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# THE ASSESSMENT OF MAJOR HAZARDS: THE LETHAL TOXICITY OF CHLORINE

## PART 3, CROSSCHECKS FROM GAS WARFARE

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### Summary

In previous papers the information available on the lethal toxicity of chlorine to animals and man has been reviewed and a model for the lethal toxicity to man has been derived. An attempt is made in this paper to crosscheck the model using information on gas attacks in the First World War. Three gas attacks are considered, including the first and best known attack at Langemarck, Ypres, in April 1915. Reconstructions of these attacks yield scenarios which are consistent with the lethal toxic concentrations given in the model. Other scenarios, including some consistent with lower lethal concentrations, are also considered, but are judged less credible.

### Introduction

In previous papers [1,2] a model was given for the estimation of the lethal toxicity of chlorine to man for use in assessment of the hazard from chlorine installations. The model was based on various types of information, but mainly on data derived from animal experiments.

It is the purpose of this third, complementary paper to describe some cross-checks on the toxicity model based on gas warfare. Accounts are given of three chlorine gas attacks, including the first and best known attack at Langemarck, Ypres, on April 22, 1915. For each attack a 'best estimate' reconstruction is made, but for the two most instructive attacks alternative scenarios are also considered.

### Toxicity of chlorine

In the model for the lethal toxicity of chlorine a distinction is made between regular and vulnerable sections of the population. It is assumed that troops come in the former category. Another distinction made is between base and

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standard levels of physical activity. It is assumed that for troops exposed to gas the level of activity is at least the standard one.

The lethal toxic load function in the model is

$$L^* = \sum C^2 T \tag{1}$$

where $C$ is concentration (ppm), $L^*$ toxic load ($ppm^2$ min) and $T$ time (min). The probit equation for the regular population at the standard level of activity is

$$Y = -8.29 + 0.92 \ln \sum C^2 T \tag{2}$$

where $Y$ is the probit. Equation (2) corresponds to an $LC_{50}$ of 433 ppm for an exposure period of 10 min at the standard level of activity. This value is referred to hereafter as the model $LC_{50}$.

It may reasonably be argued that troops are a population more resistant than the regular population. In the gas attacks considered here the British were volunteers, the French colonial and territorial troops, and the first two groups at any rate could be regarded normally as fit. However, the Ypres salient was in every sense an unhealthy place and it is judged than men who had spent large parts of the winter under these conditions should be regarded as no more resistant than the regular population.

The effect of different levels of activity is taken into account by the use of an inhalation rate factor. At the base level of activity, which corresponds to lying in bed, the inhalation rate is about 6 l/min. At the standard level, which corresponds to normal waking activity, partly standing and sitting and partly moving about, the inhalation rate is 12 l/min. This compares with 8 and 14 l/min for standing and slow walking (2 mile/h), respectively. Two other levels of activity are used here,1.5 times and 2 times the standard level. These are taken into account in the model by the use of an inhalation rate factor $\psi_1$, which is applied to the concentration for the base level of activity and which is proportional to the inhalation rate. For the base and standard levels of activity the values of $\psi_1$ are 1 and 2, respectively. Equation (2) is for the standard level of activity and incorporates a value of $\psi_1 = 2$.

## Gas warfare

### *General*

Chlorine was used extensively by both sides in the First World War as a war gas. It appears to have been first used by the Germans against the Russians early in 1915, but despite this the first use in the West in the massive gas cloud attack at Langemarck, Ypres, on April 22, 1915 was a surprise and had a powerful impact. There followed over the next few weeks a number of other attacks in which troops were exposed with little protection to chlorine gas, but elementary respirators were quickly improvised. The Germans then introduced a

more toxic chlorine–phosgene mixture. They used this against the French in October 1915 and thereafter made little use of chlorine alone. The Allies' use of gas followed a similar pattern.

The war gave rise to a considerable literature on gas warfare. Official histories include Der Weltkrieg of the Deutsches Reichsarchiv [3] and the British Official History of the Great War [4], as well as the regimental and divisional histories. On the German side a comprehensive account is given by Hanslian [5]. Other German military authors are Schwarte [6], J. Meyer [7], Seeselberg [8], Zanger [9,10] and Müller [11]. The military medical account is given by the Heeressanitätsinspektion [12]. Military aspects are also discussed by Flury and Zernik [13]. Accounts of the work on the toxicity of war gases by German research workers led by Haber were described in the previous paper [1].

On the Allied side British works include those of Foulkes [14], who led the Special Brigade which was responsible for gas warfare, Auld [15] and Lefebure [16,17]. The Official History includes two separate accounts of the medical work, the Medical Services, General History [18], and the Medical Services, Diseases of the War [19], referred to here as the Medical History and Diseases of the War, respectively. French works include those of Bloch [20], Serrant [21] and A. Meyer [22] as well as shorter accounts [23–25]. The principal Russian work is that of Chlopin [26], who was in charge of work on gas warfare at St. Petersburg. Accounts by American authors include the comprehensive work by Prentiss [27] and works by Fries and West [28] and Waitt [29]. Military medical aspects are discussed by Vedder [30]. The statistics of gas casualties are given in the official British statistics [31] and by Hanslian [5], Vedder [30], Gilchrist [32] and Prentiss [27].

There are also a number of works which deal with war gases, their toxicity and characteristics, including those of Flury and Zernik [13], Gilchrist [33], Büscher [34], Dautrebaude [35], Loschke [36], Fessler, Gebele and Prandtl [37], Sartori [38] and Wachtel [39]. Some of the works already mentioned such as Hanslian, Prentiss and Vedder also treat this aspect. More recent work includes the general survey by Robinson [40] and the study of gas effectiveness by Clarke [41].

In addition, there are a large number of unit histories and personal accounts which give information on individual gas attacks, some of which are described below. Detailed bibliographies of the literature on gas warfare are given by a number of the authors mentioned, in particular Hanslian and Prentiss.

The first gas attack was carried out by the Germans on the Russian front in January 1915. They used chlorine gas shells, but the results were disappointing, since the weather was too cold to allow the liquid chlorine to vaporise properly.

The Germans then made preparations for a major gas cloud attack on the Ypres salient. Cylinders were installed both on the north and on the south sides

of the salient. It was on the north side that favourable conditions first occurred and the first cloud gas attack was the well-known attack against the French at Langemarck, Ypres, on April 22, 1915. Further gas cloud attacks were made at other points in the salient during the following weeks, including one against the Canadians on April 24 at St. Julien and three against the British, of which two were on May 1 and May 5 at Hill 60 and one was on May 24 on the line Menin Road–Sanctuary Wood.

Although the first attack on April 22 caught the Allies unawares and punched a hole some kilometres wide in the front, the response to this new threat was rapid. Elementary respirators were devised and issued within a few days so that the troops attacked on May 1 already had them. Gas discipline was also developed and enforced with varying degrees of success.

After the April–May attacks there was an interval of some seven months before the Germans made any further gas attacks on the British. On October 19, 1915 they used a chlorine–phosgene mixture against the French at Fort Pompelle near Reims and on December 19, 1915 they used a similar mixture against the British at Wieltje near Ypres. This mixture is much more effective as a war gas and thereafter the Germans made little use of chlorine alone.

The Allies responded with gas cloud attacks of their own, notably with chlorine at Loos on September 25, 1915. Although in general the Allies had the advantage of the prevailing wind, this was not always reliable and the lack of wind greatly reduced the effectiveness of the gas on this occasion. This dependence on the weather was a major disadvantage of gas cloud attacks. So also was the danger of discovery of the cylinders in the trenches. Hence both sides sought alternative means of delivery and gas shells came into widespread use. The British also devised another effective means of delivery, the Livens projector.

In 1917 the Germans started to use mustard gas, which is much more toxic. For these reasons the period of the war during which the combattants used gas cloud attacks of chlorine only was a relatively short one. Tabulations of these gas attacks have been given by Prentiss and Hanslian and short accounts of many of them are given by the latter. The main chlorine gas cloud attacks on the Western Front during the war are listed in Table 1.

Before giving an account of individual chlorine cloud gas attacks it is necessary to describe briefly the general nature of such an operation.

*Gas cloud generation*

Cylinders containing liquid chlorine were installed in the first line trenches. When the order to start was given the nozzle on the cylinder was opened and the liquid chlorine was ejected. On emerging from the nozzle of such a cylinder a fraction of the chlorine flashes off. Another fraction forms spray and any residual liquid forms a pool on the ground, which will then rapidly evaporate.

If the chlorine is simply forced out of the cylinder under its own vapour

TABLE 1

Main chlorine gas cloud attacks on the Western Front during the First World War[a]

| Date | Place | Troops attacked | References[b] |
|---|---|---|---|
| *1915* | | | |
| April 22 | Langemarck, Ypres (Battle of Gravenstafel Ridge) | French | Official History [4, 1915/1, p. 171]; Foulkes [14, p. 18]; Hanslian [5, p. 87] |
| April 24 | St. Julien (Battle of St. Julien) | British (Canadians) | Official History [4, 1915/1, p. 214] |
| April 25 | Langemarck (Battle of St. Julien) | British | Official History [4, 1915/1, p. 240] |
| May 1 | Hill 60 | British | Official History [4, 1915/1, p. 288]; Hanslian [5, p. 91] |
| May 2 | Berlin Wood — Turco Farm | British | Official History [4, 1915/1, p. 289]; Hanslian [5, p. 91] |
| May 5[c] | Hill 60 | British | Official History [4, 1915/1, p. 304]; Hanslian [5, p. 91] |
| May 10 | | British | Official History [4, 1915/1, p. 328]; Hanslian [5, p. 91] |
| May 24 | Menin Rd — Sanctuary Wood | British | Official History [4, 1915/1, p. 340]; Hanslian [5, p.91] |
| September 25 | Loos | Germans | Official History [4, 1915/2, p. 150]; Foulkes [14, p. 66]; Hanslian [5, p. 106] |
| October 13 | Hohenzollern Redoubt | Germans | Official History [4, 1915/2, p. 380]; Foulkes [14, p. 84] |
| *1916* | | | |
| April 30 | Wulverghem | British | Diseases of the War [19, p. 278]; Foulkes [14, p. 181]; Hanslian [5, p. 93] |

[a]The gas used in these attacks is believed to have been chlorine in all cases, although there is some doubt about that used at Wulverghem on April 30, 1916. The original sources should be consulted for further details.

[b]These attacks are also listed by Prentiss [27, p. 662].

[c]Some authors refer to a gas attack on May 6. It is not clear if this is the same one.

pressure, the strong cooling effect associated with the vaporisation of the chlorine quickly reduces the flow. One method of overcoming this problem was to use an ejection tube so that the chlorine came out as liquid and then vaporised. The use of such a tube is mentioned by Foulkes in his account of the preparations for the first British gas attack, at Loos. At some stage the Germans used auxiliary compressed air to force the liquid out [27]. It is not known whether either method was used by the Germans in their first attack at Langemarck, but it seems almost certain something of this sort was done.

The time for the cylinders to empty was of the order of 5 minutes. This is the time given by Hanslian for the cylinders to empty in the German attack at Langemarck. It is also the time mentioned by Foulkes in his preparations before Loos. The evidence is, however, that after the first attack, the Germans lengthened the release nearer to 10 minutes. Such longer releases could be obtained by opening cylinders sequentially. There was also a move towards the use of successive waves of gas. Thus in the April–May attacks there appears to have been a single release so that the troops were subjected to a fairly constant flow of chlorine gas lasting some 5–10 minutes. In the British attack at Loos, however, the release period was deliberately extended in order to exhaust the protection afforded to machine gun crews by their oxygen sets, while many of the German attacks from 1916 onwards used multiple releases. In the Wulverghem attack a single release was used on part of the front and a double one on the other part.

The linear density of gas cylinders necessary to generate an effective gas cloud was high. In the first attack at Ypres on April 22 the Germans used 5,730 cylinders along a 6 km front, thus a density of approximately 1 cylinder/m. The Official History refers to British preparations for Loos with gas release points with multiple cylinders at 25 yd intervals.

*Gas cloud behaviour*

Attempts were made by the combattants to model the cloud behaviour and some of these early models are described by Prentiss and Hanslian.

The gas cloud produced by a typical release of gas from cylinders in trenches will start as a heavy gas, but will undergo transition to neutral density within a very short distance. The gas dispersion model used here is a neutral density dispersion model. Such models have been developed by Sutton [42] and by Pasquill [43] and it is the latter, in the form frequently referred to as the Pasquill–Gifford model, which is used here. Pasquill gives for an infinite line source the equation

$$\chi = \frac{2Q'}{(2\pi)^{1/2}\sigma_z u} \exp\left[-\frac{z^2}{2\sigma_z{}^2}\right] \tag{3}$$

where $Q'$ is the mass rate of release per unit distance (kg/m s), $u$ the wind

speed (m/s), $z$ the distance in the vertical direction (m), $\sigma_z$ the dispersion coefficient in the vertical direction (m) and $\chi$ the concentration (kg/m$^3$). The dispersion coefficients used in the Pasquill–Gifford model have been obtained using the method given by Clarke [44]. Concentration conversions have been made at the conventional temperature of 25°C ($1\times10^{-3}$ kg/m$^3$ = 345 ppm), which is that used in the previous papers [1,2] and thus in the derivation of eqn. (2).

