistics showed the percentages of those who recovered and returned to their units as follows:

	Per Cent
Within 30 days	0
Within 45 days	13
Within 60 days	35
Within 70 days	17
Total	65

The average American mustard-gas casualty lost 60 days in hospital.

From the viewpoint of modern warfare where the object of battle is not to destroy human life, but rather to put men out of action and thus not only decrease the enemy's combat power, but also increase his war burden by forcing him to maintain the maximum number of noneffectives, it is obvious that gas responds to an outstanding degree to every requirement of an effective military agent.

We will now conclude our consideration of casualties by a brief survey of the relative effectiveness of the principal World War gases. It has been variously estimated that between 50 and 100 chemical substances were used as chemical-warfare agents during the war. These may be conveniently grouped into the general classes:

Classes	Typical gas used by Allies	Typical gas used by Germans	Casualty effects
I. Lacrimators	Bromacetone	T-Stoff	None
II. Lung injurants	Phosgene	Green Cross	Fatal
III. Vesicants	Mustard	Yellow Cross	Seriously incapacitating
IV. Sternutators	None	Blue Cross	Slightly incapacitating

Reliable statistics showing the number of casualties inflicted by the various gases are not available. Aside from the British and American medical records, it does not appear that any effort was made in the World War to classify gas casualties in accordance with the kind of gas. There is, however, general agreement among the principal nations in the World War that mustard gas caused by far the majority of the gas casualties.

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In the British Army 124,702 out of a total of 188,706 gas casualties (66 per cent) were due to mustard gas. In our own army the segregation is not quite so clear, as will be seen from Table XXI

TABLE XXI.—BATTLE INJURIES BY GASES IN A.E.F.
(Based on Hospital Admissions*)

Kind of gas	Class	Admissions		Deaths		Case fatality, per cent
		Number	Per cent	Number	Per cent	
Gas, kind not stated		33,587	47.6	546	44.7	1.63
Mustard gas	III	27,711	39.3	599	49.0	2.16
Phosgene gas	II	6,834	9.7	66	5.4	0.97
Chlorine gas	II	1,843	2.6	7	0.6	0.38
Arsine gas	IV	577	0.8	3	0.3	0.52
Total		70,552	100.0	1,221	100.0	1.73

* Excluding United States marines serving with A.E.F

The information contained in Table XXI is not in a very satisfactory form and needs some revision in order to be properly evaluated. In the first place nearly one-half of the casualties reported are unclassified as to kind of gas. Then there is included a number of casualties charged to chlorine when, as a matter of fact, there is no known instance of where this gas was ever used against the American Army. Chlorine was only used in cloud-gas attacks and there were no such attacks against our troops in France, except possibly those serving with the British and French armies. Finally, the fatality rates in the last column of Table XXI make it appear that mustard gas was the most deadly of the war gases, when, as a matter of fact, it is quite generally known that phosgene was by long odds the most deadly gas and mustard was relatively low in fatalities.

The author accordingly believes the following revision of Table XXI would give a clearer picture of the actual facts. First, the chlorine casualties are merged with the phosgene, as the nearest allied type, and the one which most probably was actually used and caused the casualties charged to chlorine; then the unclassified cases are distributed in proportion to the relative casualties for the known gases, including the U.S. Marine casualties (Table XIX); finally, the 200 battle deaths from gas are added to the phosgene deaths since mustard has a delayed effect which would practically preclude battlefield deaths. Our gas casualties

in the war then appear as follows:

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TABLE XXII.—BATTLE CASUALTIES BY GASES IN A.E.F.
(Based on Author's Estimates*)

Kind of gas	Class	Nonfatal		Deaths		Case fatality, per cent
		Number	Per cent	Number	Per cent	
Mustard gas	III	53,500	75.0	1,114	76.2	2.04
Phosgene gas	II	16,700	23.4	342	23.4	2.50
Arsine gas	IV	1,145	1.6	6	0.4	.53
Totals	..	71,345	100.0	1,462	100.0	2.01

* Including United States marines serving with A.E.F.

A comparison of Tables XXI and XXII shows that, whereas in the former only 39.3 per cent of our gas casualties were charged to mustard gas, in the latter 75 per cent were so identified. This last percentage slightly exceeds the British experience (66 per cent mustard casualties) and is in very close agreement with the French experience with an estimated loss from mustard gas between 75 per cent and 80 per cent of their gas casualties. As high as these mustard-gas percentages were, they were (erroneously) thought by the Germans to be even higher. Thus, Hanslian (20, page 20) says: "We assume that the losses of the Allies through the Yellow Cross (mustard) shells were *eight* times as great as all the losses caused by the other gases."

