

## Chapter 2

# World War I: Militarization of Chemistry

### 2.1 The Chronicle of the Vast Scale Usage of CWAs: The Road to Mustard Gas

The opening act of the toxic gases deployment took place at the early months of WWI, when the French army fired tear gas grenades (filled with ethyl bromoacetate) against German soldiers (August 1914) [1]. These grenades were manufactured prior to the war and first deployed by French police in 1912, in order to crush riots in Paris. Following the recommendation of Walter Nernst (Nobel Prize in Chemistry; 1920), the German forces filled shells with dianisidine chlorosulfonate powder, which was readily available due to its extensive use as an intermediate in the synthetic dye industry [2, 3]. Around 300 filled shells, called Ni-Schrapnell or N-J shells, were fired against the British army from the Germans at the capture of Neuve Chapelle in France on October 27, 1914, but without any effect except of a violent fit of sneezing. In December 1914, benzyl bromides were also tried [4]. These incidents of failure served to permanently change the course of war. A chemist, who participated in the war without any military rank, became inspired and dedicated himself to apply this novel aspect of chemistry in the battlefields. His name was Fritz Haber. He played a vital role in persuading the German generals to begin the development of toxic gases for a mass scale usage as a weapon and to use them in the actual battles.

Three months later, the German forces fired more than 18,000 “T-shells” containing liquefied tear gas, xylol bromide, on the Eastern Front during the battle of Bolimów (January 31, 1915). All three isomers of xylol bromide or methyl benzyl bromide ( $C_8H_9Br$ ) are highly toxic and irritant. Due to the extreme low temperature in Bolimów, the liquid did not vaporize and the attack proved to be a complete failure. Similar unsuccessful attacks with improved tear gas mixtures were carried out against the French army in March 1915 at Nieuwpoort in Belgium. Due to the simplicity of the xylol bromide production, it was widely used by Germans during the war as a component of the white cross mixture (Weisskreuz) in the artillery

shells. Other chemical compounds were also applied in shells and grenades as tear gases, among them chloromethyl chloroformate and bromoacetone. For the mass production of these shells, specialized factories were built. The main drawbacks were the difficult and time-consuming production and transportation of those shells to the battlefields. The shell shortage in many occasions revealed the necessity of alternative ways of chemicals deployment to the battlefields.

Haber's suggestion to use gas from pressurized tanks as CWAs, instead of using them merely in the shells was approved by Germans generals in January 1915. His fast efforts led to around 5700 cylinders containing more than 340 tons of chlorine stocked by April 11 of that year [5]. The German army was waiting for a suitable speed and orientation of wind in order to launch a chlorine attack. On April 22, 1915, the first deployment of chlorine as weaponry gas became a reality at the second battle in Ypres. The consequences of a greenish-yellow chlorine cloud were more than 1100 dead and 7000 injured soldiers. The Allied troops fled in disorder, and the German infantry easily advanced and conquered the French trenches. This act rose the moral of the German troops, and Haber was promoted from a sergeant of the reserves to a captain.

Haber concluded that those toxic clouds were very effective since they not only led to asphyxiation, but also to a total depletion of the enemies' front lines. His confidence that chemistry could have an active involvement in the war as an effective weapon changed once for good the path of war. The British were the first from the Allied forces that tried to respond with a chemical gas attack on September 24th, 1915. Unfortunately, the first deployment of a mixture of smoke and chlorine gas from around 400 gas tanks, in the front line at Loos in France led to an unexpected effect, since the wind shifted and the gases were blown to an opposite direction, resulting in more British casualties than the German ones [1]. The use of pure chlorine was gradually abandoned, but it was widely used in mixtures with phosgene and chloropicrin [6]. The latter, also called trichloronitromethane, ( $\text{CCl}_3\text{NO}_2$ ) was introduced as a chemical weapon by Russian forces in July 1916. The British used a mixture of chloropicrin with chlorine (30:70), called Yellow Star gas [4]. Chloropicrin is an eye irritant, which had the ability to penetrate earliest gas masks, forcing the soldiers to remove the masks. The development of filters from charcoal eliminated the chloropicrin effects.

A more lethal combination of chlorine with a 5% choking agent, phosgene, was widely used by the German army against the Russian army of the Eastern front and against the French troops on the Western front by the end of May 1915. That mixture was also used on June 12 and July 6, 1915, in Bolimów and in October against the French army. The casualties of the latter usage were huge, since the French soldiers were totally unprotected against phosgene. Phosgene or carbonyl dichloride ( $\text{COCl}_2$ ) was synthesized by John Davy in 1812, and it is considered as one of the most dangerous existing CWAs. He named it from the combination of the Greek words "*phos*" (meaning light) and "*genesis*" (meaning birth), since sunlight exposure was mandatory for the synthesis from a mixture of chlorine and carbon monoxide [7]. The use of poison gas mixtures of chlorine with higher amount of phosgene (25%) was successfully introduced in the battlefields by the

German army, six days before Christmas of 1915. It led to 120 death and more than 1000 injured British soldiers [5]. Even though the amount of the gases deployed at that battle was significantly greater than the one against the French in October, the casualties were lower, since the British were equipped with gas masks.

Phosgene was by far the deadliest CWAs used during WWI. It is 10 times more toxic than chlorine, volatile above 8 °C, and its vapor density is almost four times higher than that of air. From the estimated 100,000 recorded fatalities from poisonous gases, 85% were attributed to phosgene. Most of the times, it was used with chlorine in order to improve the spread of the denser phosgene. The major advantage compared to chlorine was the difficulty to be sensed by the victims since its vapors are colorless and have the smell of freshly cut grass. The first symptoms such as a burning sensation of a throat, watery eyes, and nausea appear gradually after 15 min. Survival rates are very low, due to the aggressive disruption of the blood-air barrier in the lungs [8]. After 24 hours, the formed tinged liquid in the lungs or the low blood pressure results in death. In addition, contact with the skin leads to blisters.

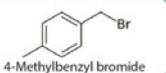
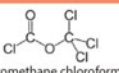
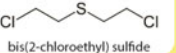
Carbonyl dichloride is an important chemical for the industrial manufacturing of dyes, pigments, plastics, and pesticides. It is used up today. The largest German industrial companies, such as BASF and Bayer, were producing phosgene prior to WWI, but its application as CWA in December 1915 is attributed to Fritz Haber [9], although the first introduction of phosgene to the battlefields in a small scale was by the French army some months prior. The French Nobel laureate Victor Grignard synthesized it [10].

Both sides developed distinct masks in order to neutralize phosgene, a few months after its first deployment. As a response to the gas masks, the German army developed another CWA, trichloromethyl chloroformate, known as diphosgene (DP,  $\text{ClCO}_2\text{CCl}_3$ ), that is related to phosgene, with comparable toxicity and with the ability to pass through or to destroy the filters used in the first gas masks. The first documented use of diphosgene was in artillery shells on the Western Front in May 1916 [5].

The French army replied to the phosgene by using the simplest unsaturated aldehyde, propenal, or acrolein, as a filler for artillery gas shells and gas grenades. Acrolein had a code name *Papite*, and its first deployment was in January, 1916. It is a colorless liquid at room temperature with a characteristic intense acrid smell. The characteristic smell of the burnt fat/oil is due to the formation of acrolein during the decomposition of glycerol. Even though this unsaturated aldehyde acts simultaneously as tear gas and, more importantly, as an irritant agent for the skin, nasal passages, and lungs at high concentrations, it was proven to be not effective in the battlefields because of its chemical instability.