The concentration calculated by eqn. (3) falls off rapidly with distance. For a typical chlorine release in slightly unstable conditions and with a wind speed of 2 m/s the calculated concentration at a distance of 100 m from the source is of the order of 0.1% (1,000 ppm). Thus much the most lethal effect of the gas cloud was on the front line trenches and even so decreased rapidly as the distance between the opposing trenches increased. Troops further back were likely to be much less affected.

A plume model for a point source is applicable only for downwind distances such that the travel time is less than the release time. This condition holds for two of the three reconstructions considered, while for the third (Langemarck) it holds for the zone within which most of the toxic load occurs.

In one reconstruction (Hill 60) the infinite line source model has been applied to a finite line source of 400 m width and for this case its applicability has been checked as follows. A model for a finite line source has been given by Sutton. This differs from his model for an infinite line source by a correction factor. A similar correction factor has been applied to the Pasquill–Gifford model for an infinite line source so as to provide a model for a finite line source. This has been used to estimate any possible error in the infinite line source model.

Chlorine gas released from cylinders is heavier and colder than air. There are available heavy gas dispersion models, but the Pasquill–Gifford model has been preferred in this case. The heavy gas models available are for instantaneous or continuous point sources. The latter can be adapted for an infinite line source, but in the present application this involves its use with a source width about a 1,000 times greater and a source strength per unit width about 100 times weaker than that typically used. There are also problems in defining the initial air entrainment. As far as the authors are aware the use of such models under these conditions has not been validated. The decay index of the Sutton model for an infinite line source was validated in experimental work on gas dispersion on Salisbury Plain and the index for the Pasquill–Gifford model is similar to that in the Sutton model.

Both types of gas dispersion model apply to level ground. The effect of other topographies is highly specific and is therefore considered in the individual reconstructions. The concentrations in a gas cloud also vary with the height above ground, but except very close to the source the model concentrations at ground level and at 2 m height are virtually the same. No distinction has therefore been made between these two cases, which correspond to those experi-

enced by a man standing in a trench with his head at ground level and a man walking across ground behind the trenches. The gas did tend, however, to accumulate in the trenches and any men lying in these would have experienced concentrations higher than the model ground level values.

*Effect of gas cloud on troops*

The response of troops to a gas cloud attack varied, even as between the different attacks in April–May 1915. In the first, and unexpected, gas attack on the French at Langemarck on April 22 it seems almost certain that the men fled, as described below. Likewise, the Official History states that in the British gas attack on the Germans at Loos on September 25, 1915:

"A German officer in this sector remarked that, as soon as the gas entered his trench, he lost all control over his men, a panic ensued and he was unable to keep them in the front line." [4, 1915/2, p. 179]

On the other hand the Canadians at St. Julien on April 24 and the British at Hill 60 on May 1 both stood firm. Once gas warfare was established and gas discipline and protection were introduced, this was the normal pattern. The military also tended to argue that this was the safest course to take. The Official History states:

"It early became evident that the men who stayed in their places suffered less than those who ran away, any movement making worse the effects of the gas, and those who stood on the fire step suffered less — indeed they often escaped any serious effects — than those who lay down or sat at the bottom of the trench. Men who stood on the parapet suffered least, as the gas was denser near the ground. The worst sufferers were the wounded lying on the ground, or on stretchers, and the men who moved back with the cloud." [4, 1915/1, p. 178]

This statement has parallels with the Army Historical Branch account of the effect of gas on the troops at Hill 60 on May 1 given in Appendix 1.

Diseases of the War [19] quotes the following account by Black et al. [45]:

"A group of 700 cases was admitted to No. 8 Casualty Clearing Station, Bailleul, the majority six or eight hours after having been gassed in the attacks during the second week of May 1915. 'Most of the men were in a choking condition, making agonising efforts to breathe, clutching at their throats and tearing open their clothes... The majority of such cases did not rally. All, except those moribund or collapsed, were fully conscious and fighting desperately for life. Fourteen men died out of the first batch of seventeen taken off the motor ambulances.' " [19, p. 384]

Also relevant is the following report, in a German newspaper, of the effect of gas on German troops at Loos, quoted by Foulkes:

"Some were killed instantaneously, but not many, comparatively speaking. Others — the greater number — were simply stupefied and lay where they fell. Most of the latter were discovered by us afterwards and brought into our lines, where they soon recovered consciousness. A good many, however, were taken prisoners by the English when in a state of coma." [14, p. 80]

There are numerous statements which describe the immediate effect of the gas on unprotected troops. Thus the accounts of gas attacks given below state that at Hill 60 "the asphyxiating effect of the gas was almost instantaneous" and at Wulverghem "the speed with which the cloud reached the trenches and the concentration of the gas were such that a man was bound to fall a victim if he hesitated in the slightest in putting on his respirator or fumbled in adjusting it." In both cases the distance between the opposing trenches was very small, being at its shortest about 20 m at Hill 60 and 40 m at Wulverghem. Despite these rapid effects, the gas did not usually cause immediate death. The account of the Wulverghem attacks states that the first death occurred after an hour and a half.

*Mortality from gas cloud attacks*

There are a number of accounts of gas casualties during the war. Most of these give estimates of the mortality of troops exposed to gas. However, these data usually relate to all gas attacks and do not distinguish chlorine gas attacks specifically.

Some information is available, however, on the mortality of gas casualties in medical units. Diseases of the War states:

"So far as can be ascertained from the war diaries of medical units, approximately 7,000 gas casualties were admitted to the field ambulances and casualty clearing stations, though these probably did not include casualties in Canadian units, which reached a large number. The casualty lists for May and June 1915 record about 350 deaths from gas poisoning. These deaths must be attributable to the April and May cloud attacks, and appear to represent only those cases that died in medical units, deaths on the field never having been recorded as specifically due to gas." [19, p. 274]

This gives a mortality of 5%. Foulkes says that for the six attacks in April–May (April 22 and 24, May 1, 6, 10 and 24) 6,455 gas casualties were treated in hospital, of whom 315 died. These data relate to broadly the same attacks as those given in Diseases of the War and again the mortality is 5%.

Hanslian states that of the 200 gas casualties among the prisoners taken in the attack on April 22, 12 died, giving a mortality of 6%.

The proportion of deaths occurring in hospital, however, tended to be relatively small. Much the largest proportion of deaths occurred on the field and in the more advanced medical units.

**Analysis of gas attacks**

Of the chlorine gas attacks listed in Table 1 three have been selected for analysis. These are the attacks on April 22, 1915 at Langemarck, Ypres, on May 1, 1915 at Hill 60 and on April 30, 1916 at Wulverghem. It is the first two

of these which are the most important. In both there are a number of uncertainties and in order to use them as a crosscheck on the toxicity model it is necessary to take the two attacks together.

The three gas attacks are now considered. In each case the attack is described and information from the original sources given, generally without comment. A reconstruction of the event is then given and the interpretation and implications of this scenario are discussed. For the Langemarck and Hill 60 attacks alternative scenarios are also given.

**Gas attack at Langemarck, Ypres, April 22, 1915**

The first cloud gas attack was made by the Germans against the French near Langemarck on the northern side of the Ypres salient on the evening of April 22, 1915. This phase of the battle is known in the British histories as the Battle of Gravenstafel Ridge.

Hanslian [5], Mordacq [46] and the Official History [4] give accounts for the German, French and British viewpoints. On the German side there are a number of first hand accounts. These include those by Helferrich [47], a meteorologist, Colonel Peterson [48], commander of Pioneer Regiment 35 (Gas Regiment Peterson), Count von Tattenbach [49], General Staff Officer of the 52 Reserve Division of the XXVI Corps, General von Tschischwitz [50], Chief of Staff of the XVIII Reserve Corps, and of General von Deimling [51], commander of the XV Corps, and Hanslian [52,53]. Some of the most detailed information is that obtained by Seeselberg from Petersen's war diary and quoted by Hanslian [53]. On the French side there are the accounts of General Mordacq [46], commander of the 90 Brigade, 45 Algerian Division, and of Colonel Oudry [54], Staff Officer to that division. An account of the situation in Ypres itself has been given by Young [55], who was with the Friends Ambulance Unit (FAU) at the Sacré Coeur Hospital. The attack has been the subject of much debate and is also discussed in many of the works on gas warfare already mentioned.

Maps of the battlefield are given by Hanslian [5,53] and in the Official History [4]. Figure 1 is a version of Sketch 9 of the Official History, simplified by omitting some unit dispositions. The order of battle may be reconstructed from the accounts given by Hanslian [5], the Official History [4] and from additional information on unit strengths supplied by the Army Historical Branch [56]. It is shown tabulated in Table 2 and in schematic layout in Fig. 2.

The following account is based mainly on that given by Hanslian, which includes lengthy extracts from Mordacq and others.

Gas cylinders had been installed on the south as well as on the north side of the Ypres salient. The original intention was to release the gas in the southern

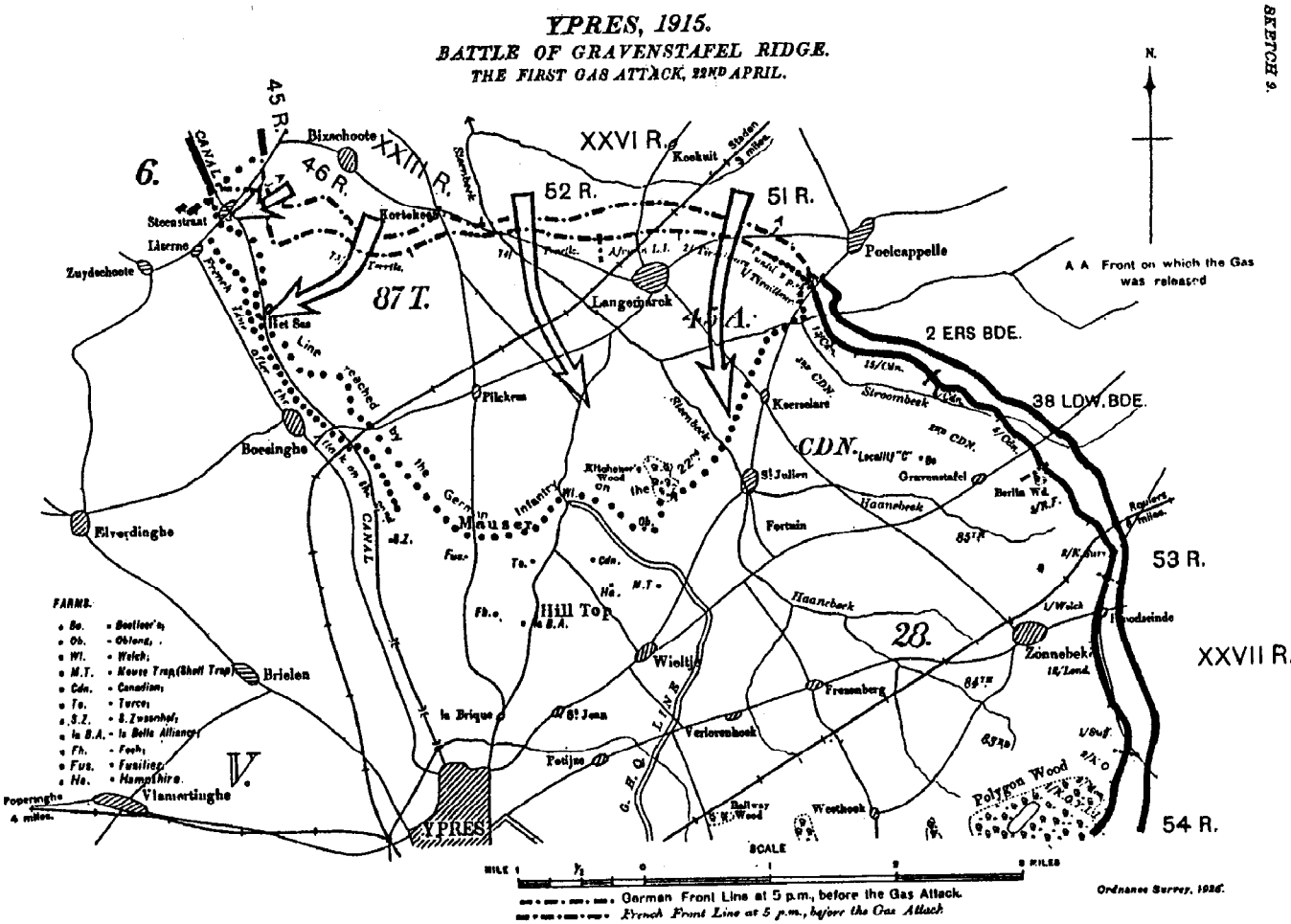


Fig. 1. Sketch map of battlefield at Langemarck, April 22, 1915 (Edmonds and Wynne [4], © British Crown Copyright).