THE AFTEREFFECTS OF CHEMICAL WARFARE

Up to this point we have considered the war effects of chemicals; but what of the aftereffects? Much time and effort have been expended in the years since the war in thoroughly investigating this subject, not only because it is important from a medical point of view, but also to settle the moot question as to whether gas really caused serious permanent disabilities, or predisposition toward such diseases as tuberculosis. A large amount of evidence has been gathered and carefully sifted and evaluated so that today these matters are no longer in doubt. Medical officers and scientists who have studied the data concerning this question are unanimous in their judgment that gas does not leave permanent disabilities or predisposing weakness to organic diseases.

To go very deeply into this matter here would extend beyond the scope of this chapter, but we cannot dismiss the subject without a few references to the leading authorities.

Unquestionably, in this country the foremost authority on the medical aspects of chemical warfare is Major General Harry L. Gilchrist, Rtd.,

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late Chief of Chemical Warfare Service. General Gilchrist, then a Colonel of the Medical Department, was detailed in the fall of 1917 as Chief Medical Advisor of the Chemical Warfare Service A.E.F., and served as such throughout the war. In 1917 and 1918 Colonel Gilchrist spent much time inspecting troops and hospitals, not only of the A.E.F., but also of the French and British armies, and so gained a comprehensive, first-hand knowledge of the effects of battle gases during the progress of the War. After the War Colonel Gilchrist also devoted much time to an exhaustive study of the aftereffects of gas poisoning and has published several very illuminating papers on this subject. We cannot, therefore, do better than to quote a few extracts and conclusions from this eminent authority.

First, we shall consider blindness. It was frequently asserted during and just after the war that gas caused permanent blindness. General Gilchrist studied this matter very carefully and reported that, of the 812 cases of blindness in the A.E.F., 779 (96 per cent) were traceable to weapons other than gas, while gas caused only 33 cases (4 per cent). Since gas was responsible for about one-third of our nonfatal casualties, it is obvious that the percentage of cases of blindness from gas were far below the general percentage of gas casualties, and, therefore, blindness as a result of gassing was relatively infrequent.

Next, we shall consider tuberculosis. It was claimed that gas caused a marked predisposition toward tuberculosis, especially among those gassed by the lung-injurant gases General Gilchrist, in collaboration with doctors from the U.S. Veterans' Bureau, examined the service records and clinical histories of nearly three thousand veterans with the following results:

> Among the noteworthy effects of poison gas, as disclosed by the analysis of these cases, are the following: Preponderance of effects on the respiratory organs; the comparative rarity of persistent effects on the eyes and upper respiratory passages, and the greater proportion of deaths from the immediate or recent effects of mustard gas, while in its remote effects there is but little or no difference from those of chlorine or phosgene; and the death rate from pulmonary tuberculosis from it, over a period in excess of five years is less than the death rate as shown in the census report of 1920 for males of corresponding ages.

General Gilchrist then says, "The clinical experiences of many who have given this subject thorough study, as well as reports from laboratory experiments, now furnish evidence sufficient to serve the purpose of convincing anyone that pulmonary tuberculosis is not a common effect of gas poisoning and certainly not one of its later effects."

This opinion is confirmed by many able investigators in this field, as indicated by the references cited by General Gilchrist, while the

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Surgeon General's Report for 1920 contains the following conclusive paragraph:

> One hundred and seventy-three cases of tuberculosis occurred during 1918 among the 70,552 men who had been gassed in action. Of this number, 78 had been gassed by gas, kind not specified; 8 by chlorine; 65 by mustard; and 22 by phosgene. The number of cases of tuberculosis for each 1,000 men gassed was 2.45. Since the annual rate of occurrence for tuberculosis among enlisted men serving in France in 1918 was 3.50 and in 1919, 4.30 per 1,000, it would seem to be apparent that tuberculosis did not occur any more frequently among the soldiers who had been gassed than among those who had not been.

From this evidence, General Gilchrist concludes:

> The above is a most remarkable showing. In brief, it shows that in the year 1918 there were one and one-half times as many cases of tuberculosis per 1,000 among all troops in France as there were among those gassed, and that in 1919 there were more than one and three-fourths times as many tuberculosis cases per 1,000 among all troops as there were among the gassed troops. This means that if gassing were not an actual deterrent to tuberculosis the small percentage of tubercular cases among the gassed can only be accounted for through the case of those patients in hospitals.