The next used CWA, Mustard gas (HD), made its debut in a gas cloud attack on Allied troops near Ypres on 12th of July, 1917. It was the most effective CWA of WWI, since it was broadly used in huge quantities to harass and disable the defense trenches before the attacks. The consequences of nearly 6000 cylinders used in the first deployment were more than 2200 casualties. Initially, Germans planned to use this gas only as a paralyzing and blister agent. However, they realized soon that in

sufficient doses, it could be lethal to the enemy soldiers. The fatally exposed victims confronted extreme pain and sometimes were afflicted for up to five weeks before they finally passed away. The first aid camps were fully occupied for months with Mustard gas exposed soldiers and civilians. More than a million tons of HD, placed in artillery shells, were launched in the following month at the battle at Ypres. Besides, Mustard gas was deployed by various means, even by spraying from warplanes. This effective CWA elevated the moral of the German forces. The shells that contained Mustard gas were marked yellow, compared to the green-marked shells contained chlorine and phosgene. The yellow assignment came as a result of the yellow-brown color of impure gas clouds. Although not as lethal as other used CWAs, the devastating consequences of the extremely painful blisters, the internal and external bleeding of the victims, the difficulties to manufacture effective protection media, and the contamination of the soil for a long period of time shocked the world and attracted the worldwide attention. Mustard gas was established as the king of the battle gases and became the most popular CWA. The most widely deployed CWAs by the German forces are collected in Fig. 2.1.

| CHEMICAL WARFARE AGENTS  |               | GERMAN FORCES                        | WORLD WAR I              |
|-----------------------------------------------------------------------------------------------------------|---------------|-----------------------------------------------------------------------------------------------------------------------|--------------------------|
| CWA                                                                                                       | first used    | chemical formula                                                                                                      | class of agent           |
| benzyl bromide                                                                                            | December 1914 | <br>bromomethylbenzene               | Lachrymatory agent       |
| xylyl bromide                                                                                             | January 1915  | <br>4-Methylbenzyl bromide           | Lachrymatory agent       |
| chlorine                                                                                                  | April 1915    | $\text{Cl}_2$                                                                                                         | Choking / Pulmonary      |
| methyl chlorosulfonate                                                                                    | June 1915     | <br>Methyl sulfurochloridate       | Choking / Pulmonary      |
| phosgene                                                                                                  | December 1915 | <br>carbonyl dichloride            | Choking / Pulmonary      |
| diphosgene                                                                                                | May 1916      | <br>trichloromethane chloroformate | Choking / Pulmonary      |
| mustard gas                                                                                               | July 1917     | <br>bis(2-chloroethyl) sulfide     | Vesicant / blister agent |

**Fig. 2.1** Major chemical warfare agents deployed by the German army during the World War I (in a chronological order)

Another lethal warfare agent was developed for the US army by Captain Winford Lee Lewis from the Chemical Warfare Service (CWS) laboratory in Washington D.C. It was formed by the reaction of acetylene with arsenic tetrachloride. Its synthesis was first reported in the PhD Thesis of a priest-chemist Father Julius Arthur Nieuwland in 1904. That organoarsenic compound, 2-chloroethenylarsonous dichloride ( $\text{ClCH=CHAsCl}_2$ ), was referred to as Lewisite. It is a blister (vesicant) and lung irritant agent that acts similarly to Mustard gas. It has the ability to penetrate the normal soldiers' clothing, and even to go through rubber or latex textiles. In its pure form, it is odorless and colorless. This new toxic compound was thought to be effective during WWI, since it was unknown to the Central Powers. A special factory was constructed in the USA (Willoughby) for a massive production of Lewisite, which started few days before WWI ended. Fortunately, this compound was never deployed, since the war ended prior to its arrival to Europe.

The chemical compounds most widely deployed as CWAs during WWI in a chronological order, along with their military code names and their effects on a human body are listed in Table 2.1. The details are collected from various sources [6, 11–16].

## 2.2 Casualties and Fatalities of WWI

The Great War (WWI) and WWII are the deadliest conflicts in the modern history. There are various estimations of casualties and deaths caused by CWAs, and it is impossible to accurately calculate the victims. The main reason is the lack of precise records, since not all the casualties were recorded, or they were initially recorded in other general categories such as “prisoners and missing people”. Moreover, not all countries released official records. Nevertheless, the existing estimations from various sources are similar. Based on the official reports from Robert Schuman European Centre (CERS) and the US War Department in 1924, the total number of the recruited soldiers/mobilized forces from both sides was higher than 64 million. The casualties (deaths, wounded, prisoned, and missing) reached more than 37 million (58% of the mobilized personnel). Details of the casualties per country can be seen in Fig. 2.2. The casualties of Russian army were the highest, followed by those of the two main empires of the Central Powers, Germany, and Austria-Hungary.

The total number of the casualties during the WWI reached almost 45 million, which includes around 7 million of non-mobilized civilians. The Allies powers lost 25.7 million and the Central Power—18.5 million. The percentages of the total casualties by country are collected in Fig. 2.3.

A detailed analysis of the casualties is presented in Table 2.2. In this Table, the percentage of the total casualties per population of the country is also included. Sadly, these numbers reached 17.4% for Serbia, 16.3% for France, 14.7% for Turkey, 14.6% for Austria-Hungary, and 11.7% for the German Empire. Even though Russia suffered from the highest number of casualties, the percentage of the

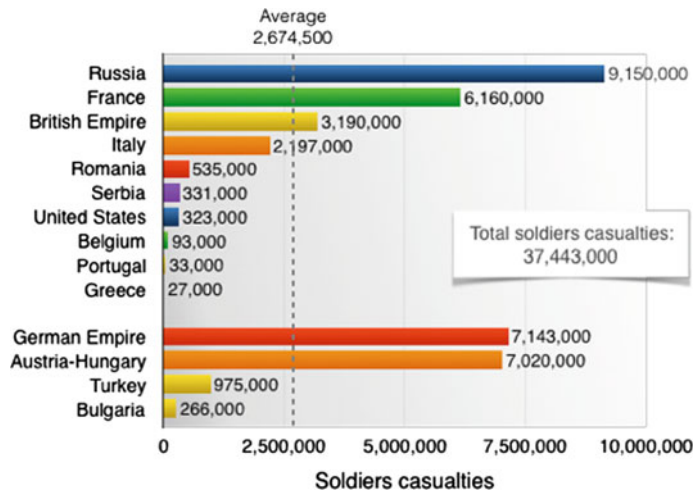
**Table 2.1** Chronicle of the most widely used chemical compounds as CWAs during WWI, their military code names, and their effects on a human body