TABLE 2

Order of battle at Langemarck on April 22, 1915

*Germans*

XXIII Reserve Corps

45 Reserve Division — Generalleutnant Schöflin
46 Reserve Division — Generalleutnant Hahn

XXVI Reserve Corps

52 Reserve Division — Generalleutnant Waldorf
51 Reserve Division — Generalmajor Kleist

Pionerregiment 35 — Oberst Peterson

*British*

Canadian Division — Lt General Alderson
28 Division — Major General Bulfin

*French*

87 Territorial Division
45 Algerian Division — General Quinquindon
90 Brigade — General Mordacq
1 Battalion African Light Infantry — Major Trousson (front line)
2 Battalion 1 Regiment Tirailleurs — Major Fabry (front line)
1 Battalion 1 Regiment Tirailleurs — Major Villevaleix (front line)
1 Battalion 2 Regiment Zouaves (2 companies) (in support)

Further breakdown of French dispositions:

87 Territorial Division

| | | | |
|---|---|---|---|
| 74 Territorial Regiment | Front line | 2 battalions | 2,286 nominal[a] |
| | Support | 1 battalion | |
| 73 Territorial Regiment | Front line | 2 battalions | 2,286 nominal |
| | Support | 1 battalion | |
| 45 Algerian Division | | | |
| | Front line | 3 battalions | 1,300 nominal $+2\times628$ |
| | Support | 2 companies | |

[a]Data on unit strengths estimated from information supplied by Army Historical Branch [56].

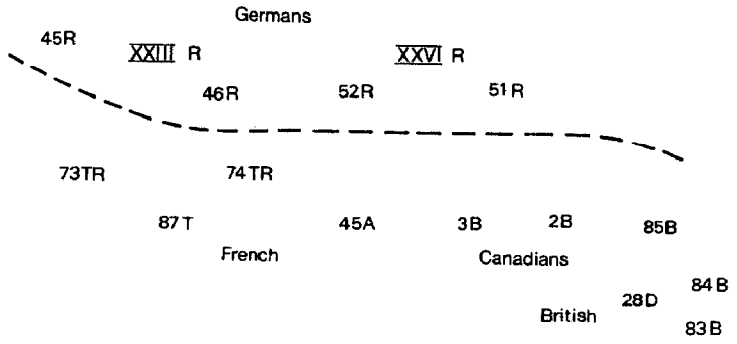


Fig. 2. Order of battle at Langemarck, April 22, 1915.

sector where the wind conditions were more favourable. In the event the decision was taken to make the gas attack in the northern sector.

The front over which the gas was released was 6 km from Steenstraat to Poelcappelle. The distance between the German and French trenches varied. According to the maps the distance was mostly between 300 and 400 m. The gas cylinders were installed in the front line except south of Bixschoote, where they had to be put 80 m back. There were 1,600 large and 4,130 small cylinders, containing 40 and 20 kg of chlorine, respectively. The weather conditions were a wind direction N.N.E. and a wind speed 2 m/s. The conditions were far from ideal, since it had been a fine spring day and the earth had been warmed by the sun so as to cause the cloud to lift. The topographical conditions also were not ideal. In front of Langemarck itself there were ruins which had the effect of causing the cloud to lift and to break up.

The gas cylinders were opened at 6.00 p.m. (German time). According to Hanslian, the cylinders were declared empty at 6.05 p.m. Other figures for the emptying time are 3 minutes (Wachtel) and 7–8 minutes (Hanslian again). Figure 3 shows an aerial view of the gas discharge. The gas cloud tended to lift due to the heat of the warm earth and in places was broken up by the ruins. Nevertheless, it had a terrifying effect on the defenders, who saw a wall of greenish–yellowish gas about 5 m high coming towards them.

The attack was supported by the German artillery. During the afternoon there was heavy shelling, which then ceased. When the attack began the guns were silent from 6.00 p.m., when the cylinders were opened, until 6.10 p.m., when the barrage started.

At 6.15 p.m. the German infantry advanced. At 6.20 came reports that Langemarck was taken and at 6.49 reports that Pilkem Ridge was taken. The troops who took Pilkem Ridge were the 52 Division, who pressed on further. The 46 Division also made good progress, reaching Het Saas and Boesinghe. On the flank, however, the advance was slower. The 45 Division met strong resistance at Steenstraat, which was taken only late in the evening and the 51 Division met strong resistance at and east of Langemarck.

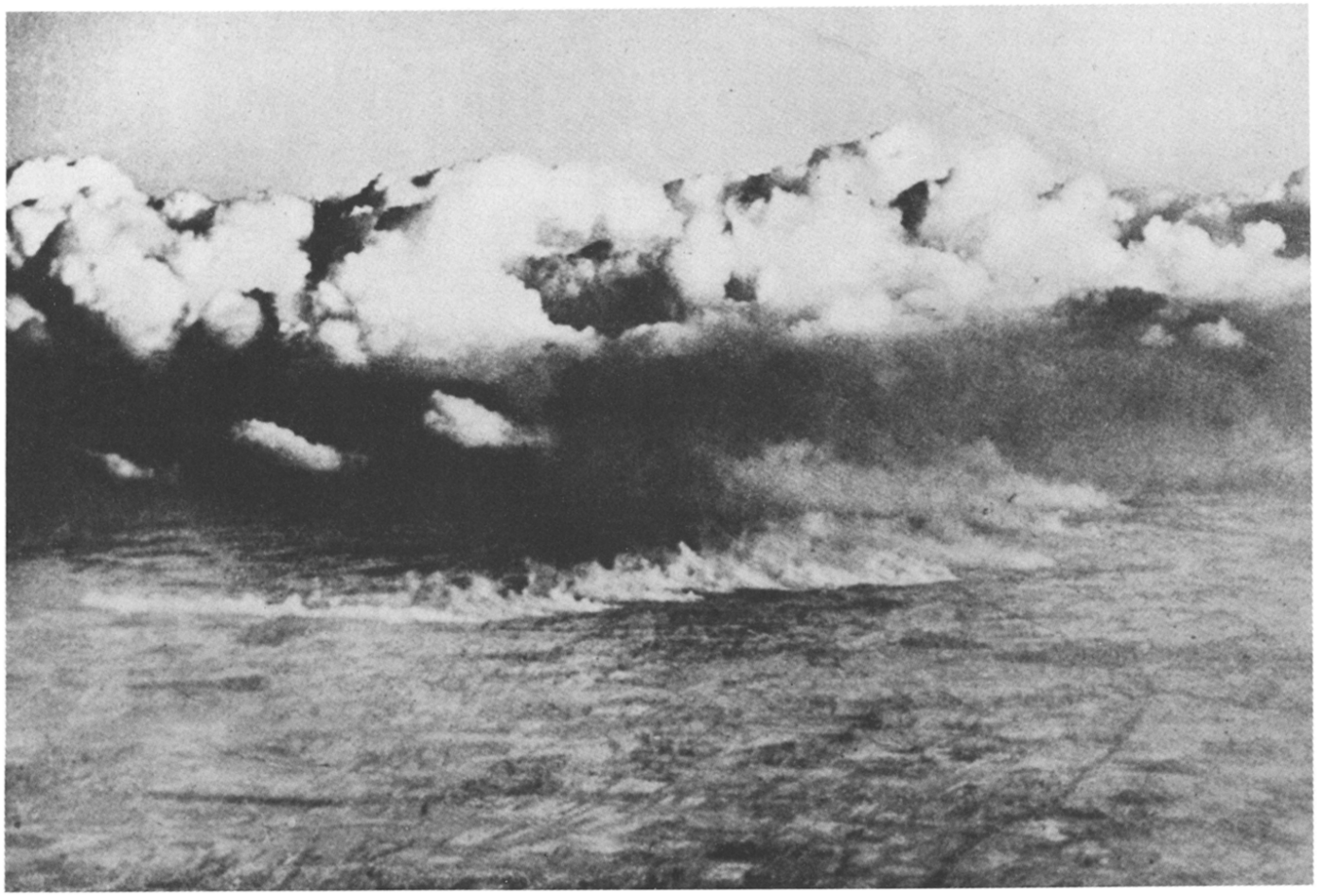

Fig. 3. Aerial view of cloud gas attack at Langemarck, April 22, 1915 (Vedder [30]).



Fig. 4. Artist's impression of flight of French troops from the cloud gas attack at Langemarck, April 22, 1915 (Reproduced by permission of the Illustrated London News Picture Library).

The German authors state that the enemy fled from the trenches at the start of the attack. Von Tattenbach says that there were only a few dead in the trenches, all with wounds, and that there were no gas dead, but also that several hundred prisoners were taken, some in a very poor condition due to gas. Hanslian states that a German medical officer visited the trenches the next day and reported no gas corpses. He himself was there on May 1 and found, in his words, that there were no, or no longer, any gas dead.

On the French side Mordacq was at his headquarters at Elverdinghe. At 5.20 p.m. (French time, equal to 6.20 p.m. German time) he was telephoned by Villevaleix opposite Poelcapelle, who was coughing and had to keep breaking off, to say that he was under heavy attack, that huge yellowish clouds were coming from the German trenches, that his men were starting to leave their trenches and go back and that many were falling down gassed. At almost the same time Mordacq heard heavy gunfire, artillery and small arms. The next moment Fabry rang. He said that he was forced to abandon his position, that he could no longer breathe, that all around him groups of men were suffocating or had fallen in the attempt to get through the artillery barrage. The position was no longer tenable, they were caught between the gas and the barrage. Villevaleix then rang back again to say that he was abandoning his position, but his sentence was left unfinished and the line went dead.

Mordacq mounted his horse and galloped to the front. Everywhere territorial and colonial troops were in flight. As his party came within 300–400 m of Boesinghe they felt the gas, the horse refused to go further and they went forward on foot towards the bridge. Near the town they were met by the sight of men with their shirts torn open, running about as if demented, crying for water, spitting blood and some rolling on the ground. It was useless to try to stop the fugitives and they soon gave up the attempt. There was a similar scene all along the canal. The situation was more comforting at the bridge, which was held by 3 and 4 Companies of the 2 Regiment Zouaves, who had been coming up to effect a relief. Later that evening French troops who had been gassed tried to get back to their own lines under cover of darkness but were fired on by the defenders of Boesinghe bridge, who took them for Germans.

Mordacq states that almost the whole of the 87 Division were killed, wounded, gassed or captured. A few who were able to escape fled over the bridges at Boesinghe and Steenstraat and were not seen again that day. Oudry states that the 45 Division lost 5,000 men killed, wounded, missing and prisoners, but this evidently covers the whole period of the battle when the division was engaged and not just the first day.

At the western end of the French front Hanslian describes how a Belgian grenadier saw the gas cloud coming from the German trenches near Steenstraat. He thought the cloud was smoke from German dugouts which had caught fire. Only the edge of the cloud reached the Belgians, but they saw the French soldiers who had been holding the bridge at Steenstraat fleeing. Several fell to

the ground. Others shouted to the Belgians that they were poisoned. The Belgians made simple masks using handkerchiefs and faceclothes, which they dipped in the canal.

The situation at the other end of the front is described by Hanslian, drawing on accounts by Conan Doyle and Rev. Watkins. According to Doyle, the Canadians adjoining the French saw the gas clouds coming from the German trenches. The French watched the cloud,then suddenly men threw their arms up, clutched their throat and rolled to the ground. Many did not get up, but their comrades broke into flight and ran back beyond the trenches behind. Many did not stop until they got to Ypres, while others ran westward to put the canal between themselves and the enemy. The road to Vlamertinghe became choked with infantry in disorder and galloping gun teams.

Watkins describes how he came out of his dugout and saw people, probably Canadians, running in confusion from the front, saying the French had broken. Then French troops, badly gassed, staggered in saying there were hundreds of dead and dying in the trenches.

The Official History states that French colonial troops began drifting down the roads through the back areas of the British V Corps. They coughed and pointed to their throats and if not suffering from gas were thoroughly scared.

There were points of resistance to the German advance. The Official History quotes a German account which states that the gas cloud did not have its full effect at Langemarck or along the Poelcapelle–Keerselaere road and that it was not until 7.00 p.m. (German time) that Langemarck was taken. Mordacq states that he was told at Boesinghe that 1 Battalion African Light Infantry and the two battalions of Tirailleurs had resisted but that they were all either dead or captured. Oudry states that on the left of the 45 Division the 1 Battalion African Light Infantry preferred to die where they stood, but the Zouaves at Langemarck had retired. Two companies of the 1 Battalion 2 Zouaves in support are said by Hanslian to have been relatively little affected and to have initially stayed put and then withdrawn onto the Canadians.