The total absence of direct sequential relation between gas poisoning and tuberculosis in the A.E.F. was also found to be true for the British Army in France. Quoting again from General Gilchrist:

> The following analysis of information supplied by the ministry of pensions shows the general character of the more protracted disabilities seen after gas poisoning, it being impossible to distinguish in the records the precise type of gas by which each casualty was briginally caused.
>
> During the 12-month period, August 1919–1920, the resurvey boards made 26,156 examinations of cases of gas poisoning. Many of these men were examined more than once during that period, and the total number of individual cases examined is calculated to have been about 22,000. But of this number 3,130 were at once classed as "nil," since they showed no disability, leaving the total number of pensioners as about 19,000.
>
> The known total of gas casualties in British Army is 180,983. But many of these were men who were gassed more than once, on each of which occasions a fresh casualty would be reported. It is impossible to determine the proportion of these, and the number of survivors from the early chlorine attacks is also unknown. As a reasonable approximation one may accept 150,000 as the total number of individuals surviving after gas poisoning, many of whom were, of course, very mild cases.
>
> The number receiving disability pensions in 1920, two or more years after gassing, was approximately 19,000; that is, about 12 percent of the total gas casualties. Gas poisoning was responsible actually for 2 percent of all the disabilities after the war, 35 percent of all pensioners being classified as suffering from wounds and injuries and 65 percent as suffering from diseases.
>
> The percentage degree of disablement from gas poisoning was generally low, as shown by actual assessments in a consecutive group of 2,416 examinations made by boards in a period of four weeks during September, 1920.

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General Foulkes, Chief of British Gas Service in France, also gives some very impressive evidence on this subject. Two-thirds of the British gas casualties were from mustard gas; concerning these casualties General Foulkes says:

> I have mentioned the low mortality amongst mustard-gas casualties; but it is not

so widely known that of the 97½ percent which survive very few are rendered permanently unfit in the end. Towards the close of the war an examination of the medical records of 4575 of these cases which had been sufficiently severe to be sent to England for treatment (and were therefore rather more severe than the average) showed that 28.5 percent were transferred direct to Reserve battalions and 66 percent to convalescent depots—a total of 94.5 percent—within nine weeks of their arrival. Out of the total in this series of cases only 0.7 percent died; 9.4 percent were classified as permanently unfit; and less than 2 percent were reduced from Class A to a lower category. In fact, apart from about 2 percent which may be presumed to have died in France (to make up the average mortality of 2½ percent), only about 3 percent of the remainder were any the worse, say, after three months. I have reproduced this record because very mistaken ideas are held, even now, of the terrible effects of this gas. Even such a careful writer as Mr. H. G. Wells has stated recently (in his 'History of the next 100 years'): "It is doubtful if any of those affected by it" (mustard gas) "were ever completely cured. Its maximum effect was rapid torture and death; its minimum, prolonged misery and an abbreviated life."

HUMANITY OF CHEMICAL WARFARE

Much has been written both during and since the World War concerning the horrors of gas warfare and the cruel and inhuman consequences resulting from its uses. After a careful study of this matter and a close analysis of the casualties produced in the war, we now know the facts concerning the effects of gas and see that much of the alleged horrors of gas warfare were pure propoganda, deliberately disseminated during the World War for the purpose of influencing neutral world opinion, and had little sincerity or foundation in fact.

The measure of humaneness of any form of warfare is the comparison of (1) degree of suffering caused at the time of injury by the different weapons; the percentage of deaths to the total number of casualties produced by each weapon; and the permanent aftereffects resulting from the injuries inflicted by each particular method of warfare.

In general, gas causes less suffering than wounds from other weapons. It is unquestionably true that chlorine, the first gas used in the late war, did at first cause strangulation with considerable pain and a high mortality. But this was due mainly to the fact that the troops against whom these first gas attacks were launched were totally unprotected. Later when supplied with gas masks, chlorine became the most innocuous of the toxic gases and was the least feared by both sides.

The two other principal lethal gases used in the war, phosgene and chlorpicrin, when employed in high concentrations, caused instant col-

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lapse with no suffering. With lower concentrations there is no pain. The pain caused by mustard gas is always delayed and depends upon the concentration, length of exposure, and parts affected. The very fact of the delay of several hours in the effects of mustard gas usually means that the soldiers are able to obtain medical treatment by the time the symptoms appear and much can be done to relieve the suffering. On the other hand, suffering from other wounds commences at once, and frequently wounded men have to endure hours of agony before medical aid can reach them and allay their sufferings.