| Year | Agent                                      | First used |        | Used by | Military code name |            |                           | Effect                     |
|------|--------------------------------------------|------------|--------|---------|--------------------|------------|---------------------------|----------------------------|
|      |                                            | Month      | By     |         | British/<br>US     | French     | German                    |                            |
| 1914 | Ethyl bromoacetate                         | Aug.       | Allies | Both    | EBA                | –          | (White cross)             | Lachrymatory               |
|      | Dianiside salts                            | Oct        | Germ.  | Germ.   | –                  | –          | –                         | Irritant                   |
|      | Chloroacetone                              | Nov.       | Allies | Both    | –                  | Tonite     | A-Stoff<br>(White cross)  | Lachrymatory, irritant     |
|      | Benzyl bromide                             | Dec.       | Germ.  | Both    | –                  | Cyclite    | T-Stoff                   | Lachrymatory               |
| 1915 | Xylol bromide                              | Jan.       | Germ.  | Both    | –                  | –          | T-Stoff<br>(White cross)  | Lachrymatory               |
|      | Benzyl iodide                              | Mar.       | Allies | Allies  | –                  | Fraisinite | –                         | Irritant, lachrymatory     |
|      | Chlorine                                   | Apr.       | Germ.  | Both    | –                  | Bertholite | Chlor                     | Lung irritant, corrosive   |
|      | Ethyl chlorosulfonate                      | Apr.       | Allies | Allies  | –                  | Sulvinite  | –                         | Lachrymatory, irritant     |
|      | Bromine                                    | May        | Germ.  | Germ.   | –                  | –          | Brom                      | Irritant                   |
|      | Phosgene (carbonyl dichloride)             | May        | Germ.  | Both    | CG                 | Collongite | (Green cross)             | Irritant, toxic, corrosive |
|      | Methyl chlorosulfonate                     | June       | Germ.  | Both    | –                  | Villantite | C-Stoff                   | Lachrymatory, irritant     |
|      | Bromoacetone                               | June       | Germ.  | Both    | BA                 | Martonite  | B-Stoff<br>(White cross)  | Lachrymatory, irritant     |
|      | Dimethyl sulfate                           | Aug.       | Germ.  | Germ.   | –                  | –          | D-Stoff                   | Irritant                   |
|      | Perchloromethyl mercaptan                  | Sept.      | Allies | Allies  | –                  | Clairsite  | –                         | Irritant                   |
|      | Ethyl iodoacetate                          | Dec.       | Allies | Allies  | SK                 | –          | –                         | Lachrymatory, toxic        |
|      | Acrolein (propenal)                        | Jan.       | Allies | Allies  | –                  | Papite     | –                         | Lachrymatory, toxic        |
| 1916 | Disphogene (trichloromethyl chloroformate) | May        | Germ.  | Both    | DP                 | Surpalite  | Perstoff<br>(Green cross) | Irritant, vesicant         |
|      | Hydrogen cyanide                           | July       | Allies | Allies  | AC                 | Forestite  | –                         | Toxic, asphyxiate          |

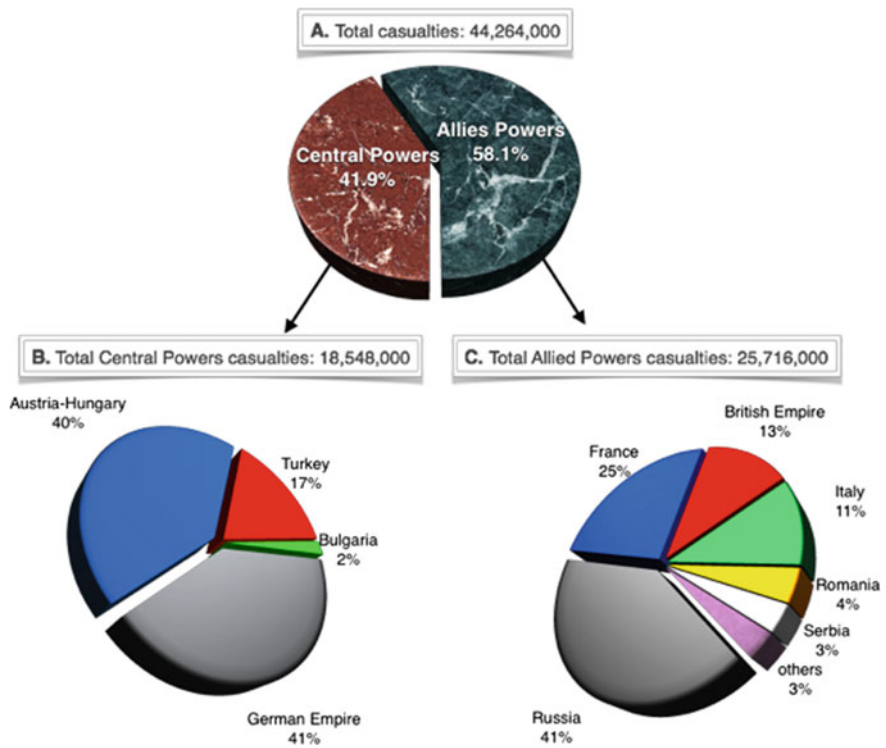
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Table 2.1 (continued)

| Year | Agent                                    | First used |        | Used by | Military code name |            |                       | Effect                           |
|------|------------------------------------------|------------|--------|---------|--------------------|------------|-----------------------|----------------------------------|
|      |                                          | Month      | By     |         | British/<br>US     | French     | German                |                                  |
| 1917 | Chloropicrin (Trichloronitromethane)     | July       | Allies | Both    | PS                 | Aquinite   | Klop<br>(Green cross) | Irritant, toxic,<br>lachrymatory |
|      | Cyanogen bromide                         | July       | allies | Both    |                    | Campilite  | E-Stoff               | Irritant, toxic, asphyxiate      |
|      | Cyanogen chloride                        | July       | Allies | Allies  | CK                 | Mauguinite | –                     | Irritant, toxic, asphyxiate      |
|      | Diphenylchloroarsine                     | July       | Germ.  | Both    | DA                 | –          | Clark I (Blue cross)  | Vomiting agents                  |
|      | Mustard gas (Bis(2-chloroethyl) sulfide) | July       | Germ.  | Both    | HD/<br>HS          | Yperite    | Lost (Yellow cross)   | Vesicant, lung irritant          |
|      | Phenyldichloroarsine                     | Sept.      | Germ.  | Germ.   | –                  | –          | –                     | Vomiting agents                  |
|      |                                          |            |        |         |                    |            |                       |                                  |



**Fig. 2.2** Casualties of the mobilized personnel by country As reported by the US War Department in February 1924. US casualties as amended by the Statistical Services Center, Office of the Secretary of Defense, Nov. 7, 1957



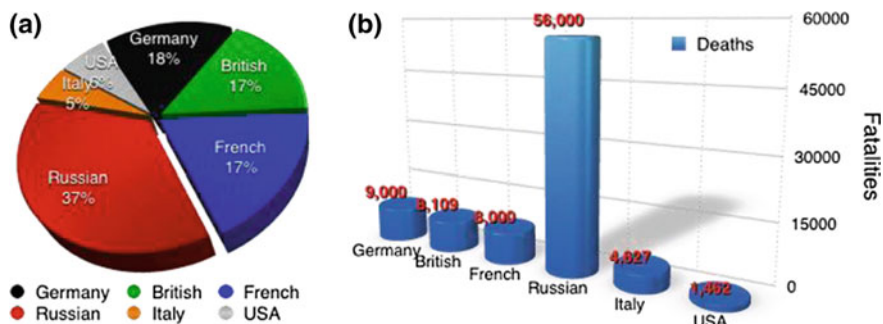
**Fig. 2.3** Percentages of the total casualties of the main countries involved in WWI