In the accounts quoted so far there is little mention of the situation in the medical stations, although large numbers of gassed troops appear to have passed through them. A description of the situation at the French dressing stations is available from the official history of the FAU by Tatham and Miles [57] and in a privately published account by Lidbetter and Monk-Jones [58]. The French army was not well equipped with motor ambulances and had accepted on attachment section SSA 14 of the FAU, who operated from the French dressing station at Elverdinghe, supporting Mordacq's division. Lidbetter and Monk-Jones state:

"From the moment the attack started, large numbers of wounded and gassed cases came streaming into the dressing station in the village, completely overwhelming the cars there... The ambulances worked that night as they had never worked before, but by the morning the chateau seemed as full

as ever, and the lawn was still strewn with khaki clad forms, some still coughing and gasping for breath, the rest either already dead or lying inert with exhaustion from the struggle."

Many of the French casualties found their way, however, to British dressing stations. The Medical History states that on the day of the attack British medical services in the salient were, in effect, in a state of flux and that the only Main Dressing Station on which the British V Corps could rely was the Canadian No. 3 Field Ambulance at Vlamertinghe, which is at the base of the salient some 4 km west of Ypres and 6 km southwest of Boesinghe. The History states:

"Streams of French and African troops gassed or wounded poured into the dressing stations of the Canadian Division, large numbers passing through Brielen and finding their way to Vlamertinghe." [18, p. 402]

In addition to this Main Dressing Station, the Medical History shows Advanced Dressing Stations at Hampshire Farm and Wieltje and Regimental Aid Posts at St. Julien and Gravenstafel Ridge.

Estimates of the casualties from the gas attack vary widely. Two figures in particular have gained currency. These are 5,000 dead and 350 dead. The figure of 5,000 is given by Lefebure [16] writing in 1923. Hanslian quotes Allied figures of 15,000 casualties,including 5,000 dead. These figures are criticised by Hanslian and by other German authors, however, who argue that they are a gross exaggeration of the numbers killed, put out by the Allies for propaganda purposes.

Foulkes, referring to the gas attacks on April 22 and 24, says:

"The Germans (in a captured document) claim that in these two attacks 5,000 men were killed by gas; and Dr Hanslian puts the casualties at 15,000, of whom 5,000 died; but both estimates are probably exaggerated, as on the 22nd the French African troops, instinctively and probably justifiably, retired too quickly to have lost many men." [14, p. 306]

Further on he states, giving a figure for 'our total known gas casualties' of 181,053:

"To these must be added about 3,000 that were unrecorded, mostly dead, in April and May 1915." [14, p. 338]

The figure of 181,053 evidently applies to British Empire casualties, since it agrees well with the figures of 188,706 and 190,000 given by Prentiss [27, p. 653] for the total British Empire and French gas casualties, respectively. Foulkes' figure does not therefore seem to cover French casualties.

Prentiss [27, p. 663] gives the number of gas deaths in the attack of Langemarck as 5,000 and the number in the other gas attacks in April and May as 350.

The origin of the figure of 350 dead is also uncertain, but it may well derive

from the report in the Medical History [18] quoted earlier. However, as the extract makes clear, this figure refers to all the April–May attacks, but only the casualties passing through the British medical stations. It also refers only to deaths in medical units and does not include deaths on the field.

Hanslian states that the Germans captured 200 Allied gas casualties of whom 12, or 6%, died.

The casualty figures have been reviewed by Haber [59], son of Professor F. Haber, who directed the German gas warfare effort. He concludes that the figure of 5,000 dead is not credible.

Another casualty figure is given in the report by Dr. Sieur [60] in the French Military Archives, which mentions 625 gas casualties. Sieur states that very few of the injured died. This report is quoted by Haber as evidence that there were not large numbers of gas deaths.

An attempt has been made by the authors to reconstruct this attack, but before describing this, it is necessary to review briefly the accounts just given. It is noteworthy that there is no first hand account from the 87 Division, although it was this division which held most of the front, had the larger number of men exposed and almost certainly suffered most of the casualties. The account of events at the canal bridges in the division's rear is given by Mordacq of the 45 Algerian Division.

German authors tend to play down the number of gas deaths in this attack and to accuse the Allies of exaggerating the number of dead for propaganda purposes. On the other hand Foulkes argues that the Germans later suffered severe losses from gas attacks by his Special Brigade and that they clamped down in information and disparaged the effectiveness of gas in order to maintain morale.

According to most of the Allied accounts some of the men were gassed and fell in the front line trenches, whereas the Germans state that no gas dead were found there. Even if doubts remain on the latter point, the general picture seems clear. It is reasonably certain that the vast majority of troops left the trenches as the gas cloud came up to them.

These men either outran the cloud or were caught up in it. Movement back from the trenches would be hampered by a number of factors. The terrain must have been broken up by shelling, even if it had not yet become the desolate landscape of interconnected shellholes which typified the front later in the war. There was harassment by the artillery bombardment. The guns evidently held their fire during the actual release, but started up just before the infantry advanced. Fabry described his men as caught between the gas and the barrage.

Some men evidently outran the gas cloud. The accounts describe men gassed only lightly or not at all fleeing to Ypres, west across the canal or into the rear of the British V Corps. Large numbers, however, came back badly gassed, as the accounts testify. Many lay on the ground beyond the area occupied by the Germans. Some of these men must have died, others came back through the

French lines, some presumably going on to the medical stations and some fit enough to take part again in the fighting. Many other gassed men appear to have walked directly to the medical stations, which were almost overwhelmed with casualties, gassed and wounded.

Some 1,800 men were taken prisoner by the Germans. The fate of this group is particularly instructive, because their numbers and, within certain limits, their position are known. The German advance created a bulge which by the end of the first day reached a line which had a maximum depth of some 4 km, but which on average was nearer 3 km. A report was received at 6.49 p.m. from the advancing troops that they had taken Pilkem Ridge. The distance to Pilkem Ridge from the start line of the advance is 2.5 km. Allowing 5 min for the report to filter back, this gives for infantry starting at 6.15 p.m. a speed of advance of 1.4 m/s. The retreating French probably had on average some 200 m and 8 min head start, but there were no doubt appreciable variations, so that only a proportion of the fugitives would be overtaken by the Germans. A speed of advance only some 0.3–0.4 m/s faster than the speed of retreat could have resulted in a large proportion, perhaps about a third, of the retreating troops falling into enemy hands.

*Reconstruction*

An attempt has been made by the authors to reconstruct this attack. The intermediate and final results of the reconstruction are shown in Table 3. The gas release conditions are taken as shown in Table 3, Section A.

The number of troops exposed is taken as those actually in the front line and is estimated to have been approximately as given in Table 3, Section B. For those units where only the nominal complement is known, it is assumed that they were at some 90% of full strength. It is also assumed that one of the Tirailleur battalions (actual strength 628) and a small proportion of the other one were exposed, but that most of the other one (1/1 Tirailleurs) and the Canadians were not significantly exposed. The nearest troops behind were support battalions some 1,500–2,000 m back and are unlikely to have been seriously affected. These support troops are therefore not considered further.

The distance between the trenches varied. In general on the north of the salient there were distances of 100, 200 and 300 m. This is in line with the map given by the Official History (Sketch 9, p. 176) to the degree of accuracy with which it can be read. The proportion of trenches with particular distances to the opposing trenches, and hence the cloud source, are taken as shown in Table 3, Section C.

In order to reconstruct events it is necessary to quantify three factors. These are the point at which the cloud reached the men, the speed with which they retreated through it and the level of activity which such movement involved.

The most likely scenario is considered to be as follows. The French troops did not leave the trenches until the gas cloud was quite close. They may well

TABLE 3

Analysis of gas attack at Langemarck, on April 22, 1915[a]

*A. Gas release conditions*

Width of release front = 6,000 m
Mass released = 146.6 te
Duration of release = 7 min
Mass rate of release = 0.058 kg/m s
Wind speed = 2 m/s
Stability conditions: slightly unstable (Pasquill C)
Roughness length = 0.1 m

*B. Unit strengths*

| Unit | No. of men |
|---|---|
| 74 TR | 2,000 |
| 73 TR | 2,000 |
| 45 A | 1,100 |
| | + 900 |
| Total | 6,000 |

*C. Distance between trenches, number of troops exposed*

| Distance from source (m) | Proportion exposed (%) | Number exposed |
|---|---|---|
| 100 | 5 | 300 |
| 150 | 10 | 600 |
| 200 | 50 | 3,000 |
| 300 | 35 | 2,100 |

*D. Toxic concentration*

| Distance from source (m) | Concentration (ppm) |
|---|---|
| 100 | 949 |
| 150 | 725 |
| 200 | 569 |
| 300 | 407 |
| 350 | 366 |
| 400 | 335 |
| 500 | 278 |
| 600 | 237 |
| 800 | 190 |
| 1,000 | 156 |
| 1,250 | 129 |
| 1,500 | 112 |
| 1,750 | 98 |
| 1,850 | 95 |
| 1,900 | 92 |
| 1,950 | 89 |
| 2,050 | 85 |

*E. Toxic loads and expected mortality*

| Distance from source (m) | Toxic load[b] ($ppm^2$ min) | Expected mortality |
|---|---|---|
| 100 | $733 \times 10^3$ | 0.45 |
| 150 | 643 | 0.40 |
| 200 | 569 | 0.36 |
| 300 | 459 | 0.29 |

*F. Fate of front line troops*

| | | Gas deaths |
|---|---|---|
| Dead by shells etc., on field | 300 | 0 |
| Gas dead on field | 1,786 | 1,786 |
| Prisoners | | |
| Gas casualties in hospitals | 200 | 12 |
| Others | 1,600 | 0 |
| Gas casualties in Allied medical stations | | |
| French | 625 | 63 |
| British | 1,000 | 100 |
| Other | 489 | 0 |
| Total | 6,000 | 1,961 |

*G. Preferred and alternative scenarios*

| Scenario | Cloud entry point (distance from trench) (m) | Walking speed (m/s) | Level of activity | Toxic concentration factor[c] | Deaths | Survivors | Mortality (%) |
|---|---|---|---|---|---|---|---|
| 1 | 200 | 1.3 | 1.5 | 1 | 1,961 | 3,739 | 34 |
| 2 | 200 | 1.3 | 2 | 1 | 3,136 | 2,564 | 55 |
| 3 | 0 | 1.3 | 1.5 | 1 | 3,136 | 2,564 | 55 |
| 4 | 200 | 1.7 | 2 | 1 | 3,062 | 2,638 | 54 |
| 5 | 0 | 0 | 1 | 1 | 2,947 | 2,753 | 52 |
| 6 | 200 | 1.3 | 1.5 | 2 | 4,609 | 1,091 | 81 |
| 7 | 200 | 1.3 | 1.5 | 4.8 | 5,660 | 40 | 99.2 |

[a]See text for basis of figures used.
[b]This is the toxic load uncorrected for level of activity. For the standard level of activity this value of the toxic load is used directly in eqn. (2). For $1.5 \times$ standard level the value is multiplied by $(1.5)^2$ and then used in eqn. (2), and so on.
[c]This is the factor by which the model $LC_{50}$ is divided.

have assumed it to be smoke, either coming from fire in the German trenches or put up as a smokescreen, and may have only realised its toxic nature as the first wisps of the gas caused them to cough. Scrambling out of the trenches they ran, coughing, as fast as they could over the broken ground behind, but were overtaken by the main cloud after a distance which is taken here as 200 m. Then they struggled on in the cloud at a speed rather less than that at which the cloud was travelling. Their walking speed is taken as 1.3 m/s and their level of activity as 1.5 times the standard level.

The results derived from this preferred scenario are now described. In order to check the sensitivity of these results to the assumptions made, several other scenarios have also been investigated as described below.

The point concentrations given in Table 3, Section D, are obtained from the gas dispersion model given in eqn. (3). The estimates of concentration are subject to some inaccuracy due to variations of topography, but these are slight between the trenches and Pilkem.

From these concentrations the toxic loads may be determined for a man leaving the trench and being caught by the cloud after 200 m, then walking at 1.3 m/s, so that for a 7 min release of gas with a wind speed of 2 m/s the man is in the cloud for 20 min. The toxic loads are then obtained by considering the exposure for different distance, and time, increments.

The toxic load so derived has then been corrected for the level of activity using the inhalation rate factor. The level of activity is taken as 1.5 times the standard level so that $\psi_1 = 3$. But eqn. (2) incorporates a value of $\psi_1$ of 2 so that the correction to be made to the concentration in this equation is 1.5 ($=3/2$) and hence to the toxic load 2.25 ($(1.5)^2$). The corrected toxic loads to be used with eqn. (2) and the mortalities obtained from this equation are then as given in Table 3, Section E.