Among those gassed the sufferings are less severe and of shorter duration than among those wounded by other war weapons. With the lung-injurant gases the casualties are fairly out of danger in 48 hours, while burns from mustard gas, although not painful after the first 24 hours, often hospitalize a man for several weeks. On an average, the period of hospitalization from gas was only about one-half that of those wounded by other weapons.

As to the ratio of deaths to total casualties, we have already shown that the mortality among those wounded by nongas weapons was over 12 times the mortality from gas, and further elaboration on this point seems unnecessary.

Finally, as to the relative aftereffects of gas as compared to other wounds, there can be no question. Gas not only produces practically no permanent injuries, so that if a man who is gassed survives the war, he comes out body whole, as God made him, and not the legless, armless, or deformed cripple produced by the mangling and rending effects of high explosives, gunshot wounds, and bayonet thrusts.

If any one has the slightest doubt on this point, he has only to take one glance at the horrible results of nonfatal gunshot wounds, as illustrated on Plate I of Colonel Vedder's book, "The Medical Aspects of Chemical Warfare".

History reveals that the death rate in war has constantly decreased as methods of warfare have progressed in efficiency as the result of scientific progress. Chemical warfare is the latest contribution to the science of war. The experience and statistics of the World War both indicate that it is not only one of the most efficient agencies for effecting casualties, but is the most humane method of warfare yet devised by man.

INCREASING USE OF GAS DURING WORLD WAR

One of the most convincing evidences of the effectiveness of chemical warfare was its rapidly increasing use as the World War progressed. This is strikingly illustrated in Chart XIX, which shows the amount of gas and gas shell used on both sides during each year of the war.

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Owing to the large number of casualties which the Germans scored against the British and French with Yellow Cross (mustard) shell in the summer of 1917, and the great success attained against the Russians by their Colored Shoots, (mixed Green, Blue, and Yellow Cross shells) in the