**Table 2.2** Numbers of the casualties of WWI (based on the reports from the US War Department and the Encyclopedia Britannica)

| Country            | Total casualties (thousands) | Total soldiers casualties | Killed and died | Wounded       | Prisoners and missing | Civilian deaths | Total mobilized forces | Soldiers casualties per mobilized forces (%) | Population (millions) | Percentage of total casualties per population |
|--------------------|------------------------------|---------------------------|-----------------|---------------|-----------------------|-----------------|------------------------|----------------------------------------------|-----------------------|-----------------------------------------------|
| Allied powers      |                              |                           |                 |               |                       |                 |                        |                                              |                       |                                               |
| Russia             | 10,650                       | 9,150                     | 1,700           | 4,950         | 2,500                 | 1,500           | 12,000                 | 76.3                                         | 175.1                 | 6.1                                           |
| France             | 6,460                        | 6,160                     | 1,357           | 4,266         | 537                   | 300             | 8,410                  | 73.2                                         | 39.6                  | 16.3                                          |
| British Empire     | 3,301                        | 3,190                     | 908             | 2,090         | 191                   | 111             | 8,904                  | 35.8                                         | 45.4                  | 7.3                                           |
| Italy              | 2,786                        | 2,197                     | 650             | 947           | 600                   | 589             | 5,615                  | 39.1                                         | 35.6                  | 7.8                                           |
| Romania            | 965                          | 535                       | 335             | 120           | 80                    | 430             | 750                    | 71.3                                         | 7.5                   | 12.9                                          |
| Serbia             | 781                          | 331                       | 45              | 133           | 153                   | 450             | 707                    | 46.8                                         | 4.5                   | 17.4                                          |
| United States      | 326                          | 323                       | 116             | 204           | 5                     | 1               | 4,355                  | 7.4                                          | 92.0                  | 0.4                                           |
| Greece             | 177                          | 27                        | 5               | 21            | 1                     | 150             | 230                    | 11.7                                         | 4.8                   | 3.7                                           |
| Belgium            | 155                          | 93                        | 14              | 45            | 35                    | 62              | 267                    | 34.8                                         | 7.4                   | 2.1                                           |
| Portugal           | 115                          | 33                        | 7               | 14            | 12                    | 82              | 100                    | 33.0                                         | 6.0                   | 1.9                                           |
| Allied Pow. Total  | <b>25,716</b>                | <b>22,039</b>             | <b>5,130</b>    | <b>12,790</b> | <b>4,114</b>          | <b>3,593</b>    | <b>41,338</b>          | <b>53.3</b>                                  | <b>417.9</b>          | <b>6.2</b>                                    |
| Central powers     |                              |                           |                 |               |                       |                 |                        |                                              |                       |                                               |
| German Empire      | 7,569                        | 7,143                     | 1,774           | 4,216         | 1,153                 | 426             | 11,000                 | 64.9                                         | 64.9                  | 11.7                                          |
| Austria-Hungary    | 7,487                        | 7,020                     | 1,200           | 3,620         | 2,200                 | 467             | 7,800                  | 90.0                                         | 51.4                  | 14.6                                          |
| Turkey             | 3,125                        | 975                       | 325             | 400           | 250                   | 2,150           | 2,850                  | 34.2                                         | 21.3                  | 14.7                                          |
| Bulgaria           | 367                          | 266                       | 87              | 152           | 27                    | 100             | 1,200                  | 22.2                                         | 5.5                   | 6.7                                           |
| Central Pow. Total | <b>18,547</b>                | <b>15,404</b>             | <b>3,386</b>    | <b>8,388</b>  | <b>3,630</b>          | <b>3,143</b>    | <b>22,850</b>          | <b>67.4</b>                                  | <b>143.1</b>          | <b>13.0</b>                                   |
| Grand total        | <b>44,264</b>                | <b>37,443</b>             | <b>8,516</b>    | <b>21,178</b> | <b>7,744</b>          | <b>6,736</b>    | <b>64,188</b>          | <b>58.0</b>                                  | <b>561</b>            | <b>7.9</b>                                    |

As reported by the US War Department in February 1924. US casualties as amended by the Statistical Services Center, Office of the Secretary of Defense, Nov. 7, 1957. <https://www.britannica.com/event/World-War-I/Killed-wounded-and-missing>



**Fig. 2.4** Percentages of soldier casualties by country, out of the around 1,131,000 total recorded gas casualties (a), and the deaths per country (b) caused by CWAs [17]

total casualties per population was only 6.1%. The lowest percent of the total casualties per population was for the USA (0.4%), since it entered the war only some months before the Armistice (11 November 1918).

From the existing data, the total casualties directly linked to CWAs exceeded one million (1,131,000), while the fatalities reached almost one hundred thousand (Fig. 2.4). Russia suffered the highest number of casualties and deaths, since the soldiers were totally unprepared during the first gas attacks. Phosgene was responsible for the most deaths, while Mustard gas contributed dramatically to the increase in the number of casualties. Only 5% of those exposed to mustard gas were killed.

As the war was progressing, the number of the casualties decreased gradually. It was owing to the gas masks development. Fritz Haber was in favor of CWAs until his death. In 1919, he stated: “Chemical warfare is certainly no more horrible than flying pieces of steel; on the other hand, the mortality from gas injuries is smaller” [18]. And from the casualties’ point of view, he was correct. Less than 1% of the total fatalities during WWI were from poisonous gases [19].

## 2.3 First Protection Attempts: Pads, Helmets, and Gas Masks

### 2.3.1 The Germans

The German Empire had many advantages at the beginning of WWI. Besides the foundation of special research groups focused on the toxic gases development, they had access to activated charcoal with an extremely high surface area, in addition to the porous mineral, diatomite. The latter is a soft, fine-grained, white siliceous sedimentary mineral, with an ultralow density (0.12–0.25 gcm<sup>-1</sup>) and high porosity, also known as diatomaceous earth, kieselgur, or tripolite [20]. Diatomite consists of predominantly silica (>80%), alumina (2–4%), and iron oxide (0.5–2%)

[21], and it is chemically inert in various gases and liquids. Diatomite is formed by accumulation and compaction of diatoms, which are single-cell aquatic plants (algae) and one of the most common classes of phytoplankton. Diatoms' cell is surrounded/impregnated by a hydrated silicon dioxide wall. The distinctive property to adsorb and retain large amounts of liquids, even more than five times of its own mass, was the main reason for the establishment of this natural material as an industrial filtration medium. Ancient Greeks were the first to use diatomite for bricks and pottery. Germans used diatomite inside the canister of gas masks. It was impregnated with liquid detoxification solutions.

Charcoal is the product of the pyrolysis of various natural substances in the absence of oxygen. It is a lightweight and porous material predominantly consisting of carbon. Depending on the origin of its precursor, a charcoal surface can contain various chemical elements and functional groups. Numerous substances were explored as charcoal precursors during WWI. The chemical or thermal modifications led to materials of extraordinary adsorption properties—activated carbons. These properties are linked to a high surface area (over 1000 m<sup>2</sup>/g) and pore volume, which made activated carbons the most widely used materials in various environmental remediation applications [22]. Rafal Ostrejko was the first one to patent activation of charcoal, and he is considered as the father of activated carbon and its industrial applications. Ostrejko was born in 1893 near Jonava in Lithuania (part of the Russia Empire during WWI) from Polish nationality parents, and he studied chemistry in Latvia. His most worth to mention patents were the chemical activation with CaCl<sub>2</sub> (1900) and thermal activation by CO<sub>2</sub> or steam at high temperatures (1903) [22].

The combination of charcoal and diatomite was used as the first filler placed in a metal drum of gas masks referred to as Gummimaske. Diatomite impregnated with a potash solution was effective against chlorine, while activated charcoal—against various organic compounds. This filter had the code name “26/8”, originating likely from the date of its establishment as the main canister. Starting in September 1915 and by the end of that year, almost all German soldiers at the front lines were equipped with gas masks. Professor of Chemistry at the University of Berlin and Director of the Kaiser Wilhelm Institute for Chemistry, Richard Willstätter, together with the chairman of Bayer Leverkusen Dyeworks, Carl Duisberg, established a procedure to produce granules of diatomite and activated charcoal [5]. Richard Willstätter was invited by Fritz Haber in 1915 to participate in the development of new toxic gases, but Willstätter agreed to be involved only in the development of new protection media. Willstätter was a Nobel laureate in chemistry in 1915, for his researches on plant pigments, especially chlorophyll [23].