There was an intensive artillery bombardment all along the front and also apparently some strong local resistance at several points. Allowance is made for these factors by taking the number killed by the shells, bullets, etc. as 300 (5%). This leaves 5,700, virtually all of whom retreated and are likely to have been gassed to some degree. Applying the estimates of the proportions of men in the trenches at various distances from the source and the corresponding mortalities given in Table 3, Section E, yields the number of gas deaths from these trenches. This gives for the 5,700 exposed 1,961 gas deaths and 3,739 survivors. The prisoners taken by the Germans comprised 1,788 survivors and 12 dead, leaving 1,951 survivors on the Allied side. These survivors have been apportioned as follows: French medical stations 562, British medical stations 900 and other 489. It is assumed that the mortality in the Allied medical stations was 10% rather than the 5% which was typical of later attacks, in order to allow for the fact that the front rolled up almost onto some of the medical stations so that there is no very clearcut distinction between deaths in the field and in the units. The gas casualties, fatal and non-fatal, in the French and British medical stations then become 625 and 1,000, and the gas deaths 63 and 100, respectively. The number of gas casualties in the French medical stations is that given by Sieur. The results are summarised in Table 3, Section F.

The overall mortality is 34% and the proportion of deaths on the field 91%. The German accounts stating that no gas dead were found in the trenches may well be strictly correct, but the implication of these results is that there were large numbers of gas dead on the field.

In addition to this scenario (Scenario 1) six others have been investigated.

In Scenario 2 the level of activity is taken as 2 times the standard level; the number of gas deaths is then 3,136 and the overall mortality from gas is 55%. In Scenario 3 the entry point of the troops into the gas cloud is taken as the trenches themselves; again the number of gas deaths is 3,136 and the mortality 55%. In Scenario 4 the walking speed is taken as 1.7 m/s and the level of activity as 2 times the standard level; the number of gas deaths is 3,062 and the mortality 54%. In Scenario 5 it is assumed that the troops remained in their trenches throughout the passage of the gas cloud with the standard level of activity. This is not regarded as a credible scenario, but it constitutes the main alternative to the flight scenarios and provides a point of reference; the number of gas deaths is 2,947 and the mortality 52%. In Scenario 6 the $LC_{50}$ is taken as half that of the model and hence as 217 ppm for a 10 min exposure at the standard level of activity; the number of gas deaths is 4,609 and the mortality 81%. In Scenario 7 the $LC_{50}$ is taken as 90 ppm for 10 min exposure, which is less than that of the model by a factor of 4.8; the number of gas deaths is 5,660 and the mortality 99.2%. This latter scenario is included for comparison with those for Hill 60. These results are summarised in Table 3, Section G.

It is appreciated that both the gas concentrations and the troops' exposure will have been more variable than these simplified scenarios imply, but the latter nevertheless provide order of magnitude estimates of the fate of the men involved.

The overall mortality, number of deaths and the number of survivors are all relevant in evaluating these results. From the accounts given a mortality higher than say 40%, numbers of gas deaths more than 2,000, or gas casualties treated in Allied medical units less than 1,200 seem unlikely. Scenario 1 is therefore judged the most credible.

The cloud entry point was initially taken as the trenches and the level of activity as 2 times the standard level, but each of these assumptions gives the number of deaths as more than 3,000 and for this reason these values are not the preferred ones.

The preferred scenario gives an estimate of 1,961 for the number of gas deaths, corresponding to a mortality of 34%. These values are higher than the authors originally expected, although they are now believed to be of the right order of magnitude. However, whether these figures are right or not, estimates based on lower $LC_{50}$ s give larger numbers of deaths. These may be reduced by assuming that almost all the men outran the gas cloud, but such an assumption does not seem to be consistent with the capture of 1,800 prisoners, who were presumably caught by the German troops within an average distance of 3 km behind the original front.

**Gas attack at Hill 60, May 1, 1915**

A few days later on May 1, 1915 the Germans made a gas attack against British troops at Hill 60 on the south of the Ypres salient. This attack is

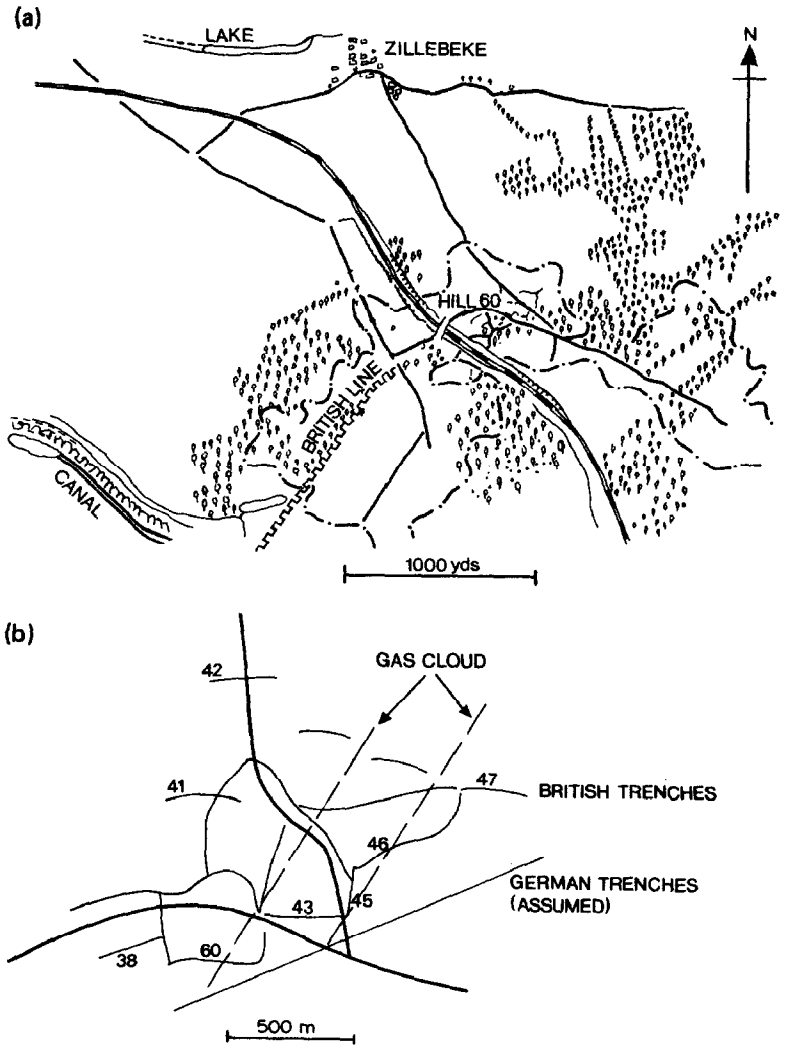


Fig. 5. Sketch map of battlefield at Hill 60, May 1, 1915 (after Army Historical Branch [56]): (a) Coarse scale map; (b) Fine scale map, showing trenches.
(Map (a) reproduced by permission of Ministry of Defence, © British Crown Copyright).

described in the Official History [4] and by Hanslian [5]. Further information has been furnished to the authors by the Army Historical Branch (AHB) [56]. Extracts from the accounts given by these and other sources are given in Appendix 1.

Maps of the battlefield have been given by the AHB and are reproduced in Fig. 5. As this figure shows, Hill 60 was only part of the front over which the gas was released. The assumed position of the German trenches and the area

covered by the gas cloud have been added by the authors to Fig. 5(b). The British front line trenches were manned by A, C and D Companies of the 1 Dorsetshire Regiment, with B Company in support 200 yd back. According to the Official History, the gas was released over a front of 440 yd and the distance between the two opposing trenches was 100 yd. The AHB states that at one point the trenches were only 20 yd apart.

The gas cylinder density is not known with certainty. As already mentioned, the cylinders had been installed on the southern sector of the salient first. Installation was completed there by mid-March. Since cylinders were installed all around the salient, the cylinder density at Hill 60 might be expected to have been approximately the same as at Langemarck on April 22, namely 0.955 cylinders/m, which is equivalent to 382 on a 400 m front. On April 17 the British blew 5 mines on Hill 60 and established themselves there. The Germans feared that their cylinders would be discovered, but this does not seem to have been the case. On April 21 they regained a foothold on the hill.

The AHB account states that the gas was released from at least 5 nozzles. This figure may have been the number of sources, possibly batteries of cylinders, reported by troops in the front line, but it is so low as to be incredible as the number of cylinders. The figure of 60 cylinders given by the German corps commander, von Deimling [51], also seems improbably low, since it represents a cylinder density 6.4 times less than that at Langemarck. The objective of the attack, which had been planned and awaiting favourable weather for some days, was one of the most important in the whole salient and was being bitterly contested and the front was relatively narrow so that it is difficult to believe that the Germans would not have used a high cylinder density, bringing up extra cylinders if necessary from adjacent sectors. Nevertheless, this evidence must be taken seriously. It is therefore considered in the alternative scenarios.

The British troops stood their ground and maintained sufficient fire to defeat the attack completely. This was the first occasion during the war when the attackers gained no territorial advantage from the use of a gas cloud attack. The defenders suffered heavy casualties, however. 90 were killed by gas and 207 others were gassed, of whom 58 later died.

The troops worst affected were those in Trenches 60, 45 and 46. Those in Trench 43, where the platoon commander ordered his men to mount the firing platform, lost only 2 men. The men had elementary respirators but the degree of protection afforded by these is uncertain. Those in D Company, and those in B Company in support, were not impregnated. C Company suffered heavily and therefore probably obtained little benefit either. After the gas cloud had passed, the gas tended to hang around in the trenches.

*Reconstruction*

A reconstruction of this attack has been made and the intermediate and final results are shown in Table 4. The mass of gas released per unit width of front

TABLE 4

Analysis of gas attack at Hill 60, on May 1, 1915[a]

*A. Gas release conditions*

Width of release front = 400 m
Mass released = 9.8 te
Duration of release = 7 min
Mass rate of release = 0.058 kg/m s
Wind speed = 2 m/s
Stability conditions: slightly unstable (Pasquill C)
Roughness length = 0.1 m

*B. Number of troops exposed, concentrations, toxic loads, expected mortality and number of deaths*

| Trench | Number in trench | Number exposed | Distance from source (m) | Concentration (ppm) | Toxic load[b] ($ppm^2$ min) | Expected mortality | Expected number of deaths |
|---|---|---|---|---|---|---|---|
| 38 | 100 | 0 | | | | | |
| 60 | 100 | 50 | 80 | 1,190 | $9{,}900 \times 10^3$ | 0.96 | 48 |
| 43 | 100 | 50 | 200 | 569 | 2,270 | 0.64 | (32) |
| | | 50 | 250 | 474 | 1,570 | 0.50 | (25) of which 2 included |
| 45 | 100 | 50 | 200 | 569 | 2,270 | 0.64 | 32 |
| | | 50 | 300 | 407 | 1,160 | 0.39 | 20 |
| 46 | 100 | 50 | 400 | 335 | 786 | 0.26 | 13 |
| 47 | 100 | 0 | | | | | |
| Support | 200 | 100 | 400 | 305 | 786 | 0.26 | 26 |
| | | | | | | Total | 141 |

*C. Preferred and alternative scenarios*

| Scenario | No. of cylinders | Level of activity | Toxic concentration factor[c] | Deaths | Mortality (%) |
|---|---|---|---|---|---|
| 1 | 382 | 1.1 | 1 | 141 | 46 |
| 2 | 382 | 1.5 | 1 | 195 | 65 |
| 3 | 382 | 1.5 | 2 | 281 | 93 |
| 4 | 60 | 1.5 | 1 | 7 | 2.3 |
| 5 | 60 | 1.5 | 4.8 | 146 | 48 |

[a]See text for basis of figures used.
[b]This is the toxic load uncorrected for level of activity.
[c]This is the factor by which the model $LC_{50}$ is divided.

and the release time are taken as at Langemarck on April 22. The weather conditions are taken as slightly unstable with a wind speed of 2 m/s. The gas release conditions are given in Table 4, Section A.

The British troops numbered 800, disposed in 3 companies in the front line trenches and one 200 yd behind. Taking an even distribution of the men in the

front line trenches yields the number in each trench, the numbers exposed to the gas cloud and the distance from the point of release shown in Table 4, Section B.

The concentration of chlorine at the various trenches has been estimated using eqn. (3). The application of this equation for an infinite line source to a finite line source of 400 m width has been checked and it is estimated that the error is no more than 5% at 400 m downwind distance. The concentration estimates are subject to some inaccuracy for the section of the front where there was a hill (Hill 60), although any error is reduced by the fact that the opposing trenches at this point were very close.

The level of activity has been taken, in order to obtain a good fit between actual and estimated mortalities, as 1.1 times the standard level. The mortalities and number of deaths estimated are then as given in Table 4, Section B. The deaths in Trench 43 are shown in brackets. These notional deaths did not in fact occur and are omitted from the total, although the two men in this trench described as 'lost' have been included. The total number of deaths calculated is then 141. The actual number, on the field and delayed, was 148.

The explanation for the relative immunity of Trench 43 is uncertain. It does not appear to be the extra height at which the men stood, since the calculated ratio of the concentrations at 2 m height and at ground level is 0.9 at 100 m and 0.99 at 300 m. More likely explanations are that the platoon commander's discipline had ensured that the men had impregnated respirators at the ready and that if the gas cloud lifted, as the German account states, it did so over this trench.

