Journal of Hazardous Materials, 22 (1989) 13-56
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

THE PREDICTIONS OF HUMAN MORTALITY FROM CHEMICAL ACCIDENTS WITH ESPECIAL REFERENCE TO THE LETHAL TOXICITY OF CHLORINE

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(Received July 9, 1988; accepted in revised form March 2, 1989)

Summary

The principles of the adaptation of animal probits to human mortality is examined. Sixteen factors by which human populations differ from caged animals are put forward; most are non-quantifiable. It is concluded that probits for human mortality from toxic gases are largely valueless.

Two papers in which their authors attempted to validate criteria for the toxicity of chlorine by analysis of gas attacks in World War I are assessed and it is concluded that because of the massive uncertainties involved such validation is impossible to achieve.

1. Relating the potential for harm to the degree of harm produced

1.1 Introduction

1.1.1 The need for predictive techniques

The European Directive on Major Accident Hazards, which is currently being implemented by the Member States, highlights the need for reliable methods of prediction of the harm to humans which may arise from the accidental release of chemical substances which give rise to fire, explosion or toxic dispersion.

Such techniques of prediction require a combination of two models. They require a physical sciences model which predicts the physical consequences of an accident and they require a life sciences model which predicts the injury to humans which these physical consequences will give rise to.

1.1.2 The problems of devising predictive techniques

Though a number of authors have commented upon some of the difficulties which arise when, for example, there is an attempt to model human injury through the translation of the results of animal experiments into human terms, this has usually borne a piecemeal or *ad hoc* character. There does not appear to have been a comprehensive, overall, analysis of the factors involved. This the present paper seeks to remedy by identifying these factors and classifying them as environmental factors, population factors, and experimental factors.

0304-3894/89/$03.50

The current paper, after a general discussion of the effects of harmful agents on human populations, concentrates upon toxic releases and upon chlorine as a particular example.

1.1.3 The effects of harmful agents

Acute harm arising from chemical processes may come to humans through a variety of causes. These causes are those that bring about changes in a person's environment which exceed the normal bounds of tolerance. Such changes can include exposure to heat or to cold, to pressure, whether general or localised, and to changes in the chemical composition of the environment including the presence of chemicals or of depletion in oxygen. However, as will be shown below, the precise nature of this environment is of crucial importance in determining the degree of harm which may ensue. But the difference in response between one individual and another may be just as important.

1.1.4 The measurement of the intensity of harmful agents

It may be assumed for the purpose of this paper that means exist whereby harmful agents may be quantified using objective physical measurement. For example explosions may be quantified by the overpressure which they produce, fires may be quantified by their radiant intensity and toxic agents by their concentration.

However, when historical events are being subject to analysis, direct physical measurements are seldom available and the measurements have to be inferred. This may lead to considerable error.

1.2 The influence of the environment

It should be noted at the outset that the human body as such is narrowly restricted in its ability to respond to environmental changes. For example the working limits for skin temperature are 10 °C to 42 °C and for the internal body temperature the limits are even narrower, ranging from 35 °C to 39 °C. In the area of inhaled toxics, in some cases only a few parts per million can cause death.

Though it is often said that the human race is able to live in a great variety of environments, examination shows that, in general, people live not in these general environments, but in artificially created sub-environments. For example in Siberia the general environmental temperature may fall as low as −40 °C. This extremely low temperature, especially when accompanied by high wind, is such that a naked person exposed to it would die in minutes. Yet the local people, appropriately clothed, and clothing is a sub-environment, can withstand the climate in the open. And they can retire to their houses, which are another sub-environment, to eat and sleep. However, to live in the same fashion in the Sahara desert would result in early death from heat stroke. A factor of importance here is that of "acclimatisation" whereby people become able, through training, to behave in a way which enables them to withstand a hostile general environment.

Taken together this means that any attempt to apply predictive techniques to estimate harm to people from chemical hazards must closely specify their circumstances, especially the sub-environments in which they are at the time or into which they can escape. Equations which purport to predict the severity of such harms cannot have validity unless they specify, among other factors, these environmental conditions.

1.3 Variation in human susceptibility

There is ample evidence that human beings differ markedly in their response to harmful agents and the evidence for this is massively reinforced by the evidence which has been derived from experiments on animals. Such differences in susceptibility may be attributed to two main causes, heredity and upbringing, sometimes contrasted as "nature and nurture".

It will be convenient to leave detailed discussion of these influences to the section devoted to animal experiments.

1.4 The determination of the relationship between the intensity of the harmful agent and the degree of harm produced

Though the discussion could concern itself with all possible harms the paper singles out acute harms arising from toxic substances as its central topic.

The ways in which data on the effects of toxic substances on humans may be acquired have been discussed by the present author in Marshall [1]. These are:

(1) Direct human experiment,
(2) Historical experience, non-military,
(3) Military experience,
(4) Animal experiments.

The central concern of the paper will be further limited to acute toxicity by inhalation. For convenience the degree of harm selected will be that of *fatal* injury as this can be much more closely defined than, say, *serious* injury.

1.5 Direct human experiment

Direct experiment upon unwilling victims in which they are treated in the same way as laboratory animals is universally regarded as barbaric and is outlawed by decent society. It will not be discussed here.

Experiments at sub-lethal levels have been conducted, for some agents, on volunteers. Heath [2] reports the testing of nerve gases by volunteers. A significant experiment using chlorine with volunteers in 1915 is reported in Foulkes [3] and is discussed in detail at a later stage of the present paper.

For purposes of training it has been a common practice to expose troops to low concentrations of some war gases and some limited experience may be drawn from this.

1.6 Historical experience, non-military

1.6.1 Routes of administration

It would appear that a study of cases of acute poisoning could give rise to data whereby relationships could be established between the level of dose and the level of harm.

For toxic substances in general there appear to be four main avenues of administration:

(1) Administration by others with criminal intent,
(2) Self administration with the aim of suicide,
(3) Accidental poisoning;
  (a) of individuals,
  (b) of groups of people.

But if the discussion be limited to that of acute poisoning by inhalation in civilian life, and carbon monoxide poisoning be excepted, the number of examples to be studied becomes very small, even worldwide.

1.6.2 Carbon monoxide

Carbon monoxide is a very significant exception. The present author has calculated that some 1,000 people a year die through carbon monoxide poisoning in the United Kingdom alone, 20% of the cases arise through faulty heating appliances, most of the rest are suicide using car exhausts. Though at one time industrial poisoning by carbon monoxide was responsible for a significant number of deaths, of the order of 10 per year, the coal based economy which gave rise to them has now largely disappeared.

A complicating factor is that, in many cases, exposure to carbon monoxide is accompanied by depletion of oxygen and the two effects may be hard to disentangle. Heavy smokers are significantly more easily poisoned by carbon monoxide than are non-smokers because their blood stream is already partly saturated with carbon monoxide.

A more detailed study of carbon monoxide poisoning as an exemplar of acute poisoning by inhalation might prove useful but it will not be attempted here.

1.6.3 Case histories of releases of toxic gases and vapours

Marshall [1] tabulates 18 chlorine incidents with 7 case histories, 11 ammonia releases with 3 case histories, one phosgene case history and one methylisocyanate case history (Bhopal).

Nussey et al. [4] citing data from Roemeke and Evensen [5] and Hoveid [6] have modelled one of the incidents in the table referred to above in which ca. 7 tonnes of chlorine were released in an incident in Norway which occurred in 1940. In this incident a woman was severely gassed at a distance of 10 km. The woman had been running. The incident was modelled using the DENZ programme of SRD (Fryer and Kaiser [7]).

A case history of an ammonia release in which a considerable amount of data relating to the position of the victims has been recorded is that of the Potchefstoom incident of July 13th, 1973 (Lonsdale [8]). This would seem a very suitable subject for modelling.

Though attempts have been made to model the Bhopal incident, in the present author's view far too little is known about the toxic properties of methyl isocyanate and about the circumstances in which the people lived to view the results achieved with any confidence.

1.7 Historical experience, military

The use of poison gas in the First World War was, to a degree, a socially sanctioned form of human experimentation. It was socially sanctioned at least to the extent that after protesting that gas warfare was contrary to international law, the Allies speedily took it up themselves. It was only to a degree a form of direct human experimentation because the scientists were only partially in control with the over-riding control being in the hands of the soldiers. The soldiers were primarily interested in the military advantage achieved and only secondarily, if at all, in how many enemy soldiers were killed by gas. Put another way a gas attack could not be a pure experiment as a battle was taking place at the same time.

There was a further consideration and that was that the experimenters had no knowledge of the concentration, at any point in the battlefield, of the gases which they discharged. It is only today, in the nineteen eighties, that it is possible to make inferences in this direction.

The present author, in Marshall [9], was perhaps the first to draw upon the experiences of the two World Wars as a source of information on major chemical hazards. However, since that time, he has concluded that a cautious approach is necessary in view of the many complications which have to be taken into account especially with regard to chemical warfare. For this reason, in order to lay bare some of the problems, detailed discussion of this subject is deferred until later in the paper.

It may be useful however at this stage to delimit the area of discussion of chemical warfare in this paper. There were three principal routes of attack of war gases. They lay through the respiratory system, through the skin and through the eyes. Chlorine and phosgene are exemplars of the first, mustard gas of the second and various tear gases of the third. The present paper will be confined to a discussion of one respiratory gas, chlorine. It will concentrate on one gas attack, at Ypres 1915, because the troops exposed had no warning and thus any complications which may have arisen in later attacks because of the use of protective devices, however primitive, did not arise.

The Ypres attack was a cloud attack in which the gas was released from a line of cylinders. Some later attacks also used shells and projectors which are even more difficult to model.

1.8 Animal experiments

1.8.1 Introduction

The significance of animal experiments is one of the principal areas of discussion in the current paper and will be accorded a section to itself in which the role of "probits" will be analysed. Immediately, however, it is intended to set the scene by discussing the functions of animal experiments and the role that they can play in the specific area of the determination of the toxicity of chlorine.

1.8.2 The scope of animal experimentation

In rough terms about 4 million animals are used in the United Kingdom every year. Two thirds of them are mice and a quarter are rats. Perhaps two main classifications of the use to which animals are put may be given, biological and chemical. The former is concerned with the control of disease whether infectious or degenerative, and the latter with the determination of the toxicity of chemical substances.

However, the determination of the acute lethal toxicity of chemical substances, a subject central to this paper, constitutes only a small fraction of the chemical toxicity testing which is carried out. The bulk of chemical testing is concerned with the possible long term effects of sub-lethal doses of medicines, for which such testing is compulsory in the U.K., and of other consumer products.

Of the relatively small number of tests for acute toxicity the great majority are concerned with the ingestion of liquids and solids and only a few are concerned with acute toxicity by inhalation.

1.8.3 The variability of animals

Though engineers recognise that many of the parameters with which they are concerned have to be expressed in statistical terms, the degree of variation so encountered is usually small compared with the degree of variation encountered in the life sciences where the systems studied are vastly far more complex. This is amply demonstrated in the field of animal experimentation. Trevan [10] recognised this over 60 years ago when he devised the LD_{50} criterion of toxicity.

The prime source of variability lies in species differences. As an example of this Bridges [11] may be quoted "Ingested TCDD (dioxin) is about 100 times less acutely toxic to mice than to guinea pigs and the Syrian hamster is about 600 times less susceptible than the guinea pig. Differences like this between three rodent species make extrapolation from rodent to man highly problematical". The case of the acute toxicity of dioxin may be extreme but nevertheless it constitutes a reminder of a general truth. However, there is a general agreement that species differences are much less for irritant gases than it is for ingested toxics.

But even within species there may be considerable differences between different strains. One has only to look at the obvious differences between the various breeds of dogs to suspect that they may react differently to toxic substances. In practice, for many experimental purposes, animals may be closely in-bred to produce pure strains and thus reduce variability to a minimum. Evenso considerable variability remains necessitating strict statistical treatment of the results.