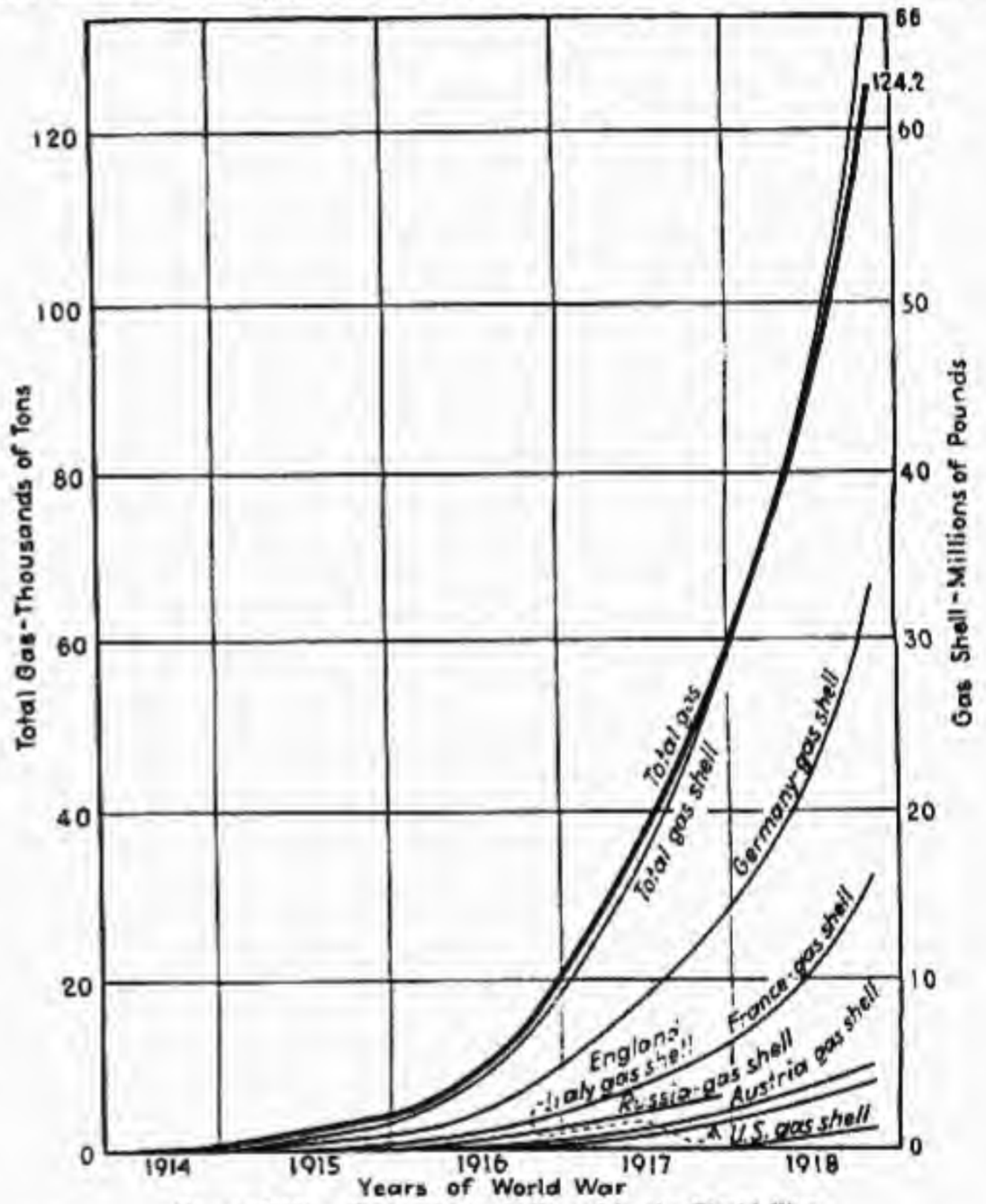

CHART XIX.—Gas and gas shell used in the World War.

fall of 1917, the Germans based the artillery preparation for their great offensives in the spring of 1918 on the use of gas shell. Thus gas shell, which in 1915, 1916, and 1917 were used only in special operations for producing casualties and in the general harassment of troops, by the end of 1917 had become so effective that they were incorporated as an important part of the comprehensive tactical plans for the 1918 offensives.

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In their first great offensive against the British in March, 1918, the Germans conducted a ten days' artillery bombardment in which they used over a half million gas shells (mostly Yellow Cross). In the ensuing attack which opened on Mar. 21, the Germans massed 1,705 batteries (about 7,500 guns) on a 44-mile front between Arras and La Fere and bombarded the British intensively for 5 hours. In this bombardment 25 to 30 per cent of the artillery shell were gas. General Ludendorff says of this attack: "Our artillery relied on gas for its effect."

The importance which the Germans attached to the use of gas shells in the artillery preparations for their great offensives in the spring of 1918 is further illustrated in a captured order of the German Seventh Army, dated May 8, 1918, which prescribed the proportions of gas shell

to be used for the attack on the Aisne on May 27th, as follows:

a. Counterbattery and long-range bombardments:
Blue Cross, 70 per cent; Green Cross, 10 per cent; H.E., 20 per cent.
b. Against infantry:
Blue Cross, 30 per cent; Green Cross, 10 per cent; H.E., 60 per cent.
c. In the "box barrage:"
Blue Cross, 60 per cent; Green Cross, 10 per cent; H.E., 30 per cent.

No Yellow Cross shell were used immediately preceding an attack.

In commenting on the great German offensives of 1918, General Schwarte says: "During the big German attacks in 1918, gas was used against artillery and infantry in quantities which had never been seen *before*, and even in open warfare the troops were soon asking for gas."

Even after they were forced to take the defensive, the Germans continued to use a large percentage of gas shell, particularly, Yellow Cross. Thus General Hartley , referring to the German retreat in the fall of 1918 says:

Yellow Cross shell were used much further forward than previously. . . . The enemy attempted to create an impassable zone in front of our forward positions by means of mustard gas. . . . In Yellow Cross they had an extremely fine defensive weapon; which they did not use to the best advantage.

The enormous consumption of artillery gas shells by the Germans in 1918 gradually became such that they were no longer able to supply the demands, although, according to General Schwarte, at the time of the Armistice Germany was manufacturing monthly almost 1,000 tons of Yellow Cross (mustard) alone.

Commenting on this situation, Lefebure writes:

The normal establishment of a German divisional ammunition dump in July, 1918, contained about 50 per cent gas shell. The dumps captured later in the year contained from 30 per cent to 40 per cent. These figures are significant, for they show

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how much importance the German Army attached to gas shell. When we think of the millions of shell and of the huge quantities of explosives turned out by our own factories to fill them, and when we realize that for a large number of gun calibers the Germans used as many shell filled with gas as with explosive, some idea of the importance of gas in the recent war and of its future possibilities can be obtained.

