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A "worst case" methodology for obtaining a rough but rapid indication of the societal risk from a major accident hazard installation

I.L. Hirst*, D.A. Carter

Methodology and Standards Development Unit, Hazardous Installations Directorate, Health & Safety Executive, St. Anne's House, Stanley Precinct, Bootle, Merseyside L20 3RA, UK

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Abstract

This paper describes a methodology developed to provide a rough but rapid indication of the magnitude of the societal risks at and in the vicinity of a major accident hazard installation. It is intended to be used by the UK Health & Safety Executive (HSE) as a first screening tool when examining safety reports submitted under The Control of Major Accident Hazards (COMAH) Regulations 1999. These are the Regulations which implement in the UK the major aspects of Council Directive 96/82/EC, the "Seveso II" Directive. Within the methodology a new weighted risk integral parameter is defined, suitable for comparison with criteria, and its value calculated. The paper includes examples to illustrate the use of the methodology.

Keywords: Quantitative risk assessment; Major hazards; Societal risk; Methodology

1. Introduction

However much care is taken in designing, constructing and operating an installation that uses large quantities of dangerous chemical substances, there remains a possibility that a release will occur resulting in a multi-fatality accident. The best available technology for studying this "societal risk" is full scope application of quantitative risk assessment (QRA). However, the technique is time-consuming and requires a high level of technical capability. Given the realities of limited time and money, operators of some such installations have been reluctant to embark on such a course in preparing the safety reports they are required to submit to the UK Health & Safety Executive (HSE) under The Control of Major Accident Hazards (COMAH) Regulations 1999. Recognising this, the Methodology and Standards

* Corresponding author.

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Development Unit (MSDU), previously the Major Hazards Assessment Unit, of the HSE has developed a methodology that can be applied by HSE to provide a rough but rapid indication of the magnitude of those risks, as a first screening tool, and thereby decide an appropriate regulatory response. Within the methodology a new weighted risk integral parameter is defined, suitable for comparison with criteria, and its value calculated. If the value is sufficiently low then HSE might be satisfied that nothing further is required. But if it is high, a more comprehensive site-specific risk assessment may be deemed necessary. Definition of criteria for “sufficiently low” and “high” in this context are operational policy matters for HSE and are beyond the scope of this paper.

The methodology assumes, on the basis of existing studies of past accidents and existing results of detailed QRAs, that sites handling dangerous chemical substances have *F–N* curves of certain characteristic shapes. Making this assumption for the particular site of interest and coupling it with site-specific calculations of the single worst case accident allows the risk integral parameter to be estimated quickly. The following sections set out the background to the methodology, describe it in detail and show two examples to illustrate its application. Finally, the methodology is benchmarked against an exact calculation of the risk integral parameter, using the results of a full QRA.

2. F–N plots as depictors of societal risk

It has already been noted that the best available technology for studying societal risk is full scope application of quantified risk assessment. Such studies lead to a relationship between the number of fatalities (N) that can follow a major accident, ranging from 1 to some maximum value ($N_{\max}$) and the frequency (f) (lower-case) at which that number of fatalities is estimated to occur. This relationship or more usually the corresponding relationship involving F (upper-case), the cumulative frequency of events having N or more fatalities, is usually presented as a graph with log–log axes.

Examples of *F–N* plots are shown below. Those in Fig. 1a and b have been generated algebraically and are typical of examples that occur in the literature. The first shows the relationship (upper-case) $F(N) = 100/N$, truncated at $N_{\max} = 500$. The second was constructed by starting from (lower-case) $f(N) = 100/N^2$, truncated at $N_{\max} = 500$; the values of $F(N)$ were then calculated by spreadsheet using the definition $F(N) = f(N) + f(N+1) + f(N+2) + \cdots$ and so on. In both cases, $f(N) = 0$ for $N > N_{\max}$. The vertical axes have units of “cpm per year”, that is, “chances per million per year”. It can be seen that in the first example the *F–N* plot has a slope of -1 over all of its length and that in the second example it has a slope of -1 initially but falls away steeply as $N_{\max}$ is approached.