This by no means exhausts the sources of variation which include sex, age, bodily health, standard of nutrition, method of caging, and the mode of administration of the toxic substance. When impact on humans is concerned there are yet further factors to be taken into account which do not arise with animals. These will be discussed in the next part of this paper.

1.8.4 Special problems with inhalation

Whereas the administration of liquid or solid toxic substances can, in principle, be conducted so that the intake by the animal corresponds to a fixed ratio between the weight of the toxic and the body weight of the animal, matters may be more complicated when the substance is taken in by respiration.

If the index sought be the LC_{50}, that is the concentration which will kill 50% of a given population if exposed for a standard time, this does not correspond directly to an LD_{50} as the rate of respiration of the animal varies with its body weight. The rate of respiration is a function of the square of the characteristic linear dimension of the animal whereas the mass of the animal is a function of its cube. Thus a mouse has a total ventilation of about 5 litres per kg of body weight per minute, a rat about 1.5 and a man about 0.1. Unfortunately it is not possible to apply simple scaling factors from animals to humans because of factors such as activity. Humans are believed to be much more active when exposed to chlorine than, say, rats, with a corresponding increase in the respiration rate. However, no quantitative data exists on the enhancement of human respiration rates in these circumstances. It might be expected on *a priori* grounds that the enhancement index would be a function of the concentration and that this would be accordingly, in itself, difficult to incorporate into a probit relationship. Furthermore we have no quantitative data on the relationship between enhanced activity and enhanced mortality.

2. Animals, human and probits

2.1 Differences between humans and animals

There are many differences between the circumstances of laboratory animals and human populations when they are exposed to harmful agents. These

TABLE 1

Some comparisons between conditions in animal experiments and in the exposure of human populations to inhaled toxics

Conditions	Animal exposures	Human exposures
Environmental and other external factors		
Source term	Concentrations directly measured or readily inferred. Constancy with regard to time and to place aimed at.	Concentrations inferred from diffusion models which are highly dependent on source term. Variable with respect to time and place. Influenced by meteorology and topography.
Sub environments	Avoided	Many possibilities which include, being on foot in open country, in a trench, on the top floor of a high rise building, in a car, in a gas proof room.
Escape	Totally prevented	May be most important single factor in reducing mortality. Depends upon other factors such as sub environments.
Clothing	Inapplicable	Clothing, especially baggage and other impediments may hamper escape or weaken resistance.
Respiratory protection	Not provided	Available in some circumstances.
Medical attention	Not provided	May be very efficacious.
Rescue and other	Not provided	Intervention by rescue and other emergency services usually highly significant.
Population factors		
Species	Variable	One only
Strain	May be in-bred or out-bred	Out-bred only
Physical condition	Only healthy animals used. Single sex usually. Narrow range of age and body weight. Standard conditions of nutrition. Not subject to secular change.	Variable medical history. Sexual composition has range of possibilities. Age and body weight may vary from full range to narrow range. Nutrition standards very variable. Considerable secular changes in twentieth century in many parts of world.
Individual behaviour	Pattern determined by species	Pattern very variable. Determined by factors such as upbringing, training. Fear may be induced before exposure.
Social behaviour	Not significant	Ties of family and group favour mutual assistance and self sacrifice.
Experimental factors		
Sample size	Sample size scientifically determined.	Sample size adventitious.
Planning of experiment	Experiment pre-planned and systems of recording made available in advance.	Exposure usually caused by accident. Even in war, where exposure planned, conditions only partly under control of experimenters. Scientific recording of conditions poor.
Nature of observers	Observers highly trained and detached.	Observers, in accidental exposures, usually not scientifically trained.
Reporting of results	Results reported objectively and accurately	Results may be distorted by vested interests or may not be accurately known.

differences are set out in Table 1 which is put forward as a schematic basis for the comparison of the human mortality ensuing from toxic gas incidents with that reported in animal experiments.

2.2 The significance of experimental error

It is well known that all experiment is subject to error. If it be assumed that the errors are random they may be expressed by the normal, or Gaussian, distribution. If a series of measurements of any particular property be carried out on any population, it will further be found that these will exhibit variation. If these variations are random then this variation may also be expressed as a normal distribution. The results of actual experiments will thus contain two elements of chance, one arising from experiment, the other from population variance.

As an illustration, let us imagine that the same experimental apparatus is being used to determine the thermal conductivity of highly purified copper in one series of tests and that of common house bricks in another. In the results for the copper it might reasonably be expected that experimental error may be a significant element of variation whereas with house bricks the dominant source of variation would lie in differences in the population.

With animal experiments in a well conducted laboratory, population variation may be expected to be dominant. But this is unlikely to be true in battles or industrial escapes where the "experimental" conditions may not be properly defined. Nor can it be assumed that the results of animal experiments conducted, say sixty or more years ago, were free from substantial experimental error.

It is also open to question whether the variations are in fact randomly distributed and where, as a consequence, the distribution is skewed. This may be a matter of significance in considering the use of probits as these assume a log normal distribution.

Throughout there must be an assumption that the size of the populations is statistically adequate.

2.3 The use of probits

2.3.1 Advantages of probits

The principal advantage of probits is that, in principle, they should not only disclose the median but also the spread; it is not only important to know the LD_{50} of a toxic gas but also to know its effect at other concentrations. A probit should be able to disclose the LD_{10} and LD_{01} as well. These might be desirable things, but they may not be possible to determine for animals, let alone humans.

2.3.2 Early use

The use of probits in animal experiments was established in the 1930s in the testing of insecticides. An early paper on the subject is that of Bliss [12] and the subject is extensively treated in Finney [13]. The use of probit relationships considerably reduced the number of experiments which needed to be performed. Evenso, as the populations in each experiment have to be small, strict statistical controls have to be exercised which are discussed in Finney.

2.3.3 The form of probit relationships

Probit relationships are based upon the assumption that the variation in the population is subject to a log normal distribution. As such it suffers from a

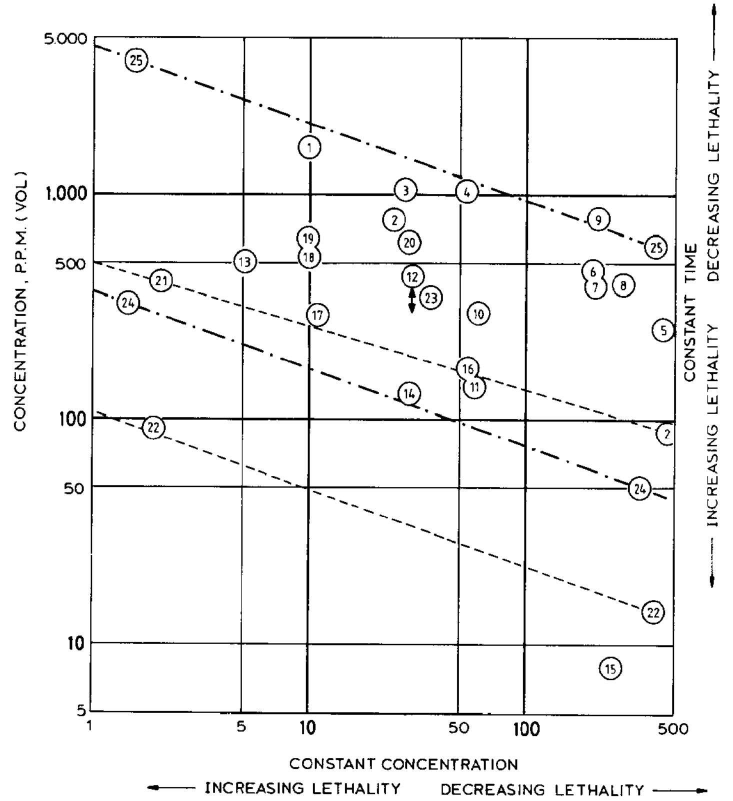

Fig. 1. Estimations of lethal toxicity of chlorine for animals and humans. Notes.

1. Coordinates of data points are derived either from citations or estimations by present author from graph in Nussey et al. (Ref. 4).

2. Upper and lower bounds of 90% of data points drawn by present author.

3. NIOSH cited below is "Registry of Toxic Effects of Chemical Substances", U.S. Dept. of Health, Education and Welfare 1978.

4. LC_{50}=concentration lethal to 50% of population. LTL_{50} is "toxic load" lethal to 50% of the population. LCL_{50} is lowest recorded lethal concentration.

number of defects one being that the distribution is unbounded and so, if applied to exposure to toxic gas, it provides a finite probability that some individual will survive a dose no matter how large and that some individual will die from a dose no matter how small.

In the most general case probits take the form

$$Y=a+b(\ln x), \tag{1}$$

where Y is the probit, a, b are numerical constants, and x is a measure of the dose of the harmful agent.

Y has the value of 5 where $a+b(\ln x)$ has the median value of the effect being studied. Probits of 6,7,... are 1,2,... standard deviations above and probits of

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Legends of Fig. 1.

Data points

No.	Experiments	Species	Dose	Conc ppm	Time Minutes	Cited by
1	Gilchrist	Animals	?	1,600	10	Nussey (Ref. 4)
2	Gilchrist		?	750	25	Nussey (Ref. 4)
3	Weedon	Mice	LC_{50}	1,000	28	LPB (Ref. 16)
4	Weedon	Rats	LC_{50}	1,000	53	LPB (Ref. 16)
5	Weedon	Rats & Mice	LC_{50}	250	440	LPB (Ref. 16)
6	Lehmann	Cats	LCL_0	450	210	LPB (Ref. 16)
7	Lehmann	Rabbits	LCL_0	400	210	LPB (Ref. 16)
8	Lehmann	Guinea Pigs	LCL_0	400	210	LPB (Ref. 16)
9	Lehmann	?	?	780	220	Nussey
10	–	Rat	LC_{50}	293	60	NIOSH
11	–	Mouse	LC_{50}	137	60	NIOSH
12	–	Human	LCL_0	430	30	NIOSH
13	–	Mammal	LCL_0	500	5	NIOSH
14	Schlagbauer & Henschler	Mice	LC_{50}	127	30	LPB
15	Schlagbauer & Henschler	?	?	8	250	Nussey
16	Bitron & Ahronson	Mice	LC_{50}	170	55	LPB & Nussey
17	Bitron & Ahronson	Mice	LC_{50}	290	11	LPB & Nussey
18	Silver & McGrath	Mice	LC_{50}	524	10	LPB
19	Silver & McGrath	Mice	LC_{50}	596	10	LPB
20	Underhill	Dogs	LC_{50}	636	30	LPB & Nussey
21	Ten Berge & Van Heemst	Mice	LTL_{50}	1,000*	0.1	Nussey
	Ten Berge & Van Heemst	Mice		100*	273	Nussey
22	Eisenberg	Humans	LC_{50}	105*	1	LPB & Nussey
	Eisenberg	Humans		10	1000	LPB & Nussey
23	Range of LD_{50} values for 30 min exposure suggested in Ref. 16					
24	Lower bound of 90% of data points					
25	Upper bound of 90% of data points					

*Log/log straight lines derived by authors cited.

4,3,... are 1,2,... standard deviations below the median. The relationship between the value of the probit and the corresponding fraction of the population which suffers a given effect is mathematically determined by the form of the normal curve. Tables are provided in standard works such as Finney [13].

Where toxics are administered as liquids or solids into an animal's body the intensity is measured as a dose usually expressed as a ratio between the quantity administered and the body weight of the animal. With inhaled toxics the intensity is a combination of the concentration of the gas and the time over which it is administered.

Thus for toxics

$$Y=a+b\ln\sum C^m T^n, \tag{2}$$

where C is the toxic concentration, T denotes the time over which any given concentration is effective, and m, n are exponents.

The toxic concentration C may be expressed as ppm by volume, or mg per cubic metre or as some other unit; T is usually expressed in minutes. The units in which C and T are expressed affect the value of b.