In addition to this preferred scenario (Scenario 1) four others have been investigated. In all these the level of activity has been taken as 1.5 times the standard level. This is the only change in Scenario 2. In Scenario 3 the $LC_{50}$ is taken as half the model value. In Scenario 4 the mass rate of release is that corresponding to the cylinder density given by von Deimling. In Scenario 5 the mass rate of release is the von Deimling value and the $LC_{50}$ has been reduced by a value which gives the actual number of gas deaths, the reduction factor being 4.8.

Scenario 1 is judged the most credible, giving the number of gas deaths as 141 and the mortality as 46% (excluding Trench 43). The level of activity was intially taken as 1.5 times the standard level, but this gives a mortality of 65% as shown in Scenario 2. Scenario 3 shows the effect of taking the gas to be twice as toxic. The mortality is 93%. Scenario 4 shows the effect of taking the von Deimling cylinder density without modifying the gas toxicity. The mortality is only 2%. In Scenario 5 the gas toxicity is adjusted to give the actual mortality of 49%. This requires an $LC_{50}$ 4.8 times less than the model value. This corresponds to an $LC_{50}$ of 90 ppm for 10 min exposure at the standard level of activity.

**Gas attack at Wulverghem, April 30, 1916***

The third gas attack considered is that by the Germans against the British at Wulverghem on April 30, 1916. This attack is described in some detail in Diseases of the War [19] and briefly by Hanslian [5]. Extracts from these two accounts are given in Appendix 2.

Maps showing the order of battle and the area of the battlefield affected by gas are given in Diseases of the War and are reproduced in Figs. 6 and 7, respectively. The position of and the casualties among the troops as given in this source are shown in Table 5. The unit strengths for the battalions 1/N. Staffs and 8/Queens have been estimated as 588 and 508 from the percentages of strength affected given in Table 5.

In considering this attack it is first necessary to take a view as to whether the gas used was chlorine only. The Germans had started to use chlorine–phosgene mixtures in October 1915 and soon established their greater efficacy. Thereafter they made little use of chlorine alone. On the other hand Foulkes states that the gas was chlorine and Diseases of the War states that the clinical symptoms are consistent with this. The analysis given here is based on the assumption that only chlorine was used.

No information is available on the quantity of gas released. It is known, however, that the combattants quickly came to appreciate that in order to achieve significant results with chlorine it is necessary to use high concentrations. It seems unlikely, therefore, that the quantities used would have been less than in the early gas attacks. The gas was released over a front of some 3,500 yd, but the pattern of release was not uniform. In the northern sector the emission was continuous for some 10 min, while further south the gas was released in two waves over a total period of some 30–40 min.

There were 512 gas casualties, of which 330 were in the four battalions listed in Table 5. From the former total, 89 men died. The location of these deaths is given in Diseases of the War as 25 in the trenches or Regimental Aid Posts, 13 in the Field Ambulances, 50 in the Casualty Clearing Stations and 1 in hospital.

In view of the uncertainty introduced by the double wave and its relatively long duration, the analysis here is confined to the northern sector, taken as that occupied by the 1/N. Staffs and 8/Queens.

*Reconstruction*

This attack has been reconstructed with the intermediate and final results given in Table 6. The mass released per unit length is taken as the same as at

*Since this paper was submitted there has appeared the following discussion of the gas attack at Wulverghem by Nussey et al.: C. Nussey, A. Mercer and R.D. Fitzpatrick, The effect of uncertainty in chlorine toxicity data on risk estimation. In: S. Hartwig (Ed.), Heavy Gas and Risk Assessment III, Reidel, Dordrecht, 1986, p. 197.

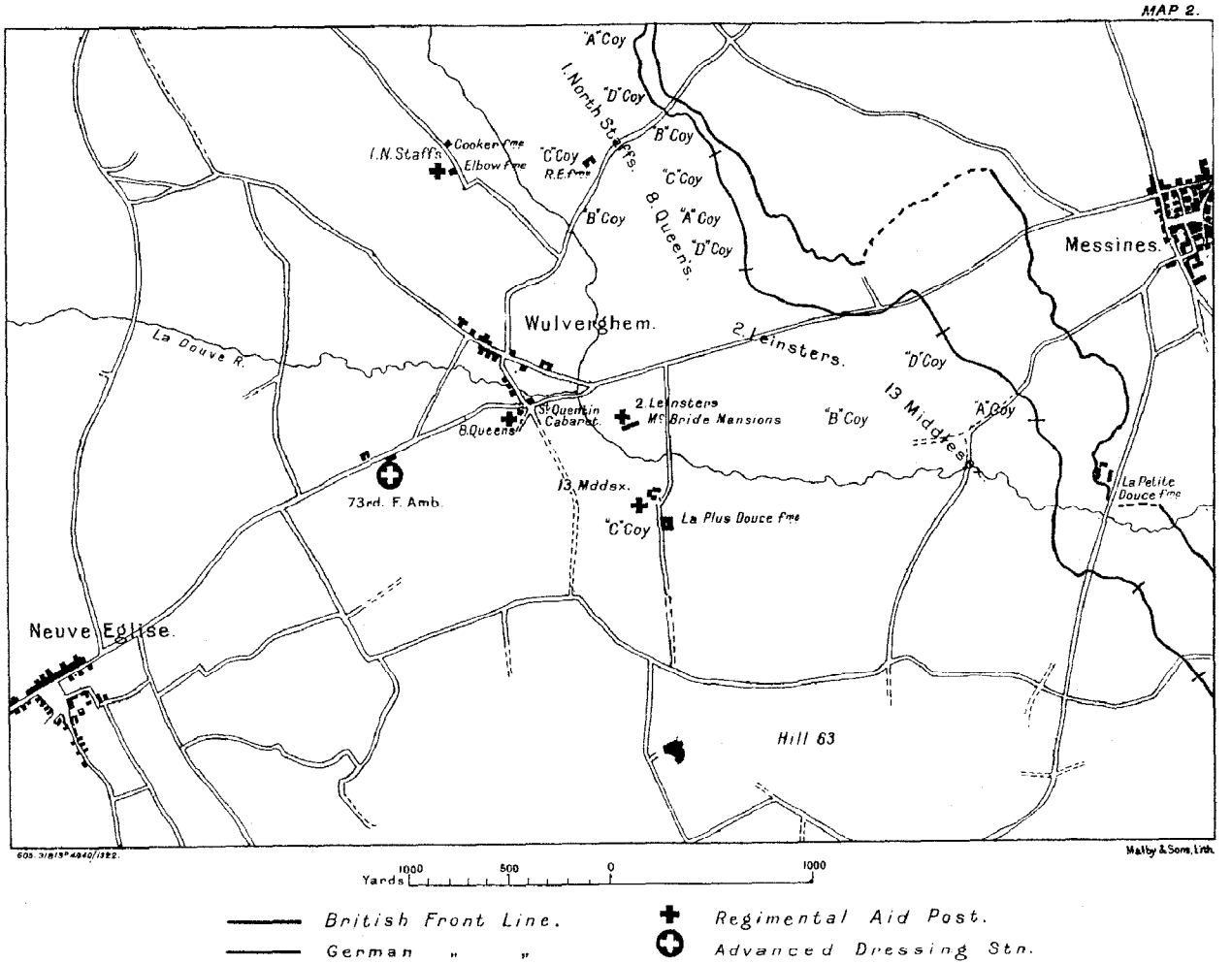


Fig. 6. Order of battle at Wulverghem, April 30, 1916 (Macpherson et al. [19], © British Crown Copyright).

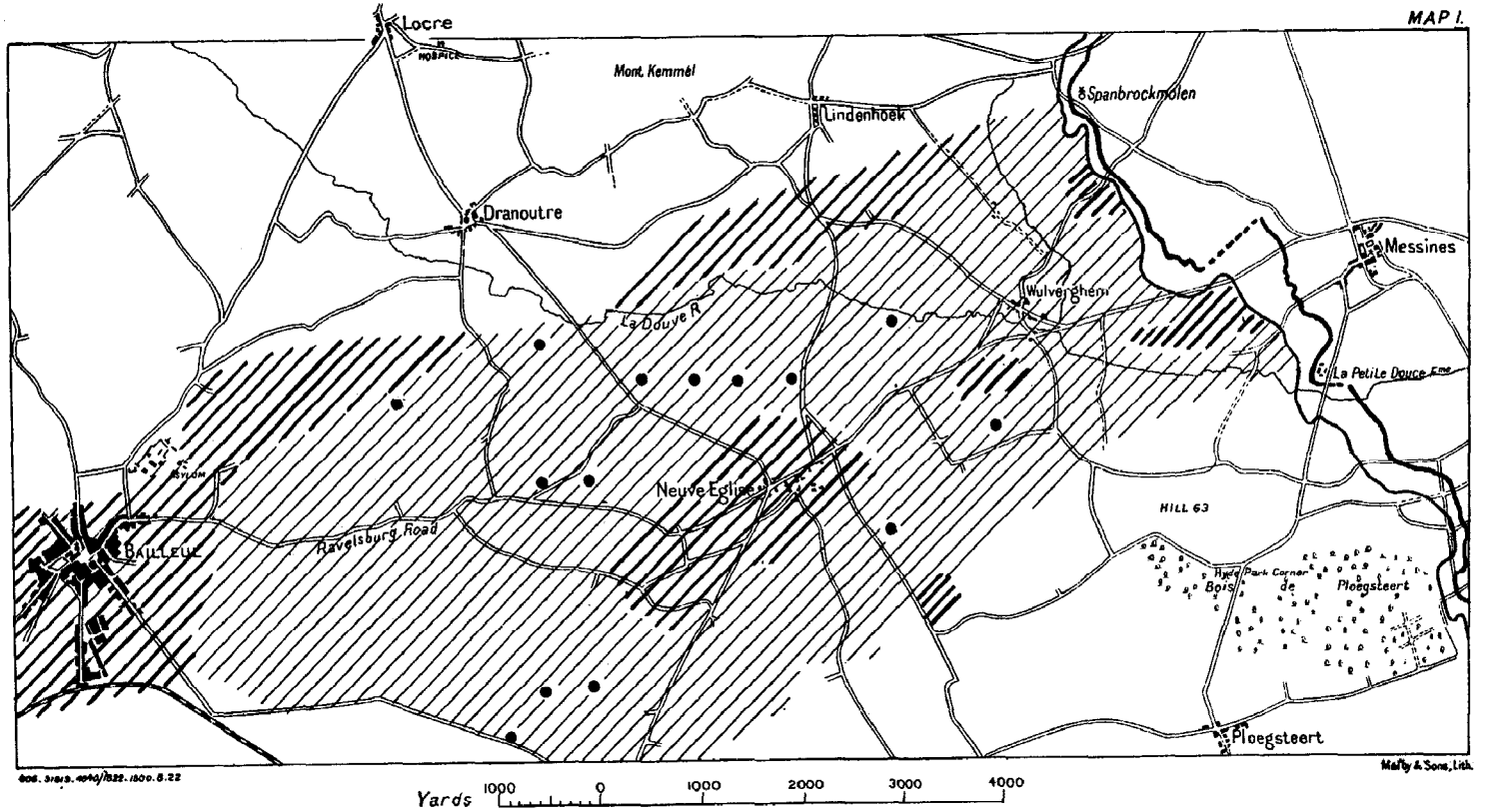


Fig. 7. Sketch map of battlefield at Wulverghem, April 30, 1916 (Macpherson et al. [19], © British Crown Copyright).

TABLE 5

Positions and casualties in gas attack at Wulverghem, April 30, 1916 (Diseases of the War [19])

| Troops | | Location | Distance from enemy lines (yd) | Number of gas casualties | Location of gas casualties |
|---|---|---|---|---|---|
| 1/N. Staffs | A | Left | 50 | 33 | Nearly all in fire trench |
| | D | Centre | 100–120 | 13 | Fire trench |
| | B | Right | 50–105 | 31 | Fire trench |
| | C | Support | 400 | 17 | At RE farm |
| | | | Unrecorded | 18 | |
| | | | Total (ca. 19% of strength) | 112 | |
| 8/Queens | C | Left | 130–220 | 25 | Fire trench |
| | A | Centre | 210–220 | 37 | Fire trench |
| | D | Right | 330 | 19 | Fire trench |
| | B | | 1,500 to nearest enemy trench NE | 14 | Near St. Quentin Cabaret |
| | | | Unrecorded | 27 | |
| | | | Total (ca. 24% of strength) | 122 | |
| 2/Leinsters | A | | | 3 | Had time to put on helmets |
| | B | | 200–300 | 3 | |
| | C | | | 1 | |
| | D | | | 10 | |
| | | | Unrecorded | 4 | |
| | | | Total (ca. 3.5% of strength) | 21 | |
| 13/Mddx | D | Left | 320–500 | 10 | Fire trench |
| | A | Right | 320–500 | 17 | Fire trench |
| | B | Support | | 13 | Close behind |
| | C | Support | 2,100 | 9 | About La Plus Douce Ferme |
| | | | Unrecorded | 26 | |
| | | | Total | 75 | |

Langemarck, the release time as 10 min and the weather conditions as neutral stability with wind speed 5 m/s. The gas release conditions are given in Table 6, Section A.