Confirming the shortage of German gas shell at the time of the Armistice, General Fries says: "Examination after the Armistice of German shell dumps captured during the advance revealed less than 1 per cent of mustard gas shell."

Throughout the war, with few exceptions, Germany maintained the initiative in chemical warfare, owing principally to her immensely superior chemical industry. Concerning this subject, Lefebure says:

As a general rule where the German lag between the approval of a substance and its use in the field covered weeks, our lag covered months. . . . The Germans used mustard gas in July, 1917. But the first fruits of allied production were not in the field for eleven months. British material was not used until a month or two before the Armistice.

And so the chemical warfare efforts of the Allies consisted largely of retaliatory measures in belated attempts to keep abreast of German initiative. For this reason the percentage of chemical shell in the German artillery-ammunition program was always ahead of that in the Allied programs.

At the time of the Armistice it is estimated that 50 per cent of the German, 35 per cent of the French, 25 per cent of the British, and 15 per cent of the American ammunition expenditures were chemical shell. The American chemical-shell program lagged considerably behind those of the other belligerents on the Western Front, principally because of production difficulties and the consequent lack of appreciation of the advantages of chemical shell in battle. However, shortly before the Armistice the American chemical-shell program was increased to 25 per cent of the artillery ammunition program to be effective Jan. 1, 1919. Gas-producing facilities in the United States were to be expanded so as to be able to provide 35 per cent chemical shell in 1919, had the war continued.

Regarding the British chemical-shell plans during the latter part of 1918, General Foulkes (12) writes:

. . . The opinion of our own General Staff of the value of gas was reflected in their last demand of the war, dated 9th August 1918, for gas shells and bombs for the 1919 campaign. 20 percent to 30 percent of all types of artillery shells were to have contained gas, the majority mustard gas, and pure lachrymators were eliminated entirely. Phosgene shells for the 18-pounder were demanded for the first time, the intention being to employ them in the moving barrage, not because any lethal effect was expected from them, but because it has been so often found advantageous to compel the enemy to meet our assaulting troops with their masks on.

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Of the German chemical-shell program in 1918, Dr. Muntsch says: "In the year 1918, German Headquarters ordered 50% gas ammunition and 50% high explosive ammunition for the artillery."

All in all, it is clear from the plans of both sides that, had the war continued for another year, the campaign of 1919 would have been largely a chemical war. This phenomenal rise of chemicals from an unknown obscurity in 1915 to the position of a military agent of the first magnitude in 1918 is without parallel in the history of warfare.

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CHAPTER XXVI

CONCLUSION

We have shown that chemical combat is a new mode of warfare which for the first time in recorded history departs from the physical blow as the fundamental principle of battle. Of all modern weapons, chemicals are destined to exert the most far-reaching effect in shaping the future character of warfare, for the action of chemicals over the areas in which they are employed is pervading as to space and is enduring in point of time, so that if aircraft may be said to have carried war into the third dimension, chemicals have extended it to the fourth dimension and no man can measure their ultimate possibilities.

Despite its crude and hastily improvised development, the remarkable effectiveness of chemical warfare was fully demonstrated in the World War, and clearly indicates that we are on the threshold of a new era in the evolution of war—an era of chemical rather than physical combat. Whereas in the late war, existing arms were employed to disseminate chemicals in addition to projectiles and explosives, in the future we may expect to see the requirements of chemical dissemination determine the character of the means employed in combat, and the resulting changes in armament will be more far-reaching than those brought about by the advent of gun powder.

We have also seen that chemical warfare is the most humane method of waging war heretofore employed, for by the use of chemicals not only may an enemy be overcome without annihilation or permanent injury, but the suffering caused by chemical action is, on the whole, far less than that resulting from the dismembering violence of explosives. Moreover, by chemical means alone may the blow be tempered and adjusted to the end in view, for with chemicals any effect can be produced from simple lacrimation to immediate death.

Also, unlike other means of combat, chemical warfare can be controlled and confined to the battlefield unless deliberately used elsewhere, for the laws governing the behavior of gases are as definite and well understood as the law of gravity.