Though m and n can be used in various combinations most investigators set $n=1$ and then seek to establish a value for m. The exponent m has been given values ranging from 1.0 to ca. 2.75. The value of 1.0, which implies that concentration and time of exposure are inversely proportional, is attributed to Fritz Haber and is quoted in Prentiss [14, p. 11 et seq.]. A table of probits is given in Problete et al. [15].

The summation $\sum C^m T$ is known as the toxic load.

2.3.4 The calculation of probits

Let it be assumed that the effect to be examined is that of mortality, within a stated time, in a given laboratory animal through the administration of a toxic gas. In principle, for a fixed time of administration, it should be possible to determine the LC_{50} for that time of administration. If the LC_{50} be determined for differing times of administration a relationship could then be established to relate LC_{50} and T. Such a set of relationships for chlorine, drawn from Nussey et al. [4], are displayed in Fig. 1. The exponent m for the concentration is positive and equal numerically to the cotan of the angle each line makes with the horizontal axis.

From this therefore the form of the toxic load has been determined and in future trials the product $C^m T$ then becomes the measure of the intensity of the toxic agent. From the results already obtained the relationship between the fractional mortality and the toxic load may be plotted and from this the probit relationship may be reduced.

At this point quantification from experiment ceases as further steps which would lead to human probits have to be made through inference. We have a number of animal probits which differ from each other and no means of decid-

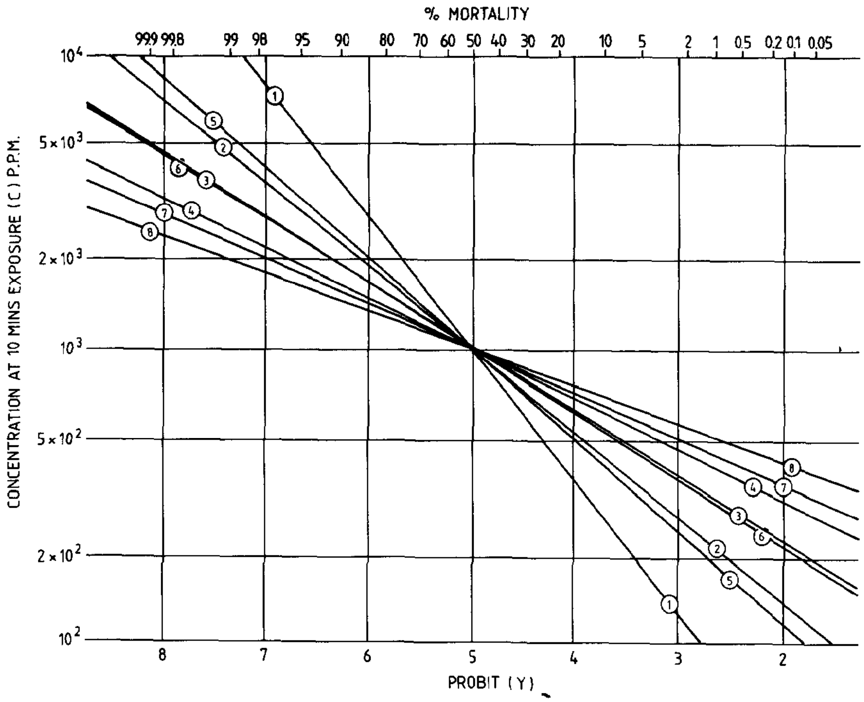

Fig. 2. Family of probits for LC_{50} of 1,000 ppm and 10 min exposure. $T=10$ min. (1) $Y=-2.875+0.5 \ln C^2T$; (2) $Y=-6.81+0.75 \ln C^2T$; (3) $Y=-10.75+1.00 \ln C^2T$; (4) $Y=-14.68+1.25 \ln C^2T$; (5) $Y=-5.45+0.5 \ln C^{2.75}T$; (6) $Y=-10.70+0.75 \ln C^{2.75}T$; (7) $Y=-15.94+1.00 \ln C^{2.75}T$; (8) $Y=-21.175+1.25 \ln C^{2.75}T$; (3) & (6) generate virtually identical lines.

ing which of them come closest to the human condition. Of necessity judgement has to be exercised to bridge the gaps which are demonstrated in Fig. 1.

2.3.5 Some characteristics of probits

Figure 2 shows a number of probit relationships, all for the same LC_{50}. They vary in slope and this is a function of the value of *b*. Slopes tending to the value of 0 are characteristic of closely matched populations whereas slopes tending to the value of 1.0 are characteristic of very variable populations. Two of the quadrants are "forbidden" as they would be occupied by the probits of agents that are the more toxic the lower their concentration. (Only oxygen would have such a probit.)

The value of the LC_{50} is also determined by the constant *a*. Adding 1.0 multiplies the toxic load term by e (2.72) and subtracting 1.0 leads to the converse.

2.3.6 The accuracy of probits

If the extreme limits of probits are to be explored the tables that relate probit to fraction affected show that, for example, for any selected animal population, at probit 2 there is a probability of 1 per 1000 of a lethal dose. Clearly an animal population of several thousands would be needed to demonstrate this with statistical reliability. Nussey et al. and I. Chem. E. [16] give figures which suggest that the animal populations used in tests have been in the region 100 to 500. Though these may have been adequate to provide a working figure for LD_{50}, they could only have provided information of any reliability on probits in the range $Y=4$ to 6. Problete et al. [15] and Nussey et al. [4] give indications of how wide can be the limits of the statistical reliability of probits.

So for experimentally determined animal probits, the accuracy of the equations is illusory. How much more illusory then are human probits which contain in addition a strong component of inference? Yet some human probits quoted in the literature have been accorded up to four significant figures; (see the table of probits in Prolete et al. [15]). Even if allowance be made that the constants are natural logs and not integers on a decimal scale, this seems quite unreasonable.

The present author entirely agrees with Nussey et al. [4, p. 201] when they say "we feel that the form and flexibility of the probits give an air of false precision".

2.3.7 The need to qualify as well as quantify

As Table 1 above demonstrates, environmental, social and personal factors play a major role in determining the risk posed to any individual. Therefore the prospect of finding a universally applicable probit equation for any specific agent seems like pursuing a will-o-the-wisp. To take an example outside of the present field, would it be possible to put forward a probit for thermal radiation which would apply equally to a fully uniformed fire-fighter and to an old woman in a nightdress? Such a probit would have to take account of the differing sub-environments provided by the difference in clothing and that, for the same fraction of body burns, old people have much lower probabilities of survival.

Where probits are put forward a narrative which describe fully the characteristics of the population and the environmental circumstances to which they apply is quite indispensible.

3. The analysis of World War I gas attacks in light of the schema in Table 1

3.1 Introduction

3.1.1 The gas attacks studied

In order to exemplify the schema set out in Table 1 of the present paper the chloride attacks at Ypres (1915) and at Wulverghem (1916) are analysed in Section 4 and, at the same time, the treatment of these two battles by Withers and Lees [17] and the previously cited Nussey et al. [4], are critically analysed.

3.1.2 An earlier study of Ypres

The present author discussed the Ypres battle in an earlier paper, Marshall [9], where his aim was to determine an upper bound mortality index for chlorine. In the course of this study he concluded that because of factors disclosed in the paper the number of lessons on the effects of chlorine in industrial situations which could be drawn from analysis of this battle were bound to be limited.

Points made in Marshall [9], set out in the order in which the subjects are treated in the present paper, included the following:

(a) Source term. Along a line 7 kilometres long at 90° to the wind under weather conditions favourable to inflicting high casualties. Release took only about 5 minutes.
(b) Sub-environments. Trenches and dug-outs formed pockets which filled up with gas.
(c) Escape. Escape to the edge of the cloud ruled out for the vast majority of victims because release came from a line source. Escape hampered by shell fire etc.
(d) Respiratory protection. None provided.
(e) Physical condition. Troops aged 15 to 45 and physically fit.
(f) Individual behaviour. Troops trained to stand fast in face of enemy attack.
(g) Reporting of results. Figures of gas dead may have been greatly exaggerated.

3.1.3 More recent publications

However, in a recent paper, Withers and Lees [17], the authors claim that their analysis of the Ypres battle cross-checks a probit equation for chlorine which they have put forward.

In addition, and for the same purpose of cross-checking their probit, Withers and Lees examine two further gas attacks, one at Hill 60, May 1st 1915, and one at Wulverghem, April 30th 1916.

This later attack, has also been analysed in the previously cited Nussey et al. [4]. These authors claim that they have used data from this battle as collateral evidence for a criterion of chlorine toxicity.

The present paper will analyse Withers and Lees' interpretation of the Ypres battle in the light of the factors set out in Table 1 together with comment, where this seems appropriate and, using this schema, on the other battles discussed by Withers and Lees and by Nussey et al.

Since the publication of the above two papers, there has appeared a comprehensive and authoritative account of chemical warfare in the First World War by Haber [18] which is drawn upon by the present author. L.F. Haber, the author of this book, is the son of Fritz Haber who is world famous for this invention of the Haber–Bosch process for nitrogen fixation for which he was awarded a Nobel Prize. Fritz Haber was employed by the German army as their scientific advisor over the Ypres gas attack.

3.2 The aims of the papers of Withers and Lees and Nussey et al.

3.2.1 Withers and Lees probit

Withers and Lees put forward the following probit:

$$Y = -8.29 + 0.92 \ln C^2T, \quad (3)$$

which they state relates to a regular population at a standard level of activity. They apply this to the battle at Ypres, April 22th 1915, (which they sometimes referred to as "Langemarck" from a village in the middle of the front), to the battle at Hill 60 of May 1st 1915 and to the battle at Wulverghem on April 30th 1916.

3.2.2 Nussey et al. and the Dicken criteria

Nussey et al., though they set out the probit advanced by Ten Berge and Van Heemst [19] which is referred to below, do not compare it with the data they adduce from the battle at Wulverghem. Instead they claim a cross-check with data advanced by Dicken [20]. These data are summarised in Table 2. The criteria quoted were given by Dicken in a short section of a paper intended to set out the safety policy of ICI Ltd. in relation to their chlorine manufacturing facilities at Runcorn. The Dicken criteria are displayed in the form of *curves* on a log/log plot of the concentration of chlorine required to produce a given effect versus the duration of exposure. They are used to delimit three categories of increasing severity of hazard. However, since these categories are set out as *straight lines* on a log/log plot of concentration versus duration of exposure rather than the curves referred to above, there can be only a rough correlation between them. The table given below displays this rough correlation for 10 min exposure.

Only general indications are given in the paper as to how ICI arrived at these figures. It should be noted that Dicken's data does not overly take account of

TABLE 2

The Dicken criteria[a]

Effect. (10 min exposure)	Concentration (ppm)	Hazard category
Detectable odour	1	I
Irritation	2	
Coughing	4	
Distress	14	II
Dangerous	30	III
Fatal	95	

[a] Based on Fig. 1 in [21].

the physical makeup of the target population in the way that Withers and Lees attempt and which is set out in the present author's Table 1.

These thus represent measures of the *threshold* values for the onset of the effects. The Dicken criteria afford no estimate of the fractional mortality to be associated with any level of chlorine concentration greater than ca. 95 ppm which may be assumed to represent LC_{00}.

The Ten Berge and Van Heemst probit quoted by Nussey et al. is:

$$Y = -4.92 + 0.5 \ln C^{2.75} T. \qquad (4)$$

Though this probit seems widely divergent from the Withers and Lees probit, nevertheless it is shown later by the present author that it can generate results which are not dissimilar.

Nussey et al. analyse the battle of Wulverghem in detail and make reference to battles at Loos September 26th 1915, and at the Hohenzollern Redoubt, October 13th 1915. They do not analyse Ypres.