Fig. 2 is an example of an *F–N* plot calculated using a detailed QRA, incorporating the impacts of a wide range of accidents on a population living near to a site with bulk storage of a liquefied toxic gas. Similar to the plot in Fig. 1b, that in Fig. 2 has a slope of -1 initially but falls away steeply as $N_{\max}$ is approached.

F–N curves may also be used to show the consequences of real accidents that have occurred at installations using dangerous substances. Two studies are available.

Firstly, a report published by one of the Joint Research Centres of the European Community [1] describes a study of 159 accidents involving flammable substances and 84 accidents

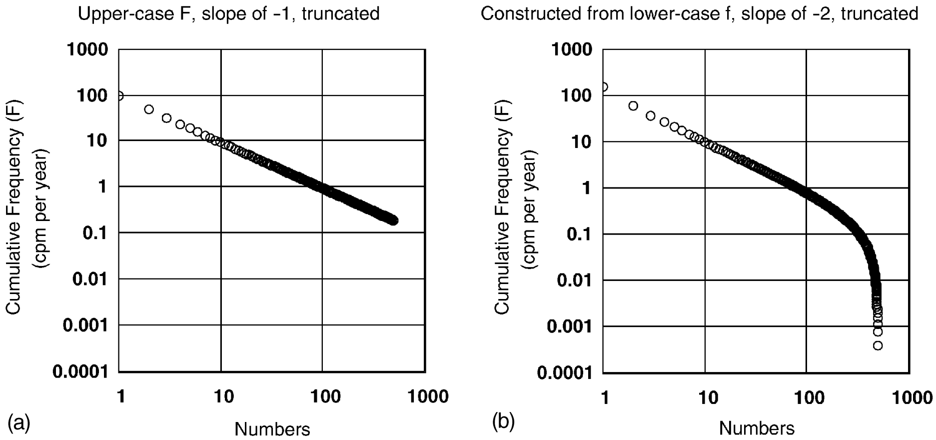

Fig. 1. (a and b) Algebraically-based examples of *F–N* plots.

involving toxic substances, all of which resulted in fatalities. Fig. 3a below is a reconstruction of a figure from that report, supporting the study's conclusion that the *F–N* plot for the accidents involving flammables was close to a straight line of slope −1 up to the maximum number of fatalities, whilst that for the accidents involving toxics was of similar slope but tended to fall away more steeply as the number of fatalities increased.

Secondly, we have ourselves performed a similar study using our Major Hazard Incident Data Service (MHIDAS) database [2], which records details of accidents involving dangerous substances that have resulted in a significant impact on the public at large. It contains

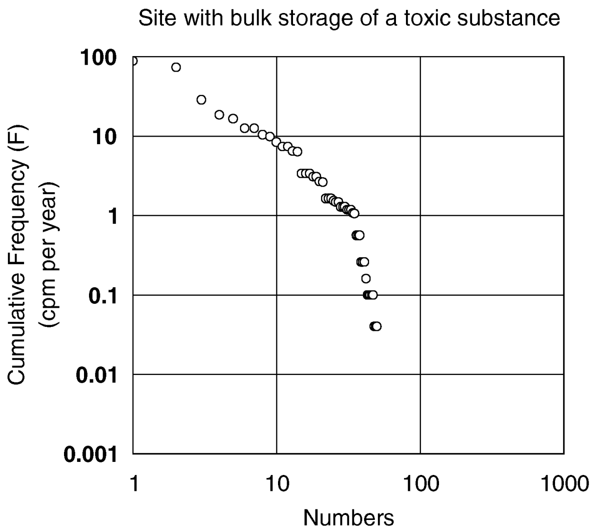

Fig. 2. QRA-based example of an *F–N* plot.