While chemical combat immensely complicates modern war, it is susceptible to complete and adequate defense, and protection against it is essentially a matter of scientific skill. The chemical war of the future will, therefore, be primarily a contest between the scientific abilities of the

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combatants, *i.e.*, a contest of brains and not brawn. This simple fact alone holds out the greatest hope for the future of civilization, for the destiny of man is safest in the hands of the most intelligent. One of the best safeguards of world peace today lies in an appreciation of the above facts and a consequent application of chemical resources to national defense.

Much confusion in the international situation has been engendered by plausible but misguided attempts to prohibit the use of chemicals in war. The history of such efforts clearly indicates both their impracticability and undesirability. Impracticable, because the gases generated by explosives are so closely akin to the gases used in chemical warfare that only hairline distinctions can be drawn between them. Such refined differentiation is impracticable of enforcement under the stress of war, even if good faith exists on both sides.

As was witnessed in the World War, sooner or later one side or the other will claim a violation of any treaty agreement against chemical war-

fare, because of a real or fancied encounter with toxic gases on the field of battle, such gases being impossible to exclude where high explosives are used.

Even if a convention against chemical warfare were possible of enforcement in war, on what real grounds is such an action desirable? Three objections to chemical warfare have been urged by those opposed to it: (1), that it is inhumane; (2) that it cannot be controlled and confined to armies in the field, but will run wild and decimate noncombatants and civilian populations generally; (3), that it is unsportsmanlike.

The casualty records of the late war and the united opinion of the medical profession and foremost toxicologists have shown conclusively that chemicals are not only more humane than other weapons, but that chemical combat is the one form of organized force that can be regulated to bring about the subjection of an opponent with a minimum of violence and injury. This is exemplified in the now widespread use of chemicals for quelling civil disturbances.

The experience of the World War and the results of extensive postwar experimentation have also shown the fallacy of the second objection—that chemical combat cannot be controlled and confined to the battlefield. Indeed, this evidence is so convincing, it may be safely said that the only danger to noncombatants and civilian populations from chemical warfare lies in the *deliberate* application of chemical weapons to such uses. In this respect there is no more to be feared from chemicals than from explosives and other weapons so misused.

The third charge that the use of chemicals is unsportsmanlike is hardly of sufficient weight to warrant serious consideration. It doubtless arose out of the situation early in the war, when gas was first used against

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an unprotected enemy and was thus conceived to confer an unfair advantage upon the user. Such a situation cannot occur in the future for no government worthy of the name can fail to take steps in time of peace to protect itself against chemicals in war, unless it is lulled into a false sense of security by adherence to a treaty convention against chemical warfare and blindly fails in its duty to protect its people.

In the last analysis, war is not a sport, but a grim contest between states for national existence. War, therefore, cannot be conducted by any code of sportsmanship, but only by the law of military necessity, however much civilization may deplore the results. This being the case, the duty of any government is clear. It must take a practical and long-sighted view of the facts of war as they exist today; it must do everything in its power to insure that its armies and its people shall not be without the best possible protection against all modern weapons; and its armies shall be ready to employ the most effective means to bring to a speedy and successful conclusion any future war into which it may unfortunately be drawn.

What is chiefly needed today is a sane and rational outlook on the subject of chemical warfare, such as was voiced in one of the earliest suggestions concerning the use of toxic gas in war. In an article on "Greek Fire," which appeared in 1864, fifty years before the World War, a British writer says:

I feel it a duty to state openly and boldly, that if science were to be allowed her full swing, if society would really allow that "all is fair in war," war might be banished at once from the earth as a game which neither subject nor king dare play at. Globes that could distribute liquid fire could distribute also lethal agents, within the breath of which no man, however puissant, could stand and live. From the summit of Primrose Hill, a few hundred engineers, properly prepared, could render Regent's Park, in an incredibly short space of time, utterly uninhabitable; or could make an army of men, that should even fill that space, fall with their arms in their hands prostrate and helpless as the host of Sennacherib.

The question is, shall these things be? I do not see that humanity should revolt, for would it not be better to destroy a host in Regent's Park by making the men fall as in a mystical sleep, than to let down on them another host to break their bones, tear their limbs asunder and gouge out their entrails with three-cornered pikes; leaving a vast majority undead, and writhing for hours in torments of the damned? I conceive, for one, that science would be blessed in spreading her wings on the blast, and breathing into the face of a desperate horde of men prolonged sleep—for it need not necessarily be a death—which they could not grapple with, and which would yield them up with their implements of murder to an enemy that in the immensity of its power could afford to be merciful as Heaven.