3.2.3 Pursuing two aims simultaneously

Both sets of authors claim that their analysis of the battles they have selected to some degree validate the equations or criteria of mortality they have used. However, they are attempting to do at least two things simultaneously. They are also attempting to validate their dispersion models by reference to these physiological effects. Thus the mortality model is verified by assuming the validity of the dispersion model and the dispersion model is verified by assuming the validity of the mortality model.

4. The schema applied to the battles

4.1 The source term

4.1.1 Laboratory versus open air

It seems apparent to the present author, on *a priori* grounds, that the accuracy of estimation of chlorine concentration on a battlefield, even for well validated dispersion models, must be much less than the accuracy with which the concentration of chlorine in a laboratory experiment is known.

It would further be reasonable to assume that the chemical composition of the gas used in the laboratory would be known with certainty. Laboratory estimations are either based upon measurement by sampling (direct) or by calibration of a flowmeter by analytical techniques. Such concentrations are expected to be invariant at any point in space. I. Chem. E. [16] gives a table setting out the techniques used in eight frequently cited references to animal experimentation on chlorine toxicity.

In the open air, on flat ground, the concentration at any point in space of a vapour cloud varies with the path length and with height above the ground. It is inferred from a combination of the rate of discharge, the dilution ratio, which is a function of wind speed, and dispersion models such as DENZ and CRUNCH. Useful as such models may be for certain purposes, they are unlikely to be capable of allowing for the complex topography of a battle field. For example they are not designed to predict the behaviour of gas in trenches. Though the meteorological conditions are an important feature, accurate knowledge of such factors as the windspeed at Ypres for example is lacking.

4.1.2 How reliable are the models for flashing liquids?

It is necessary first to define the present author's nomenclature. In the discussion below "buoyant" means having a density less than the ambient atmosphere, "neutrally buoyant" (sometimes called "passively buoyant" or "passive") means having a density substantially the same as the ambient atmosphere, and "negatively buoyant" means having a density greater than the ambient atmosphere.

Though the Thorney Island trials of 1982–1984 provided valuable data for the modelling of negatively buoyant vapour clouds in the intermediate and far field, they did not, and could not, provide validation for the behaviour of the vapour from flashing liquids in the immediate post-flashing regime. This is because the Thorney Island clouds were pre-mixed, relatively quiescent, and at ambient temperature. Their energy content lay solely in their potential energy.

In the conditions at Ypres cylinders, presumably fitted with a dip tube to enable the vapour pressure of the chlorine to effect the discharge, were, according to Haber [18, p. 31], coupled in batches often to the manifold feeding a single jet. These jets were each about 10 metres apart, again according to Haber. Unfortunately details of the actual discharge mechanism, such as the diameter and geometry of the jets are lacking. Slender indications from photo Q 57012 of the Imperial War Museum Collection suggest that connection pipes with an O.D. of ca. 5 cm were used by the British.

Nussey et al. have assumed that 14% of the liquid flashed in the pipes. As this corresponds to the theoretical adiabatic flashing fraction for chlorine stored at 9 °C, it implies that all the flashing had occurred in the pipes. It may be stated that this is impossible as total flashing would reduce the pressure to atmospheric and hence there would be no pressure to drive the two phase system from the pipes. The regime which applies to this case is that of critical two phase flow which may imply that the gas/liquid jet emerged at the sonic velocity of chlorine i.e. ca. 200 metres per second.

We must assume therefore that a two phase system emerged at high velocity and that part, if not most, of the flashing occurred after discharge. Flashing would reduce the temperature to −34 °C and would produce a fog of droplets.

Vaporisation of these drops would cool them, and the immediately ambient air, below this temperature. A further factor would be that the fog would be intensified by freezing of the water vapour in the ambient air. Any model of the immediate post flashing phase must take account of these thermodynamic effects. Nussey et al. discuss effects of this character but their paper does not disclose their calculations on the effect that these processes had upon the assumed density of the gas cloud. It would appear that Withers and Lees did not take the thermal phenomena into account.

Rough calculation by the present author suggests that chilling by flashing and evaporation accounted for more than half of the negative buoyancy of the initial cloud.

4.1.3 The ammonia anomaly

That super-cooling after flashing can produce significant effects is exemplified by the behaviour of liquid ammonia. Though ammonia vapour at its atmospheric pressure boiling point of ca. −33 °C is buoyant relative to air (relative density ca. 0.7) there is a great deal of evidence that some ammonia spillages have shown negatively buoyant behaviour, i.e. that the cloud was at least about 1.4 times as dense as it would appear from simple theory. This is discussed for example in Fryer and Kaiser [7] who conclude that the cause is due to the circumstances discussed in the paragraph above. But though they came to this conclusion about ammonia, they failed to draw the inference that this could apply to other flashing liquids. If ammonia vapour clouds are found to be negatively buoyant when expected to be buoyant, then liquefied gases expected to be negatively buoyant may prove to be even more negatively buoyant. Chlorine as a flashing liquid has similarities in its thermodynamics to ammonia and may therefore have exhibited super-heavy behaviour at Ypres. However, in one important respect chlorine differs from ammonia in that it has a much lower specific latent heat, roughly 1/5 of that of ammonia. Thus the degree of super-cooling would be less. Similar considerations apply to liquefied petroleum gases.

4.1.4 Field trials with chlorine

Though some writers today associate the first trials using chlorine with Van Ulden in 1972 [21] (though published under the title "Experiments with chlorine", in fact most of his work was conducted with Freon 12), both belligerents conducted field trials in 1915.

Haber [18, p. 30] briefly reports on field trials by the Germans including a full scale rehearsal at Beverloo, Belgium, on April 2nd 1915.

Foulkes [3, p. 42] reports on trials with chlorine released from cylinders at the Castner Kellner Works on the Manchester Ship Canal, Runcorn, Cheshire on June 4th 1915. A simulated battlefield was constructed complete with trenches. Paper discs impregnated with chemicals were mounted on poles in trenches to determine chlorine concentrations. Process workers, experienced in handling chlorine, and provided with respirators, volunteered to take part in human experiments. These included timing the arrival of the gas cloud and seeing how long they could withstand the gas before donning a respirator.

Foulkes refers to "the great fall in temperature of the air which increased the density of the cloud and helped to make it cling to the surface of the ground.... the chlorine clings to the ground in a remarkable manner and sinks into trenches; it ascended a bank 10 yards (9 m) high 200 yards (180 m) from the point of discharge, passed along the top of the bank for another two hundred yards (metres) and rolled down thirty metres into the Ship Canal". When Foulkes walked into this cloud he had to don a respirator immediately. (It would be very interesting were detailed records of these trials to turn up. They may possibly lie in the U.K. Public Record Office.)

4.1.5 The models adopted

Withers and Lees adopted a neutrally buoyant model based on the Pasquill–Gifford model and assumed that the dense gas regime was dominant over a distance so short as to be negligible. They specifically state that their model shows little difference between the concentration of chlorine at ground level and at 2 m above it [17, p. 307].

Nussey et al. say [4, p. 207] "Here we use the CRUNCH code and a passive model with Hosker's (1973) dispersion coefficients. (It can be shown using a Richardson number criterion due to Puttock et al. (1982) that treating the plume as passive from the start is reasonable for the above source strengths and wind speeds.)".

But do the models accord with the Runcorn trials? It would seem not. Foulkes noted heavy gas behaviour up to at least 400 m. If the rate of discharge was comparable with that at Ypres then this would suggest a much heavier gas, and hence a much higher concentration, than that assumed by Withers and Lees or Nussey et al. Matters are seen to be worse if account be taken of the much higher windspeed at Runcorn than at Ypres. This was ca. 9 m/s as opposed to ca. 2 m/s. The Pasquill–Gifford model quoted above suggests that the concentration, and hence the density difference, of a gas at a given distance from a line source would be proportional to the reciprocal of the wind speed.

But Withers and Lees make other and contradictory assumptions. At one point they claim [p. 213] that "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" i.e. to become positively buoyant and not neutrally buoyant. This contention can, however, be disposed of. At 5.00 p.m., the time of the attack, it would be about two hours to sunset. At such time on a clear Spring day the temperature of the earth and the temperature of the air in contact with it are equal, i.e. there is neither lapse nor inversion according to Sutton [22]. Thus positive buoyancy can be ruled out of consideration at Ypres.

Withers and Lees, on p. 308, contradict their assumption of neutral buoyancy by stating, without explanation, "The gas did tend, however, to accumulate in the trenches and any men lying in them would have experienced concentrations higher than the model ground level concentrations". Later in the same page they quote from the Official History of the War [23] that "those who stood on the fire step suffered less 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 nearer the ground. The worst sufferers were the wounded lying on the ground, or on stretchers, and the men who moved back with the cloud". This is a testimony from soldiers that in actual gas attacks the gas was negatively buoyant and stratified. No model currently exists which takes account of such stratification. It may be of passing interest that school text-books of chemistry at one time used to quote the example of a cave near Naples, the Grotto del Cane, where dogs were killed by carbon dioxide but not their owners, (Taylor [24]).

It would seem from the above that it might have been possible to survive in the near field with highly lethal concentrations round one's ankles but with sub-lethal concentrations in one's breathing zone. If this be true a probit for high concentrations based simply on a concentration/distance relationship, would have no validity as it could not take account of stratification in the near field.

A further check on the validity of the Withers and Lees model, lies in putting a figure to the height of the vapour cloud. A material balance can be drawn up to provide this height based upon the rate of discharge per metre of front and the windspeed. The authors' Table 3, p. 321, gives the discharge rate as 0.058 kg per metre of front per second, a figure with which the present author generally concurs. At 2 m/s wind speed and a mixing zone height of 1 m this gives, ca. 29,000 mg/m^3 or 12,000 ppm. At 100 m from the point of discharge, again according to Table 3, the authors give the concentration as ca. 950 ppm. If this be the mean concentration of the cloud then its height would have been 12 m. However, on p. 313 the authors speak of a "wall of greenish-yellow gas about 5 m high coming towards them". According to the Times History of the War [25] the cloud started as 1 m high and was the height of a man when it reached the French lines. These heights would indicate mean concentrations of ca. 2,400 and 6,000 ppm respectively compared with the 950 ppm calculated by the authors.

In the present author's view Withers and Lees' assumption of neutral buoyancy at the point of entry into the trenches is not in accord with their own evidence, with evidence from other military sources or with evidence from the Runcorn trials. It is a denial that the aim of the soldiers, namely to force the enemy to quit their trenches by filling them with gas, was possible of achievement.

A final point on source term is that actual gas attacks may not have been "parade ground" affairs. This is demonstrated in Fig. 3 which is an aerial photograph of a cloud gas attack taken from Innes and Castle [26] and claimed to

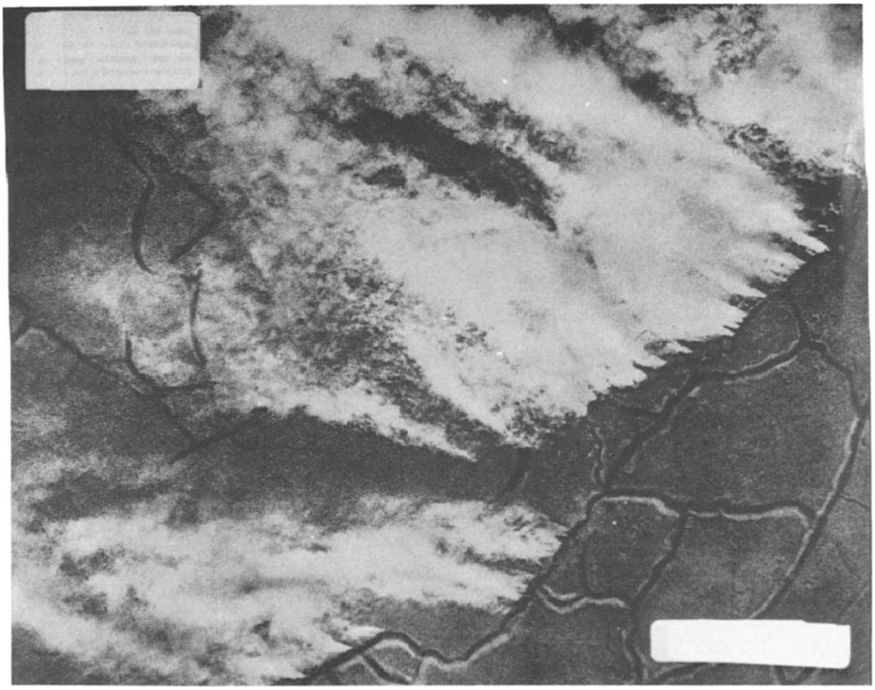

Fig. 3. Aerial view of German cloud gas attack (1917?).

be that of a German gas attack in November 1917. (The present author cannot trace this attack in the tables in Prentiss [14].) This photo shows considerable gaps and irregularities and suggests that some of the target troops in the front line may not have been affected at all. Withers and Lees acknowledge this when they say that fighting continued around Langemarck village (pp. 313 and 317) for an hour after the attack and on p. 342 they present evidence that the cloud formed at Wulverghem was not uniform and had appreciable gaps in it.