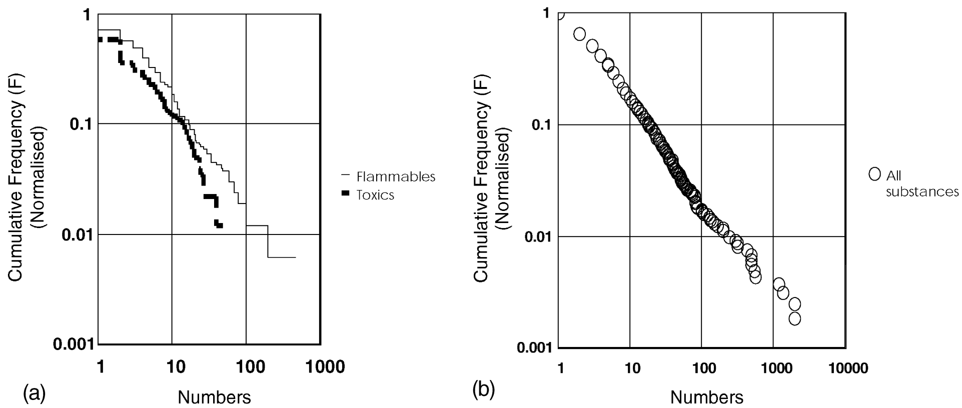

Fig. 3. (a and b) Experience-based *F–N* plots.

incidents from throughout the world and particularly the UK, USA, Canada, Germany, France and India. The compilation was started in the early 1980s, but there are references to incidents going back to the early years of the 20th century. From over 8000 records in the database (in 1994), we have extracted over 1600 accidents that resulted in fatalities. An *F–N* plot for these accidents is shown in Fig. 3b. The plot is seen to be remarkably close to a straight line of slope −1 over its whole length. Separation into accidents involving flammables and accidents involving toxics was not possible within the limitations of our study.

Plots such as those in Figs. 1–3 are frequently encountered and are generally recognised as valuable devices for presenting the societal risk from hazardous installations in a concise form.

They could be taken, moreover, to suggest that the *F–N* plots of hazardous installations have two characteristic forms; either a slope of about −1 up to some value of N_{max} or a slope that is initially about −1 but that falls away more steeply as N_{max} is approached. We rationalise this by noting that for some events, typically omni-directional events, such as fireballs and vapour cloud explosions, the maximum hazard potential is clearly defined, whereas, others which are strongly uni-directional, such as toxic gas clouds and flash fires, are subject to orientation and ambient variability. This observation will be picked up and developed later in the paper.

3. F–N plots as criteria for tolerability of societal risk

Separately, *F–N* curves are occasionally proposed as criteria for judging the tolerability of societal risk from an installation. Plots such as Fig. 4 are shown, delineating three regions within which the risks are described as “unacceptable”, “tolerable if ALARP”[1] and “broadly acceptable”. However, there are different ways of using a criterion line and the intended method of use is often not stipulated.

[1] ALARP: as low as reasonably practicable.

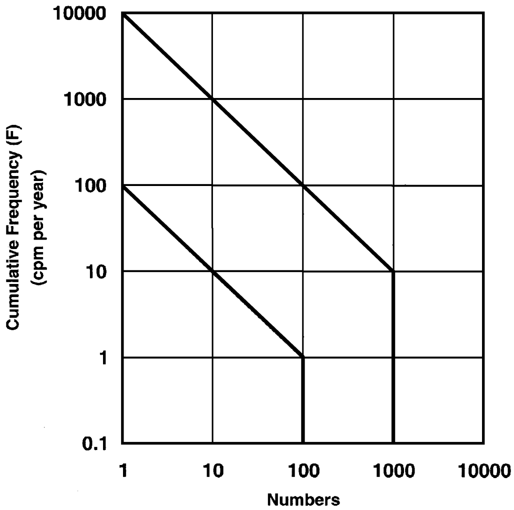

Fig. 4. *F–N* plots that have been proposed as tolerability criteria.