The concentrations of chlorine at the various trenches have been estimated using eqn. (3). The estimates of concentration are subject to some inaccuracy due to the effects of topography. The level of activity has been taken as the standard level. The mortalities and number of deaths estimated are as given in Table 6, Section B.

TABLE 6

Analysis of gas attack at Wulverghem, April 30, 1916[a]

*A. Gas release conditions*

Width of release front — not required
Mass released — not required
Duration of release = 10 min
Mass rate of release = 0.0406 kg/m s
Wind speed = 5 m/s
Stability conditions: neutral (Pasquill D)
Roughness length = 0.1 m

*B. Number of troops exposed, concentrations, toxic loads, expected mortality and number of deaths*

| Troops | | Number in trench | Distance from source (m) | Concentration (ppm) | Toxic load[b] ($ppm^2$ min) | Expected mortality | Expected number of deaths |
|---|---|---|---|---|---|---|---|
| 1/N. Staffs | A | 147 | 50 | 680 | $4{,}620 \times 10^3$ | 0.80 | 118 |
| | D | 147 | 100 | 373 | 1,390 | 0.39 | 57 |
| | B | 147 | 100 | 373 | 1,390 | 0.39 | 57 |
| | C | 147 | 400 | 132 | 174 | 0.02 | 3 |
| 8/Queens | C | 127 | 200 | 224 | 502 | 0.11 | 14 |
| | A | 127 | 200 | 224 | 502 | 0.11 | 14 |
| | D | 127 | 300 | 160 | 256 | 0.03 | 4 |
| | B | 127 | 1,500 | | | 0 | 0 |
| | | | | | | Total | 267 |

[a]See text for basis of figures used.
[b]This is the toxic load uncorrected for level of activity.

The estimated number of deaths is 267 for the two battalions considered. This compares with the actual number of deaths of 89 for all the troops exposed. Two explanations considered for this difference are as follows. One is that the gas concentrations were not as high as calculated over some parts of the front. Thus Fig. 7 shows that there was a sector of the front held by the 1/N. Staffs where the gas was slightly rather than strongly felt. The other is that many of the men did in fact have time to put on their respirators.

**Other gas attacks**

There were a number of other gas attacks on the Western Front in the early part of the war when chlorine was the gas used. The principal attacks are listed in Table 1. The first gas attack by the British was the well known attack at Loos on September 25, 1915, in which gas was used on a large scale. There are a number of accounts, including those of the Official History [4], Foulkes [14] and Hanslian [5].

There was also a German chlorine gas attack against the Russians at Bolimow on May 31, 1915, which is described by Hanslian [5].

## Discussion

An attempt has been made to crosscheck the model for the lethal toxicity of chlorine to man from gas attacks in the First World War. For most of the gas attacks during the relatively short period of the war when chlorine alone was used too little is known to be useful, but for three attacks, at Langemarck, Hill 60 and Wulverghem enough information has been found to permit reconstruction, although for each there are gaps in the data and hence some uncertainty. The three reconstructions described are intended in each case to represent a 'best estimate'. The question is whether the evidence obtained supports the model values of lethal concentrations or whether it is also consistent with higher or lower values.

There are inevitably uncertainties in the calculation of gas concentrations, but these are estimated to be no more significant than those in the other variables such as level of activity.

In the reconstructions both of Langemarck and of Hill 60 the initial assumptions were for a higher level of activity than that finally adopted. For Langemarck it was also assumed initially that the cloud entry point was the trenches themselves rather than 200 m back. These points provide some support for higher concentrations, but the latter are not argued for here.

More important is the case for lower values. In evaluating this it is essential to take Langemarck and Hill 60 together. If the Hill 60 evidence is thought to support a lower $LC_{50}$, this must be applied to Langemarck also.

The von Deimling cylinder density for Hill 60 implies a much lower $LC_{50}$. As far as internal evidence is concerned, von Deimling's account does raise doubts. It is often discursive, even sentimental, and contrasts markedly with, say, that of Petersen [48,53] with its detailed figures for the Langemarck attack. It also contains inaccuracies in its description of the latter. For example, the date is given as April 20 and the time as 5.00 a.m. (Am fünf Uhr früh). (A morning attack was planned, but the attack had to be postponed to the evening due to the wind conditions.)

The application of the lower lethal concentrations which have had to be assumed at Hill 60 to fit the von Deimling cylinder density to Langemarck gives very high mortalities (ca. 99%) for scenarios in which the other variables are of the order of those considered in the reconstruction. It is possible to construct scenarios of the type described for these lower lethal concentrations, but in order to do so it is necessary to assume that the men outran the cloud for a considerable distance (ca. 1,000 m), and were then caught up in it, but these scenarios are less credible. It seems unlikely that men who were so little harrassed by the gas that they could get as far could not then keep ahead of it

even though their life depended on it. Yet other scenarios can be devised in which there is a wider range of behaviour on the part of the troops, with some escaping the gas and the rest suffering proportionally higher casualties. In considering the credibility of all these scenarios, however, it is necessary to bear in mind the 1,800 prisoners taken by the Germans.

The reconstruction of the Wulverghem attack yields relatively less information, because a large but unknown proportion of the troops had protection from respirators.

An important variable in the reconstructions is the level of activity. The level of activity for people walking out of a gas cloud which has been used in the preferred scenario is 1.5 times the standard level, or 3 times the base level.

The reconstructions of gas attacks given here are 'best estimate', or preferred, scenarios of what actually happened. They are consistent with the lethal concentrations given in the model. Alternative reconstructions are possible which are consistent with lower lethal concentrations, but they are judged less credible.

**Acknowledgements**

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**List of symbols**

| | |
|---|---|
| $C$ | concentration (ppm) |
| $L^*$ | toxic load ($ppm^2$ min) |
| $P$ | probability of fatality |
| $Q'$ | mass rate of release per unit length (kg/m s) |
| $t$ | time (min) |
| $u$ | wind speed (m/s) |
| $x$ | distance in downwind direction (m) |
| $Y$ | probit |
| $z$ | distance in vertical direction (m) |
| $\sigma_z$ | dispersion coefficient in vertical direction (m) |
| $\chi$ | concentration ($kg/m^3$) |

**References**

1 R.M.J. Withers and F.P. Lees, The assessment of major hazards: The lethal toxicity of chlorine: Part 1, Review of information on toxicity, J. Hazardous Materials, 12 (1985) 231.
2 R.M.J. Withers and F.P. Lees, The assessment of major hazards: The lethal toxicity of chlorine: Part 2, Model of toxicity to man, J. Hazardous Materials, 12 (1985) 283.
3 Deutsches Reichsarchiv, Der Weltkrieg 1914-1918, Vol. 8 Mittler und Sohn, Berlin, 1932.

4 J.E. Edmonds and G.C. Wynne, History of the Great War: Military Operations: France and Belgium 1915,H. M. Stationary Office, London, 1927.
5 R. Hanslian, Der chemische Krieg, Mittler und Sohn, Berlin, 1937.
6 M. Schwarte, Die Technik im Weltkrieg, Mittler und Sohn, Berlin, 1920.
7 J. Meyer, Der Gaskampf und die chemischen Kampstoffe, S. Hirzel, Leipzig, 2nd edn., 1926.
8 F. Seeselberg, Der Stellungskampf 1914/18, Mittler und Sohn, Berlin, 1926.
9 H. Zanger, Die Gasschutzfrage, Huber, Bern, 1932.
10 H. Zanger, The question of protection against gas, Z. Gesamte Schiess- Sprengstoffwes., 30 (February-March, 1935).
11 U. Müller, Die chemische Waffe, Verlag Chemie, Berlin, 1932.
12 Deutsches Reichsarchiv, Deutsches Reichsministerium, Heeres-Sanitätsinspektion, Sanitätsbericht über das deutsche Heer im Weltkrieg 1914/18, Vol. 3, Mittler und Sohn, Berlin, 1934.
13 F. Flury and F. Zernik, Schädliche Gase, Springer, Berlin, 1931.
14 C.H. Foulkes, Gas. The Story of the Special Brigade, Blackwood, Edinburgh, 1934.
15 S.J.M. Auld, Gas and Flame, Doran, London, 1918.
16 V. Lefebure, The Riddle of the Rhine, London, 1923.
17 V. Lefebure, J. Roy. United Services Inst., 73 (1928) 492.
18 Major General Sir W.G. Macpherson, History of the Great War. Medical Services, General History, Vol. II, H.M. Stationery Office, London, 1923.
19 Major General Sir W.G. Macpherson, Major General Sir W.P. Herringham, Colonel T.R. Elliott and Lt-Colonel A. Balfour, History of the Great War. Medical Services, Diseases of the War, Vol. II, H.M. Stationery Office, London, 1923.
20 P. Bloch, La Guerre Chimique, 1926.
21 Serrant, La Guerre Chimique, 1924.
22 A. Meyer, Gaz de Combat, Paris, 1938.
23 R. Cornubert, Gas warfare, Rev. Gén. Sci. Pures Appl., 31 (1920) 45.
24 General Feuville, Gases in war, La France militaire, 31 (January 1922).
25 Anon., La France militaire, 43 (September 23, 1922) onwards (series).
26 Chlopin, Military and sanitary principles of gas protection, Z. Gesamte Schiess- Sprengstoffwes., 22 (1927) 192, 227, 261, 269, 297, 333, 369; 23 (1928) 29.
27 A.M. Prentiss, Chemicals in War, McGraw-Hill, New York, 1937.
28 A.A. Fries and C.J. West, Chemical Warfare, McGraw-Hill, New York, 1921.
29 A.H. Waitt, Gas Warfare, Duell, Sloan and Pearce, New York, 1942.
30 E.B. Vedder, The Medical Aspects of Chemical Warfare, Williams and Wilkins, Baltimore, 1925.
31 T.J. Mitchell and G.M. Smith, Casualties and Medical Statistics of the Great War, H.M. Stationery Office, London, 1931.
32 H.L. Gilchrist, A Comparative Study of World War Casualties from Gas and Other Weapons, US Government Printing Office, Washington, DC, 1928.
33 H.L. Gilchrist, Poisoning Warfare Gases, Appleton, New York, 1924.
34 H. Büscher, Grün- und Gelbkreuz, Hamburg, 1932.
35 Dautrebaude, Les Gaz Toxiques, Masson, Paris, 1933.
36 E. Loschke, Die wichtigsten Vergiftungen, Verlag Lehmann, Munich, 1933.
37 Fessler, Gebele and Prandtl, Gaskampfstoffe-Gasvergiftungen, Gmelin, Munich, 1933.
38 M. Sartori, The War Gases, New York, 1939.
39 C. Wachtel, Chemical Warfare, Chapman and Hall, London, 1941.
40 J.P. Robinson, The Problem of Chemical and Biological Warfare, Vol. 1, The Rise of CB Weapons, Stockholm, 1971.
41 D.K. Clark, Effectiveness of Chemical Weapons in World War 1, Opl. Res. Off., John Hopkins Univ., Bethesda, MD, 1959.

42 O.G. Sutton, Micrometeorology, McGraw-Hill, New York, 1953.
43 F. Pasquill, Atmospheric Diffusion, Van Nostrand, London, 1962.
44 R.H. Clarke, A model for short and medium range dispersion of radionuclides released to the atmosphere, Nat. Radiological Protection Board, Harwell, Rep. NRPB-91, 1979.
45 J.E. Black, E.T. Glenny and J.W. McNee, Observations on 685 cases of poisoning by noxious gases used by the enemy, Brit. Med. J., (July 31, 1915) 165.
46 General Mordacq, Le Drame de l'Yser, Editions de Portique, Paris, 1933.
47 B. Helferrich, Gas- Luftschutz, 9 (1934) 239.
48 Major-General Peterson, Gas- Luftschutz, 9 (1934) 235.
49 Count von Tattenbach, Gas- Luftschutz, 9 (1934) 236.
50 General von Tschischwitz, Gas- Luftschutz, 9 (1934) 233.
51 General B. von Deimling, Aus der alten in die neuen Zeit, Ullstein, Berlin, 1930.
52 R. Hanslian, On the history of gas warfare, Gas- Luftschutz, (October 1931) 49.
53 R. Hanslian, The German gas attack at Ypres on 22.4.1915, Gas- Luftschutz, 4 (1934) 98; 5 (1934) 123; 6 (1934) 155; 7 (1934) 184; 8 (1934) 207.
54 Colonel Oudry, 45th Algerian Division in the Second Battle of Ypres (April–May, 1915), The Ypres Times, (April 2, 1924) 47.
55 G.W. Young, The Grace of Forgetting, Country Life, London, 1953.
56 Army Historical Branch, Ministry of Defence, personal communication, 1983.
57 M. Tatham and J.E. Miles, The Friends Ambulance Unit 1914–1919, Swarthmore Press, London, 1920.
58 H. Lidbetter and N. Monk-Jones, SSA14. Motor Ambulance Convoy (printed for private circulation by J. Ellis Benson, Withington, Manchester), 1919.
59 L.F. Haber, Gas warfare 1915–1945. The legend and the facts, Stevenston Lecture, Bedford College, London, 1975.
60 Dr. Sieur, French Military Archives, Vincennes, Report for April 25, 1915, Box 16 N826, 1915.