4.2 The sub-environments of trench warfare

When probits for inhaled toxics are determined on experimental animals every effort is made to preserve a uniform environment with the concentration of the toxic being constant in relation to the spatial coordinates. It is necessary now to determine how far this was true for the Ypres gas attack.

The central feature of the battles is that they were episodes in trench warfare. Surprisingly neither Withers and Lees nor Nussey et al. pay much attention to the actual conditions of the sub-environments of trench warfare.

It became apparent in 1914 after a few weeks of war that weapons such as the machine gun and shrapnel rendered cavalry useless and forced infantry to

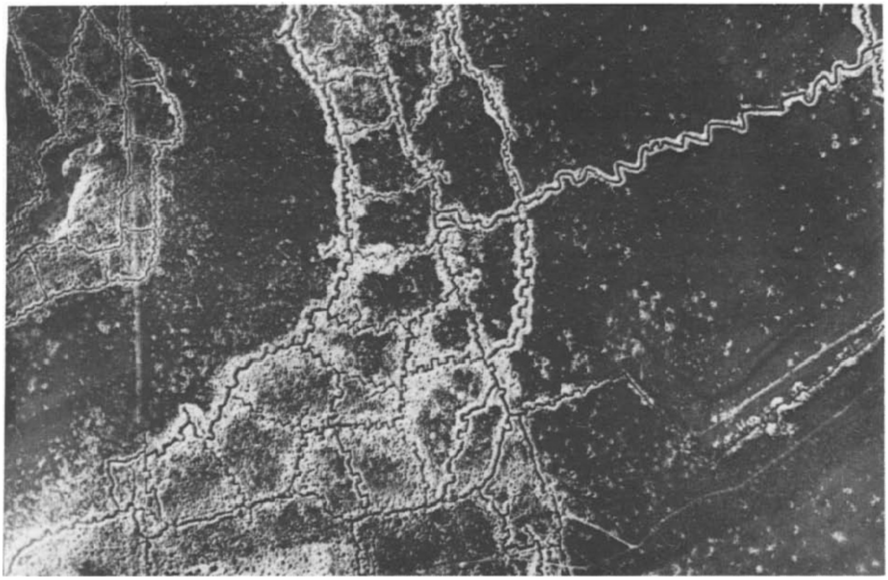

Fig. 4. Aerial view of developed trench systems.

dig in. Trench warfare then became the dominant form of warfare on the Western Front for the remainder of the war.

Gas warfare was an attempt to break the stalemate of trench warfare by forcing troops to leave their trenches and thus exposing them to machine gun and other small arms fire. But it failed to produce the dramatic effects its inventors hoped for. This was because it was tried out on a relatively small scale thus enabling counter-measures to be devised before decisive results could be achieved. Thereafter there was a continual succession of new inventions and new counter-measures with neither side gaining the upper hand for long.

As prescribed by military manuals trenches were dug down into the ground to a depth of about two metres and part of the soil was used to form a parapet (chest protector) and part to form a parados (back protector). Various devices were used to stabilise the sides of trenches and their parapets including so-called sandbags, wattle and timber. A feature of the trenches were the dug-outs which housed the headquarters of the various levels of military command, officers' quarters, dressing stations, stores etc. These could be at a deeper level than the trench floor. Less elaborate alcoves were hollowed out in which the common soldiers could sleep.

The systems, especially towards the end of the war, became very elaborate. Long straight lengths were avoided for military reasons so the trenches were either arranged in zig-zags or were crenellated. When account be taken of support and reserve trenches and communication trenches and the need for avoiding straight lengths of the total length of the trenches was perhaps ten times

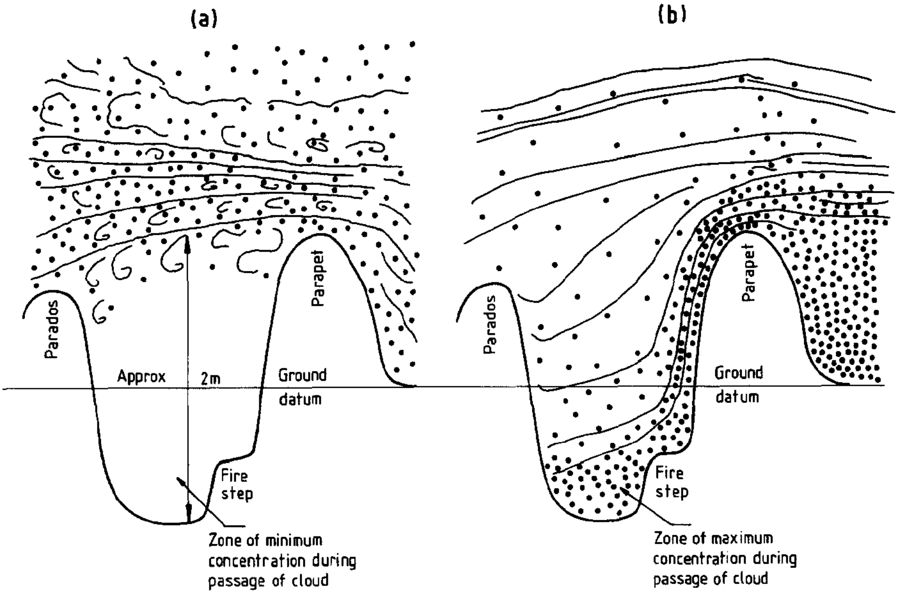

Fig. 5. Cloud behaviour at front line trenches. (a) According to model of Withers and Lees, (b) According to experience of the military authorities and of Foulkes.

the nominal length of the front. Figure 4 is an aerial photograph of an elaborated trench system at its final stage of development; it should not be taken as an accurate representation of the trenches which featured in the Ypres battle. They may, however, more accurately represent the situation at Wulverghem. The section of the front at Ypres was held by the French who were believed to favour the simpler forms of trench construction.

A major problem of trench warfare was water. If the bottom of a trench lay below the water table it would tend to flood. This was a particularly difficult problem in the Ypres sector. As a consequence the Ypres trenches probably resembled the sketches in Fig. 5. This figure also shows the differing behaviour of neutrally buoyant and negatively buoyant clouds when passing over trenches.

Trenches, as sub-environments, would be expected to provide shelter from neutrally buoyant clouds. This is borne out by the observations of Purdy and Davies [27] who consider that cellars may be the safest refuge from neutrally buoyant clouds arising from civilian releases. On the other hand trenches would be anti-shelters in the face of negatively buoyant clouds. Thus at Ypres, if both negatively buoyant and neutrally buoyant regimes were present at different locations on the battlefield the trenches may have enhanced or diminished the toxic effects according to location. It is extremely difficult to see how these factors could simultaneously be incorporated in a probit relationship.

4.3 The factor of escape

The factor of escape, totally absent from animal experiments, nevertheless plays a major role in the human situation. It is a complex question and interacts with other factors in the schema. A number of authors have explored this factor as for example Beattie [28] and Purdy and Davies [27]. It plays a considerable role in the model adopted by Withers and Lees. The physiological and psychological aspects of escape will be considered in 4.10.

4.4 Clothing

The troops had to carry a considerable weight of equipment. According to Ellis [31, p. 33] the average British infantryman carried between 27 and 35 kg and a French infantryman up to 38 kg. Such loads would have considerably hampered escape. It was a very serious offence to cast away one's equipment unless actually wounded. It would have been very difficult to get it off in a hurry.

4.5 Respiratory protection

Respiratory protection may be regarded as a high localised sub-environment and in the general case may have a considerable influence on mortality. However, to incorporate the influence of respiratory protection into probits it is necessary to be able to incorporate a probability relationship for the efficacy of respiratory protection and the probability of its availability. The question did not arise at Ypres as no protection for the defenders was provided. (But the Times History of the War [25] claims that the first wave of German troops at Ypres wore crude respirators). At all later battles it is necessary to assume that even crude methods provided some measure of mitigation thus adding a further factor of complication to an already complicated situation. By the time the Wulverghem attack took place there had been a year to develop countermeasures. Withers and Lees draw attention to these, their Appendix 2, p. 243, which quotes Diseases of the War [29] for information of the extent to which, at Wulverghem, even the civilians behind the lines were issued with respirators and shown how to gas-proof their houses.

4.6 Medical attention

This factor, completely absent from animal experiments, may, in general, assume considerable significance as, in conjunction with the provision of rescue services it forms an integral part of the emergency planning which arises from the European Directive. However, though obviously there was provision at Ypres for medical attention to the wounded and for those who fell sick, the medical authorities could not have had available the specialised provision needed for dealing with chlorine casualties. Of course by the end of the war the treatment of all forms of gas injuries was standardised. It may be reasonable to assume that for Ypres the efficacy of treatment was nil and that it made no difference to the injured whether they received medical attention or not. For later battles, as for example at Wulverghem, the influence of medical treatment would play a more and more significant role.

In the general case, and looking at present day conditions, the efficacy of medical treatment for gaseous toxics is likely to be scale dependent. Chemical works handling chlorine may make provision for, say, the simultaneous administration of oxygen to twenty victims. If there were to be a hundred cases this level of provision would be under heavy strain. No doubt at Bhopal the efficacy of medical treatment was virtually zero because the facilities were swamped.

This means that probits which aim to take account of medical treatment must incorporate scale dependency and be specifically related to the local availability of medical resources.

4.7 Rescue services

For casualties in general the armies maintained teams of stretcher bearers. However, at Ypres these would be casualties themselves and, since the efficacy of medical treatment was zero the rescue services could have contributed nothing. Nevertheless, rescue would have been a factor in later battles. In civilian release rescue services obviously play a major role which has to be taken into account when predicting mortality.

4.8 Species and strain

The problems of extrapolating from animal to human populations have already been discussed and will not be further elaborated here.

4.9 Physical condition

The question of the health of the soldiers raises many problems. Withers and Lees acknowledge this factor and equate the troops to a "regular" rather than to a "vulnerable" civilian population which is a present-day civilian population with a full range of age and bodily health.

However, the question is more complicated than the authors have given credit for. The comparison has to take account of the considerable secular changes which have occurred in the health of the population of Western Europe in the last 70 years. The main body of the French troops at Ypres were either reservists, described in some histories as "elderly" or else "Turcos", natives of Algeria.

It seems almost certain that the troops, especially the North African troops, must, as part of their medical history, have been subjected to, or were suffering from, respiratory diseases such as pneumonia or tuberculosis which are virtually extinct today. But this is impossible to quantify. Nor is it possible to assess the effects of smoking. Certainly trench life, as Withers and Lees acknowledge, was unhealthy. Thus the factor of medical condition is very hard to assess. The troops were poorly fed, short of sleep, physically weary and living under severe nervous strain. They may well have been in far worse physical condition than present day laboratory animals!