The phosgene deployment by the Allied forces raised the need of an efficient filter for phosgene that would be based on the physical adsorption of organic gases/vapors. Thus, the upgraded metal drum version, “11/11”, had three layers. The outer layer was the same mixture as that used in the version 26/8. The middle layer consisted of charcoal granules for the adsorption of phosgene and other organic toxic gases, while the last layer was again diatomite, impregnated in this case with hexamine and potash. This version was applied in battlefields from April 1916. In

order to further increase the efficiency and to add protection against chloropicrin used by the British, an updated filter drum, with the code name 11-C-11, was introduced in June 1917. More charcoal was used in that filter. Another possible reason for its development was a potential usage of mustard gas. In the later “Lederschutzmaske” (Leather protection mask) model M1917, waterproof leather embedded in oil was used instead of rubber, with glass disk-shaped eyepieces. The M1917 model was introduced in August 1917. The metal filter canister was removable, but no intake or exhaust valves were used.

### 2.3.2 *The British*

The first vast scaled chlorine gas attack caught the Allies completely unprepared. Afterward, a great effort was made to manufacture protection masks. The first home-made attempt was the usage of cotton wool mouth pads, wetted with a neutralizing solution (urine or bicarbonate soda) [24]. The British named this respiratory Daily Mail. It was used at the chlorine attack on May 1st, 1915. Sadly, it was almost completely useless, because the wetted pads resulted in a completely airtight mass with difficulties in breathing. In an updated version, a pad of cotton waste has been used instead of cotton wool in order to avoid the breathing problems. This pad was soaked with a mixture of sodium hyposulfite, glycerin, sodium carbonate, and water, which can chemically neutralize chlorine, sulfur dioxide, and nitrous fumes. This mixture was established after the analysis of a respirator obtained from a German soldier-prisoner. Gauze was used to hold the pad while the ends were plainly knotted around the head. This updated version took the name Black Veiling Respirator, because black mourning gauze was used. Although the breathing problem was solved with the Black Veiling Respirator, it was difficult to get tied in rush and its effectiveness lasted only for about 5 min. In spite of these limitations, Black Veiling Respirator saved hundreds of lives during the chlorine attack of May 24, 1915, since almost all the British troops were equipped with one respirator by 20th May. Moreover, it provided the option to protect the eyes from tear gases by using a part of the veiling to cover the eyes.

The next attempt was inspired by witnessing a German soldier placing a bag over his head during a gas attack. This new mask was made by an impregnated fabric at the shape of a bag with a rectangular window to provide visibility and had no inlet or exhaust valve. It was easy to put on in rush, since the soldier had only to wear and place the bottom part of the mask into the uniform. It was known as the Hypo Helmet or the British Smoke Hood, since it was impregnated with hypo solution (sodium thiosulfate, sodium hyposulfate, and glycerin). The main disadvantage of this early model was that the rectangular celluloid window was very fragile. More than 2.5 million units of Hypo Helmet were used between May and September 1915, since it was able to efficiently protect against chlorine for three hours.

Hypo Helmet was displaced by the P Helmet in July 1915, due to the need of protection against phosgene and hydrogen cyanide (HCN). The letter “P” was from the protection against phosgene. This helmet consisted of two layers of cotton flannelette, to increase the corrosion protection of the single woolen layer. Sodium phenate was used for the protection against phosgene and HCN. The single celluloid window was replaced by two cyclic glass eyepieces. Carbon dioxide from breathing had a negative effect against hydrogen cyanide, and for that reason a valve was applied for the exhaled air. This type of mask went through numerous stages of development until it was succeeded by canister based gas masks, in 1916. P Helmet saved lives of numerous British soldiers at the biggest gas attack with the mixture of chloride and 25% phosgene on December 19, 1915. The helmets were later impregnated with a phenate-hexamine solution after Russia reported a high efficiency of hexamine or hexamethylenetetramine ( $C_6H_{12}N_4$ ) for absorption of phosgene. This improved mask was called P. H. Helmet and it started to replace the P. H. Helmets in November 1916. In order to increase the protection against tear gases, rubber sponge goggles were placed inside the face piece in the middle of January 1916. This was the last model of the series “Helmet”, known by the name P. H. G. Helmet. In spite of the severe limitations, such as an inefficiency in high toxic gas concentrations, poor visibility, vulnerability to the rain and the blisters at the neck, these masks became the most precious asset for soldiers, encouraging them to stay in the trenches and fight.

The next step in the gas mask development was the Large Box Respirator (LBR), designed by Edward Harrison, trying to overcome the above-mentioned disadvantages of the helmets. Moreover, there was always the fear that the Germans will use new toxic gases. The Allied forces initially had no knowledge on active charcoal, which was proven to be very efficient in its application in the Germans’ canisters. First LBRs used a water flask, with three layers of neutralizing agents. The first layer consisted of potassium permanganate granules, the second—of small pumice pieces (soda lime) impregnated with sodium sulfate solution, while the third one—of charcoal. The filter-flask was connected to the mouth mask via a rubber tube. The fabric used in this mask had been soaked in hexamine-zinc solution and an exhaustion valve was installed. This complex system proved to be bulky to be used by the infantry, difficult for a massive production and very faulty. It was first introduced in February 1916 for officers and soldiers with special tasks who had stable and strategically crucial positions away from the frontlines.

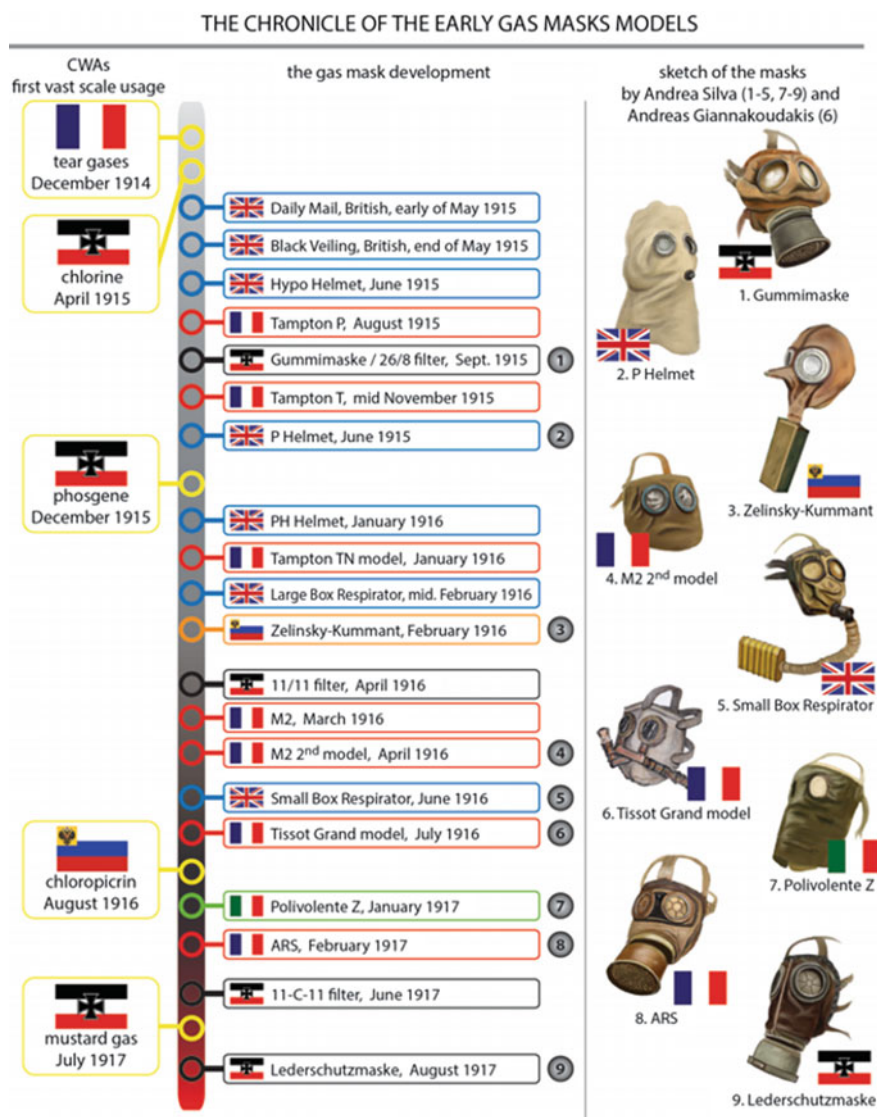
The upgraded version of LBR was the Small Box Respirator (SBR). The filter system size of SBR was more compact and lighter than the previous one. These features enabled the use of those masks by the infantry. The lime-permanganate granules were deposited between two layers of charcoal. From August to October 1916, all LBRs were replaced by SBRs.