The question is, shall these things be? I think they must be. By what compact can they be stopped? It were improbable that any congress of nations could agree on any code regulating means of destruction: but if it did, it were useless; for science becomes more powerful as she concentrates her forces in the hands of units, so that a nation could only act, by the absolute and individual assent of each of her repre-

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sentatives. Assume, then, that France shall lay war to England, and by superior force of men should place immense hosts, well armed, on English soil. Is it probable that the units would rest in peace and allow sheer brute force to win its way to empire? Or put English troops on French soil, and reverse the question?

To conclude. War has, at this moment, reached, in its details, such an extravagance of horror and cruelty, that it cannot be made worse by an act, and can only be made more merciful by being rendered more terribly energetic. Who that had to die from a blow would not rather place his head under Nasmyth's hammer, than submit it to a drummer boy armed with a ferrule?

If the statesmen who control the destinies of nations could but achieve this enlightened viewpoint, the future of mankind would be far more secure.

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APPENDIX

RELATION OF VOLATILITY TO VAPOR PRESSURE

The vapor pressures of many chemical compounds are given in chemical literature under the physical properties of the compounds. If the vapor pressure of a gas at any given temperature is known, the volatility of the substance may be obtained as follows:

Let M = the molecular weight of the gas, in grams.
T_1 = the temperature (absolute) at which the vapor pressure is known.
T = normal absolute temperature = 273°C.
P_1 = the vapor pressure at a temperature T, in mm. Hg.
P = normal atmospheric pressure = 760 mm. Hg.
V_1 = volatility of the gas at a temperature T, in grams per liter.

The gram molecule (*i.e.*, the molecular weight of the substance expressed in grams) of any gas occupies 22.4 liters at 0°C. and 760 mm. pressure.

Therefore

$$V = \frac{MTP_1}{22.4 \times 760T_1}$$

Thus, the molecular weight of phosgene is 99, its vapor pressure at 25°C. is 1,400 mm. Hg, and its volatility at 25°C. is

$$V = \frac{99 \times 273 \times 1{,}400}{22.4 \times 760 \times 298} = 7.488 \text{ grams}$$

or 7.488 mg. per liter (see Chart I, page 9).

Proceeding as above, the volatility curve for any gas may be constructed from its vapor pressure curve, as shown in Chart I.

RELATION OF VOLUMETRIC RATIOS TO WEIGHT RATIOS

The concentration of a toxic gas in the air is variously stated as: (1) grams of gas per cubic meter of air; (2) milligrams of gas per liter of air; (3) ounces of gas per 1,000 cu. ft. of air; and (4) parts of gas per million parts of air. In order to compare concentrations expressed in these different ways, it is necessary and convenient to know the conversion factors, which may be simply stated as follows:

Grams per cubic meter are numerically exactly the same as milligrams per liter, since a milligram is $\frac{1}{1000}$ gram and a liter is $\frac{1}{1000}$ cubic meter.

Since 1 oz. = 28.35 grams and 1 cu. ft. = 28.32 liters, 1 oz. per cubic foot = 1.001 grams per liter, and ounces per thousand cubic feet = 1.001 mg. per liter. Therefore, ounces per thousand cubic feet are numerically the same as milligrams per liter to the third decimal place.

Parts per million are converted to milligrams per liter as follows:

1 liter of air at 0°C. and 760 mm. weighs 1.293 grams.

1 cu. mm. of air at 0°C. and 760 mm. weighs 0.0001293 mg.

For air, or any gas of the same density, 1 part per million (1 p.p.m.) would be 1 cu. mm. per liter.

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Hence under standard conditions 1 p.p.m. of any gas of the same density as air would weigh 0.001293 mg. per liter.

But the average molecular weight of air = 28.9; for any other gas the figure 0.001293 would vary in proportion to the molecular weight of the gas.

Therefore, if M = molecular weight of a gas, P = barometric pressure, and T = the absolute temperature, then

$$\text{Milligrams per liter} = \frac{M \times 0.001293 \times P \times 273}{28.9 \times 760 \times T} \text{ p.p.m.}$$

This may be reduced to the following:

$$\text{Milligrams per liter} = \frac{0.0000161MP}{T} \text{ p.p.m.}$$

or

$$\text{p.p.m.} = \frac{T}{0.0000161MP} \text{ mg. per liter.}$$

CHEMICALS IN WAR

A Treatise on Chemical Warfare

BY

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