The activity levels which Withers and Lees introduce into their analysis may, because of these factors, have been beyond the powers of the troops to sustain.

Nussey et al. quote the view of Wachtel who, in the course of pointing out that a typical civilian population is more vulnerable to poison gas than troops, claimed: "In war men exposed to the gas are selected for their physical fitness, they are in perfect health and represent more or less exclusively a limited age group. The men between 21 and 35 years of age...". This may have more nearly applied to the British troops at Wulverghem than to the French troops at Ypres but even at Wulverghem one must doubt the validity of such an estimate.

4.10 Individual behaviour

Withers and Lees in their reconstruction of the Ypres attack place much emphasis upon their claim that the defenders were terrified by the gas and that they retreated in front of it. P. 313 "Nevertheless it had a terrifying effect upon the defenders", p. 319 "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". P. 320 "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 have assumed it to be smoke coming from fire in the German trenches or put up as a smokescreen and may well have only realised its toxic nature as the first wisps of gas caused them to cough".

These interpretations in the present author's view, take no account of the role of military discipline. To retreat without orders could lead to a firing squad. It does not seem reasonable that men would desert their posts in great numbers just because they saw what they thought was a cloud of smoke coming towards them.

The view that the troops fled before the gas reached them is contradicted by a witness whom Withers and Lees cite on p. 316. General Mordacq is reported there as claiming that he received a phone call from an officer in the front line 20 minutes after the attack started stating that his troops were then starting to leave their trenches.

It must be emphasised that the troops were totally ignorant about chlorine and its effects. If there had been a shout "C'est le chlore!" it would have meant absolutely nothing. Only after harsh experience either at first hand, or seeing its effects on others, would military discipline have broken down in the face of chlorine.

But there is a further, highly significant factor. The troops were deeply conditioned to regard trenches as places of safety. They knew that to raise one's head above the parapet was to invite sudden death. They therefore would not have left their trenches unless they had become places of danger, not of safety.

All observers are agreed that there had been a fierce artillery bombardment by the Germans all day which ceased shortly before the gas was released. The French would thus have been alerted to the possibility of a German attack. It is likely therefore that the appearance of the cloud, which would have taken some minutes to cross no-mans-land, would be interpreted by the French officers as a herald of some form of enemy activity. The standard reaction to this would be to order a "stand to" in which the support troops would be whistled up into the front to meet whatever emergency arose. However, once the cloud reached the trenches, and assuming, contrary to Withers and Lees model, that it was negatively buoyant and rolled down into them, then, within a very short time there would be something like total panic. This panic may later have communicated itself to unaffected troops but initially it must have arisen from the direct experience of being engulfed in chlorine.

A factor which seems not to have been discussed is the physical/mental condition of troops facing imminent attack. This state could be described as fear but the present author would prefer to describe it as "traumatic apprehension". Such a state would be accompanied by the secretion of adrenaline with effects on the heart and lungs. Such effects would be absent in animal experiments. Their effects on human mortality seems not to have been investigated.

It has to be said that any soldiers who fled from, and kept ahead of the gas cloud, should logically be excluded from the probit calculations, as they were subjected to a zero concentration of chlorine. Withers and Lees assume a purposeful retreat for those who were gassed. However, this may have little applicability to serious cases who probably staggered about, half blinded, and fell into trenches and shell holes. As Wren [30] put it "The gas billowed along the ground and rolled down into the trenches...screaming survivors clutched their throats as they ran blindly in crazy quilt patterns". The authors' picture of this retreat seems to assume that the men somehow instinctively grasped the best pattern of behaviour to adopt and were well versed in local topography. Neither of these may be true.

The assumptions by Withers and Lees that heavily gassed troops could gain more by retreat, as the lower concentration of gas more than made up for the extra effort involved, can only be rated as conjecture. It is an assumption which is contradicted by the Official History of War [23] which claimed on p. 178 "The worst sufferers were the wounded lying on the ground, or on stretchers, *and the men who moved back with the cloud*". (Present author's italics.)

The activity factors they use in their calculations relating to escape, for reasons explained in para 1.8.4, can only be treated as conjectural.

4.11 Social behaviour

This is difficult to assess. The behaviour of troops would be conditioned by esprit de corps and some who might have survived perished in helping their comrades.

4.12 Sample size

The sample sizes of the order of thousands would seem less open to criticism than many of the other factors discussed. It was large compared with most toxic incidents on record.

4.13 Planning of the "experiment"

The Ypres attack, though it may formally be regarded as an experiment, indeed it was described as such by Fritz Haber (Haber [18], p. 34), was not planned to determine the mortality arising from the release of a given quantity of chlorine. Its purpose was to determine the *military effects of such a discharge.* The kind of investigations conducted by Withers and Lees, Nussey et al. and the present author, are dictated by considerations of the present day and would be of a sort not necessarily envisaged by Fritz Haber who directed the technical, though not the military, preparations for the attack. Still less would they concern the German commanders.

4.14 The nature of the observers

It is therefore not surprising that, to this day, accurate figures of the total numbers gassed at Ypres are not available. The collection of such data on the German side, if it took place at all, would be the responsibility of the field commanders, not Fritz Haber. Thus most of the information which has been discussed in the recent papers referred to above arose adventitiously and not from scientifically trained observers. This is not to dismiss such testimony, as the views of unsophisticated observers who don't know what they are supposed to be seeing is often very valuable.

4.15 Reporting the results

4.15.1 The results of Ypres

4.15.1.1 Mortality fraction. In complete contrast with animal experiments where the numbers of those exposed and the numbers who die are accurately known, at Ypres neither of these sets of figures are known with any degree of accuracy. To make matters worse, if any cross-check of a probit is to be made, it is necessary to know the mortality fraction for a number of sub-groups representing different levels of exposure. If one also allows for the possibility that the positions of those found gassed differed from the positions in which they were when they first encountered the gas, then the problem is made even worse. Thus the mortality fractions would be fractions in which neither the numerator nor the denominator would be known with any degree of certainty.

4.15.1.2 How many French troops were there at Ypres? Withers and Lees claim that there were two French divisions at Ypres which would total about

20,000 men. British practice, according to Carrington [32] would have involved only about 10% of these, i.e. ca. 2,000, being in the front line trenches. This tactic of placing only a minor proportion of the troops in the firing line was determined by three main factors. First of all to commit all the troops to standing shoulder to shoulder along the line of the trenches would have created grave difficulties in responding to a break-through at any point at which the enemy chose to concentrate. Secondly it would have enormously increased the rate of attrition. Thirdly the troops would have been worn out by such continuous exposure.

The troops in the front line trenches, when in a defensive posture, would thus be more of a forward screen intended to delay an enemy attack until the reserves could be brought up. The French no doubt had a similar philosophy to the British but the actual number ratio of troops in the trenches to troops in the line may have varied.

Withers and Lees estimates of how many troops were exposed to gas seem contradictory. In their Table 2, p. 312, they allocate a total of 7,128 to the front line, i.e. 2 1/2 battalions, plus, say, 5,000 "in support" which they may mean in reserve at distances up to 1,500 to 2,000 metres and not affected by the gas. The proportion of front line troops, i.e. those in the front line and support trenches, seems very high by the standards of the British army but this does not disprove the figures. However, if they are too high this would seriously weaken Withers and Lees arguments. Later, p. 321, they seem to accept a figure of 6,000 for the numbers actually affected by the gas. How they establish their distribution in relation to the distance from the source of the gas is not clear from their paper.

4.15.1.3 The estimation of gas deaths. If there are difficulties over the estimation of the numbers affected, these are small in relation to the estimation of the numbers who died. The only reasonably certain figures are those reported as having died in Allied field dressing stations which totalled 163 out of 1,625 admitted. Less reliable are German figures of 12 deaths out of 200 treated. If these can be grouped together they correspond to a mortality fraction of 9.5% which corresponds to a probit of 3.7. It seems reasonable to assume that those who managed to reach the rear dressing stations were the sub-set of the exposed troops who were among the less affected. If we accept Withers and Lees estimate of 6,000 present and affected, then it would follow that of the remaining ca 4,400 more than 9.5% or more than 418, would die of gas. This would establish, by inference, the total deaths at more than 600. Haber [18, p. 244] estimates a total of 1,000 dead. In the present author's opinion this may be an underestimate. But no one today would support the figure of 5,000 which once gained credence.

Withers and Lees' attempt to arrive at more exact figures for those dead in the field by starting from their figure of 6,000 vulnerable troops and then subtracting those killed by other battle wounds = 300 (this is an arbitrary figure), the known gas deaths in dressing stations = 175, those who survived in dressing stations = 1,462, others (not specified) = 489 and prisoners not requiring treatment = 1,600. This gives a total of 1,786 gas dead on the field and a grand total of 1,961 gas dead.

However, the total of prisoners must have been swollen by the capture of the troops in reserve who are not counted in Withers and Lees' set of vulnerable troops, which would inflate the number of gas dead in the field, nor does it include those vulnerable troops who managed to escape unscathed which would reduce the number.

Haber [18] devotes an entire chapter to the difficulties in obtaining statistics on gas warfare during 1914–1918. It was only quite late in the war that the belligerents instituted a category of "gas dead" and so there are no official records of such a separate category for a year or so after the battle of Ypres. Obviously nothing in the nature of *post mortem* examinations were conducted in the field; only perfunctory examination was possible. It would have been a physical impossibility for Fritz Haber and his staff to have combed approximately 10 km^2 of battlefield to count and classify the dead. If we take the view that the German High Command wanted the military advantages of gas without the odium of admitting that it killed many soldiers, it might have been expedient for them not to want to know how many they had killed in this way.

The business of burying the dead was one relegated to the lowest class of troops who could no doubt be relied upon to get this highly unpleasant task over as quickly as possible with the minimum of questions. They probably treated the bodies of the despised Algerians with even less respect than customary. In the present author's view they probably used the abandoned French trenches as mass graves. These were, in the event, not disturbed by war for the next two years.

Even if further examination of the records could more closely bracket the number of dead on the field there is no means today of telling how many died of gas and how many died of other battle wounds.

4.15.1.5 Comparing probits. Withers and Lees calculations for Ypres are summarised in Fig. 6 in which the log of the concentration C which they calculate from their model, is plotted against the log of the distance D from the point of release. This is virtually a straight line relationship which suggests that C is a function of $D^{-0.8}$. The scale of the standard probit of Withers and Lees and the scale of the probit advanced by Ten Berge and Van Heemst are also displayed. An alternative form of these relationships are shown in Fig. 7 in which the two probits are plotted against the log of the distance.

The present author has conducted a rough calculation of the fractional mortality using these two probits on a battlefield using the Withers and Lees concentration/distance relationship and a range of distance from the source of

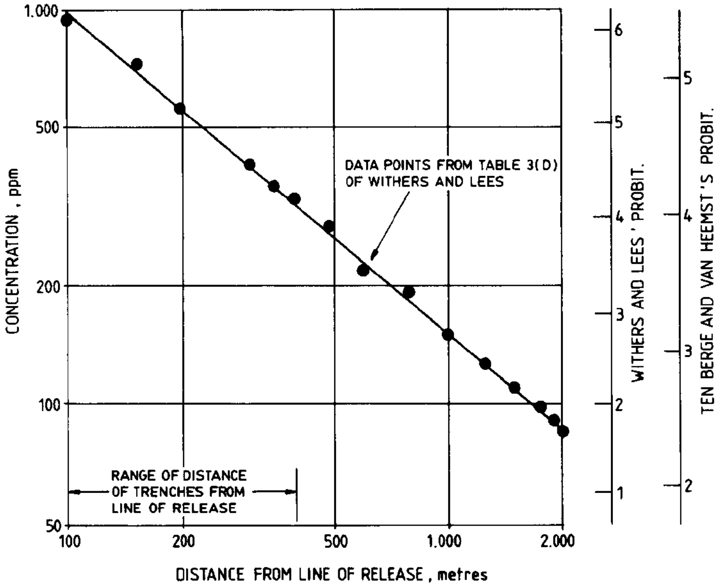

Fig. 6. Concentration of chlorine vs. distance at Ypres.