### 2.3.3 *The French*

The French military responded to the tear gases with a pad mask, Tampon P, together with goggles. The first model had one pad impregnated with castor oil and sodium ricinate, and it could protect also against chlorine and bromide. The anticipation of phosgene deployment led to the addition of a second pad impregnated with sodium sulfanilate. This pad was known as Tampon P1. For the protection of the soldiers from HCN that was released by the French against the German army, a third pad impregnated with nickel acetate was added leading to a new mask with the code name Tampon P2. The French army used more than 4.5 million Tampon P masks between August and September 1915. These masks were not efficient for high concentrations or for a long-term usage, since only the part of the pad in front of the mouth was breathable and the chemical were quickly exhausted in this part. The next version of the mask had a cone shaped pad, which was covering both the nose and the mouth. The manufacturing of this Tampon T model allowed almost all the surface of the pad to come in contact with the gases and as a result the time efficiency increased. The first Tampon T masks arrived to the battlefields in the middle of November, 1915. An improved version was produced in January 1916, with a waterproof cover and a redesigned shape for a faster usage. It was referred to as a TN model. By the end of February, around one million of T and 6.8 millions of TN models were produced. On the Tampon masks, goggles were a separate part.

The first attempt from the French to combine the pad inside a one-eyepiece mask that could cover the whole face was the first M2 model. The thicker pad could protect against phosgene up to 6 h, and it was introduced to the battlefields in March 1916. The second M2 model had two eyepieces and three sizes. It was introduced in April 1916, and it was the main face protection medium for the French infantrymen until the middle of 1918. Between March 1916 and November 1918, almost 30 million of all M2 models were manufactured.

Simultaneously with M2 and later with the ARS Gas mask, the French army used also another gas mask, the Tissot Large/Grand model or “APPAREIL T” (Apparatus Tissot). The name originated from the inventor of this breathing respirator apparatus, Dr. Jules Tissot. These masks were used in a mine rescue for a year prior to WWI. The filtration medium was a rectangular metal box that was carried at the back, due to a large size. The box was filled with iron potash and wood chips impregnated with a mixture of sodium bicarbonate and castor oil [25]. The facial part was made from rubber. The inhalation/exhalation system was made of varnished copper tubes. The eyepieces were surrounded by a metal ring and they were glued to the rubber. The most important asset of this mask was a design based on the “Tissot Principle”, where the inhaled air flew around the inside part of the eyepieces in two rubber pipes. The continuous flow of cold and fresh air on the lenses prevented water condensation and in this way the problem of fogging was overcome. The defogging of the lenses and the absence of the uncomfortable nose clip and mouthpiece set made the Tissot gas mask the most comfortable and



**Fig. 2.5** Chronicle of the most important gas masks models and the CWAs' deployment dates until 1917 (Sketches 1–5 and 7–9 by Andrea Silva, sketch 6 by Prof. Andreas D. Jannakoudakis: (Aristotle University of Thessaloniki, Greece))

effective gas mask used during WWI. The delivery of the first 450 masks to the frontlines began in July 1916. In 1916 and 1917 an updated version of the Tissot Large/Grand model appeared [5]. The characteristic fragile “flapper” type outlet valve (Fig. 2.5) was protected with a cylindrical piece, while the rubber material was thicker and was impregnated with boiled linseed oil [25]. Almost one year after the first appearance in the battlefields, the wood chips were replaced with charcoal.



The main drawbacks of the Tissot mask were the size and weight. For these reasons, these masks were assigned to soldiers with critical duties who had fixed positions, like artillery and trench mortar crew, snipers, messengers, medics, combat engineers. In 1917, a new and smaller filtration box was used, and thus, the usage of the mask by infantrymen was possible. This model was known as Tissot Small model or 1917 Tissot. More than 100,000 units of the Large and Small models were manufactured, until the Armistice (November 11, 1918). The Tissot mask is now one of the rarest apparatuses, since almost no units survived, mainly due to the decomposition of the rubber part.

The French army also provided their infantry with a more advanced mask with a changeable filter cartridge in the front of the face mask, similar to the *Lederschutzmaste*. This mask was referred to as ARS Gas mask (Appareil Respiratoire Spécial Modèle 1917) and was first used on the battlefields in November of 1917. A rubber face piece impregnated either with wax or oil had two celluloid eyepieces. Similar to the Tissot mask, the inhaled air flow was directed through the canister to the eyepieces, preventing their fogging. Because of the smaller size than that of SBR, the absence of the uncomfortable noise-clip and mouthpiece, and the anti-fogging property, ARS was established as the most desired gas mask by the soldiers of the Allied forces, and almost 5.3 million of these types of masks were used from November 1917 to November 1918.

### 2.3.4 *The Italians*

The Italian army used the French knowledge to manufacture gas masks. The first mask was made of a thick wad of gauze impregnated with hydrosulfate and carbonate soda solution, while the goggles were worn separately. It was effective only against chlorine. Many different mask versions were developed later and because of their single purpose use, they were called monovolente. These masks were abandoned after the disaster at Mount San Michele on 29th of June, 1916, where the Austrian army used phosgene. The Italian casualties were more than 2000 soldiers while about 5000 were poisoned [26]. The first multipurpose (polivolente) mask was based on the French TN model. The new mask had the same pad-based setup and separate goggles, but it offered protection against phosgene. The next polivolente model (Z), called a funnel type, was based on the M2 French mask. It was introduced in January 1917 [27], and it covered the entire head with a rubber cloth and later with leather. The inside gauzes presented an improved performance against phosgene, while the goggles were incorporated into the mask. In spite of all alterations, this mask had limited lifetime and inability to protect against newer toxic compounds, such as mustard gas. The polivolente mask models were abandoned and the Italian army started to be equipped with the British SBR British masks during the battle of Caporetto in 1917 (24 October–19 November).



### **2.3.5 *The Russians***

The Russian casualties and fatalities from the CWAs were the greatest compared to all other nations. The Russian generals assigned the task of the gas mask development to Nikolay Zelinsky, one of the founder of the theory and application of catalysis [28]. He had reported that ordinary charcoal had a supreme efficiency for the adsorption of organic fumes. Zelinsky, before the war had also studied the production of activate carbons by calcination. Even though Zelinsky had designed the filter system of a mask before the first gas attack by German forces, there were many difficulties in its application as a full face mask. After many trials, the engineer Kummant designed a rubber mask. The first model of the Zelinsky-Kummant mask with the code name “Petersburg”, equipped with a round filter hanging from the mask, arrived in battlefields in February 1916, saving the lives of numerous Russian soldiers. The next improved model “Moscow” had a square shaped filtration system. More than 11 million masks were used in the battlefields during WWI. It is worth to mention that most of the modern gas masks use activated carbon as the main desiccant.