One way of using a criterion line would be to require that for an installation to be acceptable its *F–N* curve should be everywhere below the criterion line. Alternatively, it might be sufficient that the *F–N* curve of the installation be below the criterion line in some integral sense, allowing it to be above the line locally provided it is sufficiently far below the line elsewhere.

The first way of using the criterion line is the simplest, but it has been shown by Evans and Verlander [3] that it can be lead to decisions that appear unreasonable and, more seriously, to decisions that are inconsistent; they go on to suggest that it would be preferable to use a criterion based on an "expected utility function". According to classical decision theory, tolerability decisions should be made on the basis of expected utility if their consistency is to be assured [4].

In decision theory, "utility" is a number that expresses the merit or attractiveness of a consequence. If there are n different consequences with likelihoods $f(1),\ldots, f(n)$ and utilities $u(1),\ldots, u(n)$ then the expected utility is the value of:

$$\sum_{i=1}^{n} f(i)u(i).$$

In the present context, where the consequences are accidents with multiple fatalities, the term "disutility" seems more appropriate and will be used from here on, following [3].

For a number of years, in formulating advice on major accident hazard installations to local planning authorities, the HSE has been using a "risk integral" which has been shown elsewhere [5] to be a disutility function. We discuss below a number of other disutility functions that may be suitable for the present purpose.

One measure of the societal risk from an installation could be obtained by calculating the expectation value (EV) of the number of fatalities per year from accidents involving the dangerous substances. The EV is sometimes called the fatal accident rate (FAR) and sometimes the potential lives lost (PLL). If the *F–N* curve of the installation is known then the value of the EV can be calculated. Thus,

$$\mathrm{EV} = \sum_{N=1}^{N_{\max}} f(N)N.$$

The EV can be seen to have the form of an expected disutility function, with the number of fatalities (*N*) being used as the measure of disutility. It could, therefore, be used in a tolerability criterion, the risk from the installation being judged tolerable if the EV is less than some agreed criterion value.

However, a criticism that could be made of using the EV as a criterion for societal risk is that it does not include an allowance for aversion to multi-fatality accidents. It gives equal weight to the frequencies and consequences of accidents. By not distinguishing between one accident causing 100 fatalities and 100 accidents each causing one fatality over the same period of time, the EV fails to reflect the contrast between society's strong reaction to major accidents that occur occasionally and its quiet tolerance of the many small accidents that occur frequently.

The view that more weight should be given to the consequences of accidents than to their frequencies is widely held. In fact many countries in Europe disregard numerical estimates of frequencies almost completely, as did the UK's Advisory Committee on Major Hazards in its First Report [6], "hazards should be minimised", and in its Third Report [7], "if the possible harm from an incident is high, the risk that the incident might actually happen should be made very low indeed".

Recognising this, risk assessment practitioners have suggested using instead of the EV an "enhanced EV" which gives greater emphasis to the number of fatalities. In [8], for example, Okrent suggests using:

$$\text{“equivalent social cost”} = \sum_{\text{accidents}} f(N)N^a,$$

which resembles the EV but has the number of fatalities raised to some power >1. Quoting other sources, Okrent notes that values of "*a*" as high as 2 or 3 have appeared in the literature, but he adds that adoption of a value at the higher end of this range would prohibit many existing technological endeavours and would be beyond what society could afford.

At this stage we make the decision to define an enhanced EV, which we shall call the Risk Integral (COMAH) and denote by $\mathrm{RI}_{\mathrm{COMAH}}$, as follows:

$$\mathrm{RI}_{\mathrm{COMAH}} = \sum_{N=1}^{N_{\max}} f(N)N^a.$$

The value of "*a*" will be something >1; we will make a decision later in the paper.