100 m to 1100 m. It assumes that the target population is evenly distributed and makes no allowance for escape. The calculation shows that the Withers and Lees standard probit would predict a mortality fraction of 0.14 whereas the apparently quite disparate probit of Ten Berge and Van Heemst would predict a mortality fraction of 0.12.

4.15.2 The results of Wulverghem

As compared with Ypres the problem of estimating casualties and mortality is relatively easy. This is because the attack was not succeeded by an enemy advance and hence there is no need to rely on two sets of data.

However, the problem of determining how many were present and affected is still not without difficulty as there is no satisfactory definition of "vulnerable", especially in terms of probits which do not recognise the existence of LC_{00}.

The Official History of the War [25] cited by Nussey et al., claims that 14,000 men put on respirators, though many were too far back to be affected. This gives an overall figure, including support troops, of ca. 4,500 soldiers per km of front which appears to be a somewhat higher density that at Ypres.

The number vulnerable to gassing may be derived from Withers and Lees' Table 5 as ca. 2,250 but this table does not account for all the troops who fell into that category. Nussey et al. provide no figures of vulnerable troops.

Casualties are given by both sets of authors as 512 of whom 89 (17%) died. Of the troops listed in Withers and Lees' Table 5 there were 330 casualties.

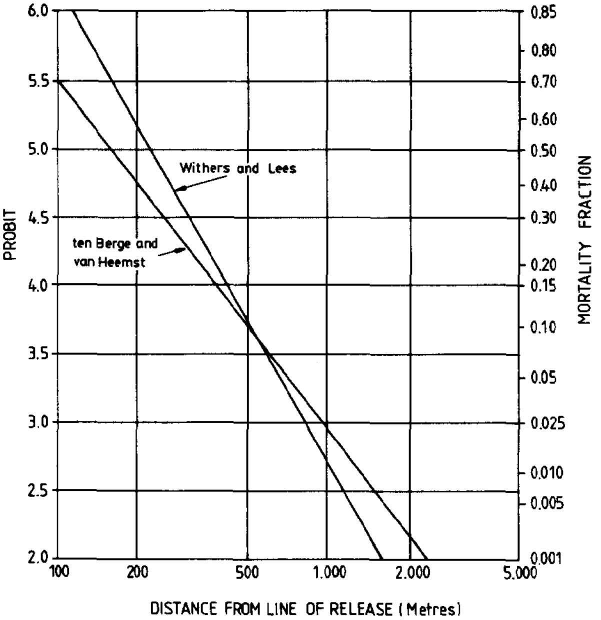

Fig. 7. Values of two probits vs. distance from line of release. (1) The scales of the probits in Fig. 6 and in the ordinate of Fig. 7 relate to the chlorine concentrations at Ypres inferred by Withers and Lees from their neutral buoyancy dispersal model, and assuming a duration of exposure of 7 min. (2) The Withers and Lees probit is that quoted in Section 3.2.1 of the present paper as applying to a regular population at a standard level of activity. (3) The Ten Berge and Van Heemst probit is that quoted in Section 3.2.2 of the present paper.

Withers and Lees note that their probit calculation suggested that the number of deaths should have been 267 compared with 89 who actually died.

Though Withers and Lees state that the quantity of gas discharged at Wulverghem is unknown, Prentiss [14], which is one of their references, gives the quantity discharged as 71 tonnes of chlorine/phosgene mixture. This is ca. 24 tonnes per km of front which is identical with the figure for Ypres. Prentiss' figure is adopted by Nussey et al.

From the point of view of mortality indices, for Ypres the mortality index was probably in the range of 6 to 12 fatalities per tonne whereas at Wulverghem it was about 1.25. The likely reasons for this are discussed below in the Conclusions section.

5. Conclusions

5.1 Relating the potential for harm to the degree of harm

There are many difficulties in establishing such relationships. Direct laboratory experimentation on humans, except at levels well below lethal levels, is out of the question. Studying the results of accidents has many problems. The data are usually statistically unsound and the level of harmful agent often has to be inferred. This leaves two other possibilities. One is to extrapolate the results of animal experiments. The other is to try to obtain data from warfare which is a form of socially sanctioned field experimentation.

In the particular field of interest of the present paper, the lethal effects of inhaled toxics, the data, compared with the data from drug testing for example, are very few. However, recent studies have gathered together such data as exist from experiments on the inhalation of chloring by chlorine. These are discrepant and there is no direct means of telling which results come nearest to the likely effect on humans.

Moreover when attempts are made to compare and analyse the mortality arising from incidents in which humans are exposed to gas, with the mortality in animal experiments, considerable differences are found. These arise from the great discrepancies which exist between the conditions of human populations exposed to gases and the condition of caged animals in laboratory experiments. These may be summarised under the headings of differences in environmental conditions, differences in individual susceptibility and differences arising from the methodologies of analysis. Sixteen such differences are tabulated in the paper which does not claim that the list is exhaustive.

5.2 Analysis of the Ypres and Wulverghem gas attacks

For the purposes of the present paper the two significant gas attacks were those of Ypres 1915, analysed by Withers and Lees, and Wulverghem 1916, analysed by both Withers and Lees and by Nussey et al. Withers and Lees were concerned to use the two battles to cross-check a probit equation they advance; Nussey et al. claim that their analysis of Wulverghem showed that chlorine toxicity data based on the Dicken criteria and with the dispersion models used by HSE produce predictions reasonably consistent with the historical experience.

5.3 Analysis of Ypres

5.3.1 The source term

The source term at Ypres is assumed by the authors to be neutrally buoyant at all points in the battlefield but this is criticised in the present paper as being not in accord with the evidence of observers. Nor do the authors give due attention to the confidence which can be attached to results of their dispersion calculations. The present author raises doubts as to the validity of other commonly used models when applied to the near field where the source term is that of a flashing liquid.

5.3.2 The influence of the environment

The present paper calls attention to the influence of the trench environment on the concentrations of gas to which the troops were exposed arguing that the trenches would be places of danger if the gas were negatively buoyant and places of shelter if the gas were neutrally buoyant and that both sets of conditions probably existed at different points in the battlefield.

5.3.3 The physical condition of the troops

The medical condition of the troops is analysed by Withers and Lees who give a rating to the troops which sets them on a par with a present day regular population, i.e. excluding old, young, and invalids. The present author contends that, though young or in middle life, their general condition would have been inferior to that of a similar age group today both because the general standard of health was lower in 1915 and also because trench life was very unhealthy. Their state of health would be inferior to that of present day laboratory animals.

5.3.4 The behaviour of the troops

Withers and Lees argue that many of the front line troops fled before the gas reached them. In the present author's view they would have been heavily conditioned by military discipline which would have required them to stand fast and also by harsh experience which taught them to regard the trenches as places of safety. They would thus have been most unlikely to have fled from their posts and left the safety of the trenches unless the chlorine had actually affected them. This would considerably affect predictions of mortality.

Withers and Lees devote attention to the ability of the troops to escape by running away but this causes them to introduce "activity factors" which increase the rate of up-take of chlorine and which counter-balance to some extent the relief occasioned by moving into a zone of lower concentration. Though endorsing in principle the correctness of introducing these factors, the present author is sceptical of the extent to which these effects may be quantified in the present state of knowledge. He also calls attention to the difficulties imposed by the tortuous nature of the trench systems and by the weight of the equipment the troops had to carry.

5.3.5 How scientific was the experiment?

The present author argues that Ypres was only partially a scientific experiment. The aims set by the scientists, who were only partially in control, have not been set down, but we can be reasonably certain that the soldiers who were in overall control were interested almost entirely in how much ground they gained and at what cost to themselves.

For this reason it is much to be doubted whether there was any systematic attempt to discover even the overall mortality fraction let alone the relationship between mortality fraction and distance from the point of discharge. We do not know whether even the scientists would have been interested. Perhaps both scientists and soldiers, because of the international odium attached to initiating gas warfare, preferred not to know.

5.3.6 How accurately can we determine the total numbers killed?

There are considerable difficulties attached to determining the numbers of battle dead let alone to determining the numbers killed on the battlefield by gas. The fraction of those killed on the battlefield who were killed by gas will never be known with certainty.

5.3.7 How many died of gas?

The only reasonably accurate knowledge we have is that of the minimum number who were killed by gas which can be set at 175. Inference suggests that Haber's figure of a total of 1,000 may be of the right order but is likely to be on the low side. The figure which once gained credence, namely 5,000, appears to be much too high.

5.3.8 Does the study by Withers and Lees cross-check their probit?

The study seems neither to cross-check nor to disprove their probit. This is because a whole family of probits could give predictions which could fall within the wide range of uncertainty surrounding the data associated with the chlorine gas attack at Ypres on April 22nd 1915. Moreover, it would be possible for a probit to be wrong and yet apparently predict correctly because of self cancelling errors as for example by the combination of a wrong probit with a wrong dispersion model.

5.4 The analyses of Wulverghem

5.4.1 Differences between Ypres and Wulverghem

Though Wulverghem is possibly the most fully documented of all official accounts of the gas attacks of World War I, there are compelling reasons why analysis of this attack is not capable of giving results which are meaningful in the determination of present day public policy regarding safety distances for chlorine.

5.4.2 Anti gas precautions

The first of these differences is that in the year which had elapsed since Ypres both sides had taken steps to counter the effects of gas. This was achieved by measures of discipline and training, by the institution of warning systems and, most importantly, by the provision of respiratory protection. These measures taken together ensured that gas did not become the dominant weapon of the war.

This is exemplified by the difference in mortality index between Ypres and Wulverghem though the rate of gas discharge and numbers of troops per kilometre of front were roughly the same. Because of the uncertainties already discussed, at Ypres the mortality index, fatalities per tonne, can only be bracketed between, say, 6 and 12. The corresponding, and reasonably reliable figure for Wulverghem is ca. 1.25.

It seems difficult to account for the five to tenfold reduction in fatalities if the probit equation and the dispersion model remain unchanged.

5.4.3 Was phosgene present?

The second problem is that there is strong evidence that the gas used at Wulverghem was not chlorine on its own but a mixture of chlorine with phosgene. Phosgene is about ten times as toxic as chlorine but, because of its relatively low volatility, it could not be used on its own except perhaps in hot weather.

Both sets of authors admit the possibility that the gas used at Wulverghem was not chlorine but a mixture of chlorine and phosgene. That the Wulverghem gas was a mixture is the view taken in Haber [18, p. 102] "For example the Germans used...phosgene/chlorine mixtures at...Wulverghem in April 1916 against which the "P" and "PH" helmets offered only limited protection".

The view that phosgene was present is given in Prentiss [14]. The data given in this latter reference, in Table XVII (p. 663), supports the view that after December 1915, chlorine was never used again on its own. The table shows that in all of the 18 cloud gas attacks by either side which took place between December 1915 and January 1917 the gases were mixtures of chlorine with phosgene. Thereafter the chlorine was sometimes mixed with chlorpicrin (CCl_3NO_2). On the other hand Foulkes is cited by Nussey et al. as saying two contradictory things – (1) "that in this battle (i.e. Wulverghem) it was thought that chlorine only was employed" and (2) "after the first few discharges on both sides (in the war) phosgene was added...the enemy varied his percentage according to the season of the year".