### **2.3.6 *The Americans***

The United States of America entered WWI after the declaration of the Congress on April 6, 1917. The US army had limited knowledge or experience on toxic gases and gas masks, even though WWI started almost three years before. This was because the updates were coming with a delay from the Western Front. In many cases, the Allied forces intentionally did not reveal the entire picture of the war situation because of fear that it will decrease the willingness of the USA to actively participate in the battles. The first order to produce 25,000 gas masks similar to those of the British Small Box Respirators was placed on May 16, 1917. Twenty thousand copies were ready and shipped to England for inspection in less than a month. Unfortunately, these copies, known as Bureau of Mines Mask, were found as improper for use, since the soda lime granules formed big clusters that were blocking air inlets. Moreover, the rubber face piece was vulnerable to chloropicrin.

In July, the second production resulted in the American Training Gas mask (ATS). This model was almost the same as the first one and never had never been shipped overseas. ATS classified as “experimental model” and was used for training purposes, since the production started before the British army informed the US army that these masks were ineffective. The US army training regulations stated that 9 seconds should be the maximum time to put on/wear the SBRs or ATS masks. The production of this model took less than three months.

The first limited number of soldiers/infantryman (around 14,000), known also as doughboys of WWI, arrived in France on June 1917. Although, the first involvement of the doughboys (First Division) in the battlefields took place on October 21 of that year, owing to time needed for US troops for training. Meanwhile, on July 5,

**Table 2.3** The masks and canisters developed during WWI along with the month of their first usage in the battlefields, CWAs targeted, and the chemical composition of the filtration media. (Type of masks: pads with separate goggles (P), Full face mask with pads inside (FP), Full face with drum canister (FC), Full face with the filter separated and connected via tube (FS), and canister only (C). The masks that were never used in battlefields are indicated with asterisk.)

| Name | Date introduced            | Force | Type                                                                                | Designed to protect against | Chemicals                                 |                                                                                                |
|------|----------------------------|-------|-------------------------------------------------------------------------------------|-----------------------------|-------------------------------------------|------------------------------------------------------------------------------------------------|
| 1915 | Chlorine attack April 2015 |       |                                                                                     |                             |                                           |                                                                                                |
|      | German pads                | April |    | (P)                         | Chlorine                                  | Sodium thiosulfate                                                                             |
|      | Daily mail pads            | May   |    | (P)                         | Chlorine                                  | Urine or bicarbonate soda                                                                      |
|      | Black veiling              | May   |    | (P)                         | Chlorine, SO <sub>2</sub> , nitrous fumes | Sodium hyposulfite, glucerine, sodium carbonate, water                                         |
|      | Hypo helmet                | June  |    | (FP)                        | Chlorine, SO <sub>2</sub> , nitrous fumes | Hypo solution (sodium thiosulfate, sodium hyposulfate, glycerin)                               |
|      | P helmet                   | July  |    | (FP)                        | Phosgene, HCN                             | Hypo solution plus sodium phenate                                                              |
|      | Tampon P                   | Aug   |    | (P)                         | Chlorine, bromide                         | One impregnated pad with Castor oil and sodium ricinate                                        |
|      | Tampon P1                  | Aug   |    | (P)                         | Phosgene                                  | Tampon P plus a second pad impregnated with sodium sulfanilate for protection against phosgene |
|      | Gummimaske                 | Sept  |    | (FC)                        | Chlorine, tear gases                      | Diatomite and charcoal                                                                         |
|      | PH helmet                  | Oct   |    | (FP)                        | Chlorine, tear gases                      | Hypo solution plus sodium phenate and phenate hexamine                                         |
|      | Tampon P2                  | Oct   |  | (P)                         | HCN                                       | As P1 plus a third pad impregnated with nickel acetate                                         |
|      | Tampon T                   | Nov   |  |                             | tear gases, chlorine                      | As P2, different mask shape                                                                    |
|      | Phosgene—December 1915     |       |                                                                                     |                             |                                           |                                                                                                |
| 1916 | PHG helmet                 | Jan   |  | (FP)                        | Chlorine, tear gases                      | As PH, plus rubber sponge goggles                                                              |
|      | Tampon TN                  | Jan   |  | (P)                         | Phosgene, tear gases, chlorine            | As T model plus one waterproof cover                                                           |
|      | Tampon TN                  | Jan   |  | (P)                         | Phosgene, tear gases, chlorine            | As T model plus one waterproof cover                                                           |
|      | Zelinsk-Kum                | Feb   |  | (FC)                        | Phosgene, tear gases, chlorine            | Activated carbon                                                                               |
|      | Large Box Respirator (LBR) | Feb   |  | (FS)                        | Phosgene, tear gases, chlorine            | Lime-permanganate granules, pumice pieces impregnated with sodium sulphates and charcoal       |

(continued)

**Table 2.3** (continued)

| Name                       | Date introduced | Force                                                                               | Type | Designed to protect against                 | Chemicals                                                                               |
|----------------------------|-----------------|-------------------------------------------------------------------------------------|------|---------------------------------------------|-----------------------------------------------------------------------------------------|
| M2                         | Mar             |    | (FP) | Phosgene, tear gases, chlorine              | Impregnated pads inside one-eyepiece mask                                               |
| 11/11                      | April           |    | (C)  | Phosgene, tear gases, chlorine              | Charcoal granules and Diatomite impregnated with hexamine and potash                    |
| M2 2nd model               | April           |    | (FP) | Phosgene, tear gases, chlorine              | Two eyepieces instead of one                                                            |
| Tissot large               | July            |    | (FS) | Phosgene, tear gases, chlorine              | Iron potash and wood chips impregnated with sodium bicarbonate and castor oil           |
| Chloropicrin—August 1916   |                 |                                                                                     |      |                                             |                                                                                         |
| Small Box Respirator (SBR) | Aug             |    | (FS) | Phosgene, tear gases, chlorine              | Charcoal and lime-permanganate granules                                                 |
| 1917 Polivolente Z         | Jan             |    | (FP) | Phosgene, tear gases, chlorine              | Various impregnated pads inside a face piece                                            |
| Tissot small               | Mar             |    | (FS) | Phosgene, tear gases, chlorine              | Iron potash and wood chips impregnated with sodium bicarbonate and castor oil           |
| 11-C-11                    | June            |   | (C)  | Chloropicrin, mustard gas                   | More charcoal than 11/11                                                                |
| ATS (Training) *           | July            |  | (FS) | Phosgene, tear gases, chlorine              | Based on SBR                                                                            |
| Mustard Gas—July 1917      |                 |                                                                                     |      |                                             |                                                                                         |
| Lederschutzmaske           | Aug             |  | (FC) | Mustard gas                                 | Waterproof leather embedded in oil instead of rubber                                    |
| CE                         | Oct             |  | (FS) | Phosgene, tear gases, chlorine              | Activated charcoal from coconut shells                                                  |
| ARS                        | Nov             |  | (FS) | Mustard gas, Phosgene, tear gases, chlorine | Tissot principle, rubber face piece impregnated with oil or wax                         |
| 1918 RFK                   | Feb             |  | (FS) | Mustard gas, Phosgene, tear gases, chlorine | Activated charcoal from coconut shells, soda lime granules, and impregnated cotton pads |
| AT *                       | Jun             |  | (FS) | As RFK                                      | Tissot principle                                                                        |
| KT *                       | Aug             |  | (FS) | As RFK                                      | Tissot principle                                                                        |
| KTM *                      | Oct             |  | (FS) | As RFK                                      | Tissot principle                                                                        |

1917, the US army established a special expeditionary force for the frontlines in Europe, the American Expeditionary Force (AEF). Large numbers of US troops started to arrive gradually on Europe in 1918. It is worth to mention that the rate of the arrived soldiers per day reached 10,000 by June. AEF experienced the first gas attack close to Pargny (France) on March 16, 1918 [29]. The German army, knowing that the American forces did not have any experience, except an in-door theoretical training consisted of a two hours lecture about the protection against toxic gases and demonstrations of how to use the gas masks, launched various gases. Even though the US infantryman were equipped at the beginning with SBRs, purchased from the British, and with M2 obtained from the French, many soldiers did not manage to put on the masks on time, because they did not realize the presence/deployment of the toxic gases, until it was too late. The soldiers suffered also from the contamination of food.