Our $\mathrm{RI}_{\mathrm{COMAH}}$ has the form of an expected disutility function and therefore provides a sound basis for consistent decision making. If the *F–N* curve of the installation is known the value of $\mathrm{RI}_{\mathrm{COMAH}}$ for the installation can be calculated from it. Similarly, from a criterion *F–N* line a criterion value of $\mathrm{RI}_{\mathrm{COMAH}}$ can be derived. Requiring "installation $\mathrm{RI}_{\mathrm{COMAH}}$" to be less than "criterion RI_{COMAH}" is tantamount to requiring the *F–N* plot of the installation to be below the *F–N* criterion line in an integral sense; the plot may be above the criterion line locally provided it is sufficiently far below it elsewhere.

All that is now required for completeness is a means of estimating RI_{COMAH} for an installation whose *F–N* plot is not known. We describe our methodology below.

4. Overview of the new methodology

The methodology requires that firstly, for the installation in question, the worst case (that is, maximum number of fatalities) accident is identified, using judgement and past experience of installations of a similar nature. For this accident, site-specific calculations are then performed in which the accident consequence footprint is overlaid on a map showing the surrounding populations. Where the footprint is elongated, it must be orientated as necessary to capture the greatest number of persons within it. Arrangements for storing and using the dangerous substance on the site are also examined. These considerations lead to estimates of the severity and the likelihood of occurrence of the worst case accident; in effect, we have located the right-hand end of the *F–N* plot.

An assumption is then made about the form of the *F–N* plot, based on the observations recorded in the first part of this paper. We assume that if the worst case accident is an omni-directional event then the *F–N* plot will be approximated by the theoretical approach underlying Fig. 1a, that is, by assuming an (upper-case) *F–N* plot of slope -1, whilst if the worst case accident in a uni-directional event then the *F–N* plot can be better approximated by the theoretical approach underlying Fig. 1b, that is, by assuming a (lower-case) *f–N* plot of slope -2.

We now have sufficient information to estimate our risk indicator RI_{COMAH}. But as we have made an assumption about the shape of the *F–N* curve that would not have been necessary if it had been calculated rigorously we refer to the approximate RI_{COMAH}, or ARI_{COMAH} for short.

A more detailed description of the methodology and examples of its application follow.

5. Details of the method of application

The dimensions of the worst case accident footprint are calculated using the appropriate fire, explosion or toxic gas dispersion model, the endpoint being that thermal dose, over-pressure or toxic dose that corresponds to the LD_{50}. Allowance is made for attenuation of toxic dose for an indoor population when appropriate (e.g. a residential population at night). The number of survivors within the contour is assumed to equal the number of fatalities outside the contour. This will be cautious in most cases. We now have the value of N_{max}.

The frequency of the worst case release is then set using either the generic value normally used in MSDU's QRA methodology RISKAT [9] or a site-specific value if sufficient information is available to satisfy HSE that that value is warranted. Where the consequence is uni-directional additional multipliers are then introduced, making the frequency of the worst case accident equal to:

failure frequency (RISKAT or site-specific) × conditional plume probability
×weather and windspeed probability × wind rose bias factor
×population distribution factor.

The conditional plume probability is the fraction of the complete 360° circle which the plume occupies at the distance of its maximum width, calculated from:

$$\frac{2 \times \arctan\,(\text{max plume half width}/\text{distance to max plume half width})}{360}.$$

The weather and windspeed probability is the likelihood of the atmospheric stability and windspeed combination that gives the worst case consequence, obtained from the RISKAT data file appropriate to the locality of the installation. This could be the frequency of F2 conditions if the event is dispersion of a dense gas or perhaps the frequency of D15 conditions if the concern is knock-down of a buoyant fire plume.

The wind rose bias factor takes account of any bias in the wind rose. This too is taken from the RISKAT data file appropriate to the locality of the installation. If the wind rose is uniform then this factor should be set to 1. But if there is a non-uniformity in the wind rose, giving a lesser or greater likelihood that the wind will blow in the worst case direction, the factor should be set less than or greater than 1 accordingly. A value of 0.9, for example, would signify that the likelihood of the wind blowing in the worst case direction is 90% of what it would be if there were no bias.