Withers and Lees cite "Diseases of the War" [29] as claiming that the clinical symptoms of Wulverghem were consistent with chlorine on its own. Yet p. 342 of Appendix 2 of Withers and Lees, which is an extract from [29], states "some of the severe casualties who reached the casualty clearing stations exhibited the pallor and collapse associated with phosgene poisoning; in a few cases cyanosis gave place to pallor before death... The clinical evidence therefore suggested that the gas cloud in this case *did not contain a very high proportion of phosgene to chlorine*". (Present author's italics.) If the Germans used chlorine on its own at Wulverghem this was contrary to their established pattern. But it cannot entirely be ruled out they may have been short of phosgene at the time. This could have meant that some cylinders contained chlorine only and some only a fairly small proportion of phosgene and thus that conditions differed in different parts of the battlefield.

5.4.4 Animal deaths

The Official History [23] gives a map which shows the positions at which farm animals died. Nussey et al. draw attention to this and point out that their dispersion model gives concentration levels much below the Dicken fatal threshold at these points. They seek reasons and one which they advance is that the gas may, after all, have contained phosgene. But, if so, what becomes of some of their other arguments? Can the Dicken fatal threshold be verified if this be the case?

An alternative which they do not advance is that their dispersion model could have been wrong. Yet, on p. 204, they attribute to McQuaid a statement that predicted concentration levels may differ by a factor of 10. This they use to justify a concept that the criterion could be the combination of a predicted, concentration level with a threshold level of mortality even though neither may be validated.

5.4.5 Withers and Lees conclusions

From an examination of a portion of the front, Withers and Lees assuming that only chlorine was present, using a standard level of activity for the troops and applying their previously discussed probit, predict 267 deaths against an actual total of 89. They were thus out by a factor of 3. For this they offer two explanations, (a) errors in calculating the gas concentration, (b) the use of respirators.

Withers and Lees' calculation of the gas dead at Ypres was 1,961 which constitutes a mortality index of 1,961/168 or 11.5. They make no attempt to explain why the mortality index at Wulverghem was only one ninth of this figure.

5.4.6 Nussey et al.'s conclusion

These authors claim that analysis of the Wulverghem battle supports a combination of the Dicken criteria with current Health and Safety Executive dispersion models, even if these are not independently validated. The Dicken criterion for mortality is the onset or threshold value for mortality.

It is the present author's view that conclusions cannot validly be drawn about the lethal toxicity of chlorine through the study of an incident in which it is not known whether the gas involved was in fact chlorine or whether it was an admixture, in unknown proportions, with phosgene, a much more toxic gas.

Moreover there are not any data of a quantified nature which treats the efficacy of the respiratory protection provided.

The Wulverghem battle presents a tangled web of uncertainties. If phosgene were present, this would have increased mortality above that predicted for chlorine; if respirators were worn, this would have reduced mortality if the gas were chlorine alone. However, if phosgene had been present, mortality might not have been reduced by wearing respirators because the respirators used, according to Haber [18, p. 102], though effective against chlorine, were less effective against phosgene. This circumstance may account for observations by Nussey et al. [p. 214] that men wearing respirators died and that deaths occurred at low predicted concentrations. An additional problem is that there seems to be little data on the symptoms exhibited by the victims of chlorine/phosgene mixtures as opposed to those arising from each gas on its own.

5.5 Probits and the Dicken criteria

5.5.1 Probits applied to Ypres

Probit analysis attempts to relate fractional mortality to a couplet of exposure concentration and duration in which the couplet has the general form: $\sum C^m T^n$. For convenience, and assuming that C does not vary during the duration of exposure, this may be reduced to $C^m T$. Under idealised conditions, for the line sources used, the field of exposure may be treated as a rectangle with one side being normal to the direction of the wind. If this rectangle then be divided into parallel strips with sides normal to the direction of the wind then each strip could have calculated for it, using an appropriate dispersion model, a mean concentration of chlorine. This technique was used by the present author above in para 4.15.1.5.

If the duration of exposure is deemed to be known then, for each strip, the fractional mortality should, in principle, be possible of calculation. A cross-check of the probit for each strip would comprise a comparison of the predicted mortality fraction with what actually occurred. This was not attempted by Withers and Lees and, in the present author's view, given the chaotic conditions of the battlefield, it would be impossible to do so.

A summation of the mortalities calculated for each strip would then be the predicted total mortality for the incident. Comparison of this with the actual mortality would provide a cross-check, though a much cruder one, than would be achieved by individual comparisons, strip by strip. This is because a whole family of probits could produce the same summations even though they differed markedly in their predictions for each strip. The most that could be claimed is that such a cross-checking of summations would not *disprove* the validity of a given probit.

How far did analysis of Ypres on these lines justify Withers and Lees' claims? The answer is that it did not.

To produce such an overall cross-check requires that the overall total of gas deaths be known. It must be said that this is a question which had not hitherto been answered with assurance by the military historians who have put forward figures ranging from 350 to 5,000. The authors therefore had to make their own computation which was 1,961. The present author has argued earlier that the methodology they used was unsound and that there is no reliable figure for the Ypres gas deaths. There is therefore no possibility of an overall cross-check.

But even if the figure of 1,961 actual fatalities as computed by the authors be accepted does it cross-check with their overall predicted figure? The authors, in their Table 3, give 7 scenarios in which there are a limited number of permutations of the factors cloud entry point, walking speed, level of activity and toxic load factor, to give numbers of deaths ranging from 1,961 to 5,600. The authors say that they judged their Scenario 1 with a death toll of 1,961 to be the most credible. So a figure of 1,961 estimated death cross-checks with a figure of 1,961 predicted deaths. In fact both of these figures must be subject to considerable doubt, and as is pointed out above a whole family of probits could provide the same estimated overall total deaths.

5.5.2 Probits applied to Wulverghem

At Wulverghem the total number of gas fatalities is known with some degree of reliability. Withers and Lees had to compare their predicted overall mortality of 267 with the actual mortality of 89. They were thus out by a factor of 3 as has previously been noted.

5.3.3 The Dicken criteria at Wulverghem

Though Nussey et al. comment that the incidence of coughing agreed with the Dicken criterion for this sympton, this paper is concerned with mortality only. The authors give a table of *casualties* at various distances from the release front with predicted ranges of concentration of chlorine but do not locate the line of transition from casualties with fatalities from casualties without fatalities. As has been discussed in detail above, the authors are unable to be sure whether the gas was chlorine or a chlorine/phosgene mixture. Moreover the predicted concentrations listed have a range of 3:1. The present author has concluded that the uncertainties at Wulverghem invalidate any conclusions which the authors draw.

5.5.4 The Dicken fatality criterion of lethality and the Ten Berge probit

Figure 8 shows a plot of the Dicken criterion of threshold fatality together with the Ten Berge LC_{01} as calculated by the present author, together with the straight line presentation of it in Nussey et al. Because Dicken's criterion is a curve, it is mathematically incompatible with a probit but this does not mean that it may not, over a range, generate similar results. Dicken's curve may correspond, in its form, more closely to reality than a probit because it is compatible with a threshold limit in a way that a probit is not.

What Dicken's criterion and Ten Berge's probit have in common is that they may both relate to individuals to which some or most of the conditions listed in the present author's Table 1 may not apply. Thus there is a minimum difference between their condition and that of a laboratory animal. They would

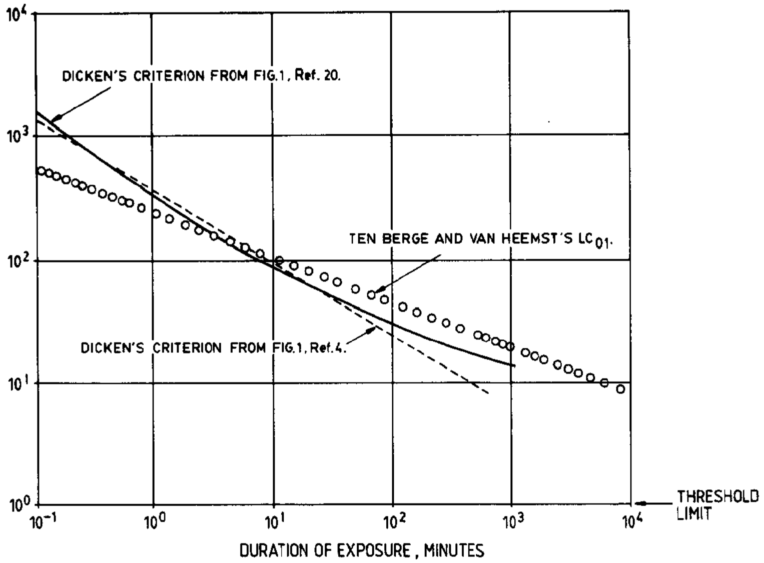

Fig. 8. Dicken's lethal criterion compared with Ten Berge and Van Heemst's LC_{01}.

apply to individuals caught in the open, disoriented in relation to the source, lacking a place of escape and dying before they can be rescued.

Such individuals would suffer a low probability consequence of what is, in industrial terms, a low frequency event.

5.6 Criteria of lethality, a general critique

Probits, as a measure of the effects of harmful agents, rest upon three basic assumptions. The first is that there is, for any given physiological effect, a relationship between the intensity of the agent, I, and the duration of exposure, T, which has the form I^mT. The second is that susceptibility is governed by a log/normal distribution. Neither of these has any *a priori* basis and they may be merely approximations of convenience. As such they may have become so widely, and uncritically, accepted that deviations from them are dismissed as abberations.

The third assumption is that probits from animal experiments may be applied to human populations. The earlier part of the present paper has been devoted to the analysis of those factors which would, taking account of the special features of humans as social animals, modify animal derived probits. Sixteen such factors are disclosed.

The present author has concluded that probits advanced in the literature convey a totally misleading picture of accuracy and are of dubious value.

The analysis of the World War I battles of Ypres and Wulverghem which have been adduced in the paper by Withers and Lees as a cross-check on such a probit for chlorine lethality are dismissed by the present author as invalid notably because of their failure to take full account of the difficulties of analysing these incidents.

The Dicken criterion of threshold lethality does not have any clear scientific basis and is put forward solely on the claim that it is based upon experience and private communications. As such it may be a useful practical guide but it can hardly be accepted as a basis for the formulation of public policy. The claims by Nussey et al. that the analysis of the battle of Wulverghem confirms this criterion are rejected by the present author on the grounds of the massive uncertainties surrounding that battle.

6. Recommendations

6.1 The limitations of quantifying relationships

It is very important, if the science of prediction is to advance, that those who put forward quantifying relationships should clearly state the circumstances to which they apply. This requires that the factors set out in the present author's Table 1, and others which may later be established, be examined for their applicability to the case under investigation. Thus a probit for fatal injury by inhaled chlorine, in the negatively buoyant regime, for troops in trenches without respirators, may have some meaning whereas a generalised probit has not. Probits should be accompanied by an assessment of their confidence limits. As a minimum requirement this should be disclosed by the number of significant figures to which the constants and exponents are expressed.

Otherwise there may be confusion and a belief may spring up that a probit is universally applicable and is known with the accuracy of, say, a heat transfer coefficient. As a consequence, in the hands of well meaning amateurs, probits may be used in a way which will be embarrassing to companies and to public authorities alike.

6.2 Further studies on flashing liquids

The present author recommends that there should be a re-examination of the behaviour of vapour clouds arising from flashing liquids, in the near field, negatively buoyant regime, in order to guarantee that dispersion models predict this behaviour correctly. The study should include the determination of criteria of the characteristics of the transition between the negatively buoyant and neutrally buoyant regimes.

The analysis could include information from manufacturers and users on the observed fluid mechanics of such vapour clouds including their behaviour on encountering obstruction including trenches. It should be noted that this latter problem has present day significance in chemical works and petroleum refineries where it is a common practice to run pipes in trenches.

The subject should also be explored by experiment to supplement the results of the Thorney Island trials by including data for the near field for flashing liquids.

A search should be made to see if the report of the Runcorn, 1915, chlorine trials still exists.

Acknowledgement

Figure 4 is reproduced by kind permission of the Imperial War Museum, Lambeth Road, London.

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