## Appendix 1: Gas attack at Hill 60, May 1, 1915

*A Extract from official history [4]*

*Hill 60. The first failure of a gas attack — attack by the German XV Corps on the 15th Brigade*

During the 1st May a gas attack was made against Hill 60; it marks a stage in history, as it was the first by which the enemy gained no advantage. The hill, in the sector of the 15th Brigade (Br. General E. Northey), was held at the time by the 1/Dorsetshire, under Major H.N.R. Cowie. About 7 p.m., after a severe bombardment, the Germans, from less than a hundred yards off, released gas on a front of a quarter of a mile. It shot over in thick volumes so quickly that very few men had time to adjust their extemporized respirators, and one company that was in the act of practising putting them on was caught with them dry. As soon as the cloud reached the Dorsetshire trenches the enemy opened rifle fire, attacked both flanks of the battalion with bombing parties,

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and concentrated the guns to form a barrage on the approaches to the hill. A few of the Dorsets, all suffering from gas, jumped on the firestep, and, under 2/Lieut. R.V. Kestell-Cornish, opened rapid fire. This for the moment saved the situation and just gave time for the supports of the Dorsets, which were close at hand, the 1/Devonshire (14th Brigade), which was led up by Lieut.-Colonel E.G. Williams on his own initiative, and reinforcements of the 1/Bedfordshire (15th Brigade), to charge through the gas cloud and reach the front before the Germans gained a footing, when bombers of the Devons and Dorsets drove them back. The forbidden weapon had been faced and defeated for the first time. But the Dorsets by sticking to their posts had suffered heavily: 90 men died from gas poisoning in the trenches or before they could be got to a dressing station; and of the 207 brought to the nearest stations, 46 died almost immediately and 12 after long suffering; and of 2,413 cases from all fronts admitted in this period, 227 died in hospital.

*B Account from Army Historical Branch [56]*

*German chlorine gas attack Hill 60, Ypres Salient, 1st May 1915*

The 1st Battalion the Dorset Regiment, at this time some 800 all ranks strong, was holding the main Hill 60 feature. Three of its four companies, A, C and D were in the front line, while B Company was in support some two hundred yards to the rear. The German front line was in places only twenty yards away. (A sketch map showing the trench layout is shown in Fig. 5).

At 19.30 hours the Germans released chlorine gas from at least five 'nozzles', three in front of Trench 38, two in front of Trenches 43 to 45 and probably from others in front of Hill 60. The wind carried the gas away from Trench 38, Trenches 43, 45, 46 and Hill 60 receiving the full 'benefit'.

By this date, most front-line units had been provided with some form of 'respirator'. The type available to the troops in their location consisted of pieces of flannel and gauze fastened over the nose and mouth having been dampened with a solution of bicarbonate of soda, or sodium hypochlorite.

Two of the Companies, B and D, were parading for night duty with their respirators round their necks; however, these were not impregnated. It is not clear what state of readiness A and C Companies were in, though as C Company apparently suffered very heavily, the presumption is that they were unprepared.

The asphyxiating effect of the gas was almost instantaneous and was increased by the gas lingering for hours in 'dug outs' and low traverses of Trenches 43, 45 and 46. Nearly the whole of three platoons on Hill 60 were affected, as were the garrisons of Trenches 45 and 46. In Trench 43, the platoon commander forced every man able to use a rifle to mount the firing platform thus raising their heads as high as possible, the result being that only two men were 'lost' — presumably this means died.

The total casualties suffered by 1st Dorsets were: Killed by gas 90; Admitted to Field Ambulance suffering from gas poisoning: 207, of whom 58 subsequently died.

The unit on the Dorsets' left — 1st Beds — was relatively less affected by the gas (possibly because many of the fumes blew back towards the Germans lines) and pushed some platoons into the Dorsets' position. Of these men (number unknown) a total of 3 died from gas poisoning and 26 others were admitted to hospital as gas casualties. The 1st Devons, who were in reserve in the Larchwood position some six to seven hundred yards to the rear, rushed six platoons forward into the Dorsets' trenches but as the gas was by now dispersing they apparently suffered negligible casualties.

*C Account by Hanslian [5]*

*The first group of German cloud gas attacks against British positions near Loos, Hill 160, south of the Menin Road**

On May 2nd** there was a second cloud gas attack in the area of the XXVI Reserve Corps. The gas cylinders were turned on about 6 p.m. As the wind was not constant and the ground had clearly been well warmed, the cloud was in places lifted high and was almost without effect. Some parts of the cloud even came back onto the German trenches. Some people were affected but there were no deaths. The attacking infantry sustained relatively heavy losses and only a few hundred metres of ground were won.

*D Account by von Deimling [51]*

On May 1st the opportunity seemed to present itself to smoke the enemy out of Hill 60 by means of gas. The field weather station had announced a wind from the south-east. At eight o'clock in the evening at the position of the 105 Regiment some sixty cylinders were opened, but the gas cloud spread not to the enemy but along our front to the right. A number of casualties resulted.

*E Account in German dispatches* (quoted by Lefebure [16])

On May 1st another attempt to recapture Hill 60 was supported by great volumes of asphyxiating gas which caused nearly all the men along a front of about 400 yards to be immediately struck down by its fumes.

**Appendix 2: Gas attack at Wulverghem, April 30, 1916**

*A Extract from Medical History [19]*

The gas attack was not unexpected. More than once British artillery fire had broken up gas cylinders in the German trenches, and two deserters on 25th

*It is probable but not certain that this account refers to the same incident. The Hill number is 60 not 160. It is some 30 kilometres from Loos and much nearer Ypres itself but it is south of the Menin Road.

**Hanslian states that the date given by the British for this attack is May 1st.

April stated that gas had been installed and was to be used as soon as the wind was favourable. Since 22nd April the wind had remained continuously in a dangerous quarter, and ever since that date the "gas alert" had been in force. At 9.25 p.m. on 29th April two more deserters entered the trenches held by the 3rd Division and stated that the enemy intended to make a gas attack the same night or early on the following morning, and warning was immediately circulated to all troops in the threatened sector.

The gas was released at 12.35 a.m. on 30th April under cover of heavy rifle and machine gun fire all along the front of 3,500 yds, from Spanbroekmolen to La Petite Douce Ferme with the exception of two small sectors (see Figs. 6 and 7 of this paper). The alarm was effectively propagated back from the trenches by gongs and sirens. In the northern part of the sector the emission of gas was continuous and only lasted some ten minutes, but farther south the gas was released in two distinct waves, the total duration of the gas attack at this point being from thirty to forty minutes. Heavy artillery barrages were simultaneously laid down by the Germans on points a short distance behind the trenches, and immediately after the gas cloud had drifted away they attacked, mainly at those points opposite which no gas had been liberated, apparently for the purpose of destroying mine shafts. Shell or trench mortar bombs containing chlormethyl–chloroformate were used against the front line and a few lachrymator "T" shells were fired upon the support lines, but they do not seem to have done any damage worth mentioning.

The gas cloud was carried by an E.N.E. wind with a velocity of 9 to 12 miles per hour over Wulverghem, Neuve Eglise, and Bailleul, passing south of Lindenhoek and Dranoutre, and its course is shown in Fig. 6. The concentration of the gas fell rapidly on the flanks of the cloud, but even in Bailleul, some 11,000 yds from the line, it was still sufficiently strong to cause coughing and even vomiting in a few cases, amongst those who were in the open air, though closure of windows and doors prevented the gas from attaining a material concentration within the houses. On the high ground just about Neuve Eglise the concentration was fairly low, but it was again severe on the Ravelsberg Ridge farther to the west.

Grass and other vegetation were turned yellow by the gas as far back as 1,200 yds from the front line. Rats were killed in the trenches in large numbers. Eleven cows, twenty-three calves, one horse, one pig, and fifteen hens were killed in the field behind the lines by gas, and a number of other cattle and pigs showed signs of being affected by the gas. Places at which cattle were killed are shown in Fig. 6. Taking all the facts together, a really dangerous concentration for an unprotected man must have extended up to about 1,500 yds from Bailleul, or 9,000 to 10,000 yds from the point where the gas was installed. It was estimated that approximately 14,000 of the troops had to put on gas helmets during the attack, but this figure is bound to include a good many men on the

outskirts of the cloud who assumed their helmets as a precautionary measure on receiving the alarm rather than from actual necessity.

In spite of the fact that the troops were standing to arms in expectation of the attack, the men in the front line received hardly any warning that the gas had actually been released before it was upon them. In some places the cloud was seen to arise from the opposing trenches as a white mist. The hissing of the gas as it escaped from the cylinders was audible at some points of the line, but it was effectively drowned by the rifle and machine gun fire at other points. In the north of the sector attacked the opposing trenches were in places only 40 yards apart, and it was merely a matter of seconds before the gas cloud reached the British line in high concentration for with the prevailing wind the cloud would traverse 50 yds in ten seconds.

At this time the standard anti-gas equipment of the troops was the "PH" helmet, though the original "large box respirator" had been issued to special troops such as machine gunners, signallers, and selected artillery personnel, as already stated. The latter device proved extremely successful in this attack for the facepiece of the respirator could be adjusted more rapidly than could the "PH" helmet, and hardly a casualty occurred among the men so equipped. In the 72nd Brigade the helmets were carried in their protective satchels. In the 76th Brigade the helmets were, however, removed from their satchels previous to the attack and worn like caps on the head with the skirt rolled up, a method which had recently been advocated as it has been found that full protection could be obtained more rapidly by this method than if the helmet had to be taken from its satchel and unfolded when the alarm was given.

The number of gas casualties that occurred amongst the troops was considerable in spite of warnings that had been circulated and their consequent readiness for the attack. There were, of course, a few more or less isolated details who had received inadequate warning or had failed to appreciate the significance of their instructions, and some men were caught by the gas whilst asleep, but casualties resulting from this cause formed but a fraction of the whole. The speed with which the cloud reached the trenches, and the concentration of the gas, were such that a man was bound to fall a victim if he hesitated in the slightest in putting on his respirator or fumbled in adjusting it. As one would expect, therefore, the great bulk of the casualties occurred among the troops actually holding the line at the time, and in any one of these battalions the majority of the casualties occurred in the trenches nearest to the enemy...

It is possible that the gas may have been strong enough to penetrate the helmets in some degree in the trenches nearest the point of emission of the gas, but there was no distinct evidence of this. The 10th Royal Welsh Fusiliers of the 76th Brigade only suffered 41 gas casualties (about 10 per cent of their strength), with 5 casualties among R.E. and 5 among trench mortar personnel in their trenches, as compared with 112 casualties suffered by the 1st North Staffs and 122 by the 8th Queen's of the 72nd Brigade. The evidence pointed

to the fact that the relatively small number of casualties suffered by the 10th Royal Welsh Fusiliers was due largely to the improved method of carrying the helmet, though at this point of the line the gas blew sideways, and only the front line, which was in places but 40 yds from the opposing trenches, was badly affected...

With regard to the clinical symptoms those most severely affected showed intense cyanosis and frothy exudation from the mouth and nose, though some of the severe casualties who reached the casualty clearing stations exhibited the pallor and collapse associated more particularly with phosgene poisoning: in a few cases cyanosis gave place to pallor before death. Those who died rapidly in the trenches — the earliest deaths occurred about an hour and a half after the attack began — invariably showed deep cyanosis and copious frothing. Paroxysmal coughing, too, was a prominent feature in the early stages. The clinical evidence therefore suggested that the gas cloud did not in this instance contain a very high proportion of phosgene to chlorine...

A number of civilians were living in the area traversed by the gas cloud, and about twenty of these were affected by the gas, though non fortunately very severely. These civilians, who had been instructed what to do in the event of a gas attack and had been furnished with respirators, protected themselves by closing the windows and doors of their houses and filling up all apertures through which gas might penetrate with wet clothes, and in many cases they wore anti-gas helmets. It speaks well for the speed with which the alarm was propagated that the civilians were able to escape so lightly, for many were in areas in which the gas cloud was in great concentration, some even as far east as Neuve Eglise.

*B Account by Hanslian [5]*

According to Foulkes [14] in the fourth gas cloud attack at Wulverghem on April 30th only chlorine was released. As a result of previous shelling several gas cylinders in the German trenches had been exploded so that the British were warned by the gas released and could take anti-gas precautions. From April 22nd on they were on constant gas alert; on April 30th at 0.35 the Germans released the gas. The gas cloud moved across a front of 3.2 km and, according to Foulkes, with the very high wind speed of 12–15 miles per hour, i.e. 5 to 7 m/s, on to the British trenches. The gas cloud formed was not uniform but had appreciable gaps in it.