The updated version of the training mask was the first mask that started in October 1917 to be produced and used in the battlefields by the USA. This Corrected English Model Respirator (CE) had a canvas face piece with two celluloid lenses surrounded by metal rims. The CE masks were more comfortable to wear, since the metal nose clip and the snorkel-like rubber mouthpiece were redesigned. A steel bracket was added in order to protect an ultrasensitive outlet/exhale valve. The yellow “H” filter canister was also improved, and it was filled predominantly with activated charcoal derived from coconut. An updated version of the CE mask had glass lenses and a more effective protection bracket. Almost two million CE masks were produced and used by AEF until March 1918.

The next version was the gas mask referred to as RFK and named after the designers Richardson, Flory, and Kops. It was the primary WWI gas mask for the troops. It had a wider face piece with a redesigned two-pieces adjustable head strap, and the glass lenses were yellow. The updated green colored “J” canister had a combination of activated coconut-based charcoal with soda lime granules and impregnated cotton pads. It provided less breathing resistance. Over 3 million masks of this version were used from February 1918 until the WWI Armistice. Three more models were developed until the end of the war: Akron Tissot (AT), Kops Tissot (KT), and Kops Tissot Monro (KTM). All of them utilized the advanced Tissot breathing respirator apparatus, eliminating the necessity for the nose clump and mouthpiece. Manufacturing problems limited their production to around 200,000, 335,000, and 2,000 masks of each type, respectively.

The need for a more reliable respirator, which would be based on the adsorption and not on neutralization was clear. Moreover, the increased need for the development of advantageous adsorption materials, that can be applied in various protection media, rose after the deployment of Mustard gas. The ability of this blister agent to penetrate cloths as well as skin, and to exist/last even for weeks in trenches, expanded the necessity of the protection also to uniforms, gloves, and shoes.

A collective chronicle of the most important gas masks models and the CWAs’ deployment dates until 1917 is presented in Fig. 2.5. All the masks and canisters

that were developed during WWI along with the month of their first usage in the battlefields, CWAs targeted, and the chemical composition of the filtration media are collected in Table 2.3.

## References

1. M. Duffy, *Weapons of War—Poison Gas* (2009). <http://www.firstworldwar.com>
2. E.A. Croddy, J.J. Wirtz, *Mass Weapons of Mass Destruction*, 1st edn. (ABC-Clio, 2004)
3. D. Stoltzenberg, F. Haberm, *Chemist, Nobel Laureate, German, Jew: A Biography*, 1st edn. (Chemical Heritage Foundation, 2005)
4. J.J. Wirtz, E.A. Croddy, *Weapons of Mass Destruction: An Encyclopedia of Worldwide Policy, Technology, and History*, 1st edn. (2004)
5. J. Simon, *World War I Gas Warfare Tactics and Equipment*, vol 13 (Osprey Publishing, 2008)
6. R. Black, Development, historical use and properties of chemical warfare agents. *Chem. Warf. Toxicol. Fundam. Asp. R. Soc. Chem.* **1** (2016). <https://doi.org/10.1039/9781849739696-00001>
7. J. Davy, On a gaseous compound of carbonic oxide and chlorine. *Philos. Trans. R. Soc. Lond.* **102**, 144–151 (1812). <https://doi.org/10.1098/rstl.1812.0008>
8. M. Vargic, (2013). [www.historyrundown.com](http://www.historyrundown.com)
9. M. Gunther, (2015). [chemistryworld.com](http://chemistryworld.com)
10. H.B. Kagan, Victor Grignard and Paul Sabatier: two showcase laureates of the nobel prize for chemistry. *Angew. Chem. Int. Ed. Engl.* **7376–7382** (2012). <https://doi.org/10.1002/anie.201201849>
11. J. Patocka, K. Kuca, Irritant compounds : military respiratory irritants. Part I. Lacrimators **84**, 128–139 (2015)
12. T. Marrs, R. Maynard, F. Sidell, *Chemical Warfare Agents: Toxicology and Treatment*, 2nd edn. (Wiley, West Sussex, England, 2007)
13. L. Szinicz, History of chemical and biological warfare agents. *Toxicology* **214**, 167–181 (2005). <https://doi.org/10.1016/j.tox.2005.06.011>
14. D.A. Giannakoudakis, Synthesis of Complex/Multifunctional Metal (Hydr) oxide/Graphite Oxide/AuNPs or AgNPs Adsorbents and Analysis of their Interactions with Chemical Warfare Agents. Thesis, CUNY Acad. Work 2017
15. C.H. Heller, *Chemical Warfare in World War I: The American Experience, 1917-1918* (Leavenworth Pap, 1984), p. 109
16. K. Kim, O.G. Tsay, D.A. Atwood, D.G. Churchill, Destruction and detection of chemical warfare agents. *Chem. Rev. (Washington, DC, United States)* **111**, 5345–5403 (2011). <https://doi.org/10.1021/cr100193y>
17. M. Duffy, (n.d.). [firstworldwar.com](http://firstworldwar.com)
18. D. Charles, *Master Mind: The Rise and Fall of Fritz Haber, The Nobel Laureate who Launched the Age of Chemical Warfare*, 1st edn. (2005)
19. 100 years of chemical weapons. *Chem. Eng. News.* (2015). <http://chemicalweapons.cenmag.org>
20. J.P. Smol; E.F. Stoermer (eds.), *The Diatoms: Applications for the Environmental and Earth Sciences*, 2nd edn. (Cambridge University Press, 2010)
21. L.E. Antonides, DIATOMITE, *Sophia*, pp. 1–7 (1998)
22. T.J. Badosz, *Activated Carbon Surfaces in Environmental Remediation* (Elsevier, 2006)
23. D. Trauner, Richard Willstätter and the 1915 nobel prize in chemistry. *Angew. Chem. Int. Ed. Engl.* **54**, 11910–11916 (2015). <https://doi.org/10.1002/anie.201505507>
24. T.M. Maguire, B. Baker, *Em38 British Military Respirators and Anti-Gas Equipment of the Two World Wars*, 1st edn. (The Crowood Press, 2015)

25. French Tissot Apparatus (AKA Tissot Large Box Respirator)[Gas Mask and Respirator Wiki| Fandom powered by Wikia, (n.d.)
26. Itineraries of WWI-Travelling in history (2010). <http://www.itinerarigrandeguerra.com/code/43726/The-attack-with-phosgene-on-Mount-San-Michele>
27. N. Thomas, D. Babc, *Armies in the Balkans 1914–18*, 1st edn. (Osprey Publishing, 2001)
28. A.N. Nesmeyanov, A.V. Tophiev, B.A. Kazansky, N.I. Shuikin, To the memory of academician Nikolai Dmitrievich Zelinsky. *Bull. Acad. Sci. USSR Div. Chem. Sci.* **2**, 683–690 (1954). <https://doi.org/10.1007/BF01178843>
29. T.I. Faith, *Behind the Gas Mask: The U.S. Chemical Warfare Service in War and Peace* (University of Illinois Press, 2014)

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