The population distribution factor reflects whether a small deviation in the direction of the worst case plume could produce a significant change in the number of persons caught within it. If a significant change would not occur then the factor should be set equal to 1. But a significant change could occur when the population of interest is localised and in the far field of the hazard range. Practice has shown that in these circumstances a value for the factor as low as 0.2 could be appropriate. The value to be used in a particular case should be judged by visual inspection, with a value of 0.5 being typical.

We now have the values of $N_{\max}$ and $f(N_{\max})$, and so are in a position to evaluate our risk indicator $\mathrm{ARI}_{\mathrm{COMAH}}$. Details of the derivation of the required formulae are contained in Appendix A. It is sufficient to state here that where the consequences of the worst case accident are omni-directional then:

$$\mathrm{ARI}_{\mathrm{COMAH}} = f(N_{\max})N_{\max}\left[\sum_{N=1}^{N_{\max}-1}\frac{N^{a-1}}{N+1} + N_{\max}^{a-1}\right],$$

and that where they are uni-directional:

$$\mathrm{ARI}_{\mathrm{COMAH}} = f(N_{\max})N_{\max}^{2}\sum_{N=1}^{N_{\max}}N^{a-2}.$$

Neither of the formulae can be simplified further and their evaluation by hand is not practicable. So a suitable BASIC routine is given in Appendix B. The Appendix also contains sample inputs and outputs, which may be used to verify correct implementation.

But we have yet to make our choice of the constant "a".

6. Choice of the constant "a"

When earlier in the paper we defined our risk indicator RI_{COMAH} we postponed until later our choice of the constant "a". It will be recalled that the role of "a" is to introduce scale-aversion into our risk indicator. If there were no scale-aversion ($a = 1$) then our risk indicator would be simply the EV. With scale-aversion ($a > 1$) the EV is enhanced and the higher the value of "a" the greater is the enhancement. Using our BASIC software routine we have calculated the factor by which the EV is enhanced, with different values of "a" and over ranges of values of N_{max} and $f(N_{max})$ that we expect to encounter in practice. Having done so we have decided to set $a = 1.4$.

The justification for our choosing this value of "a" is illustrated by the following table, which shows the results of five of the cases we examined, spanning a range of N_{max} with $a = 1.4$. The values of $f(N_{max})$ were chosen so that all five cases have the same value of EV.

N_{max}	1	10	100	1000	10000
$f(N_{max})$ (cpm per year)	1000	34.1	1.93	0.133	0.0102
EV	1000	1000	1000	1000	1000
ARI_{COMAH}	1000	1898	3598	6913	13854
Scale-aversion enhancement factor	1	1.9	3.6	6.9	13.9

It can be seen that with this choice of "a" the scale-aversion enhancement factor is between 1 and 10 for the great majority of cases that we expect to encounter and will exceed 10 only in exceptional circumstances. We believe this to be reasonable.

Greater enhancement may be appropriate for particular installations where the adjacent population has sensitive components, such as schools and hospitals.

7. F–N example criterion lines

It is noted here that with $a = 1.4$, the value of ARI_{COMAH} for the lower of the two example criterion lines shown in Fig. 4 is just under 2000 and the value for the upper line is just over half a million.

8. Use of the methodology: example 1—LPG

A (fictitious) site uses a large sphere for storing LPG at ambient temperature. The worst case is a BLEVE of the sphere, for which the hazard range (to a thermal dose of 1800 $(kW/m^2)^{4/3}$ s) is about 700 m in all directions. Overlaying the footprint on a map of the locality (Fig. 5), we find that the number of persons captured within it (N_{max}) is about 500.

The frequency ($f(N_{max})$) for a BLEVE of the sphere is 10 cpm per year.

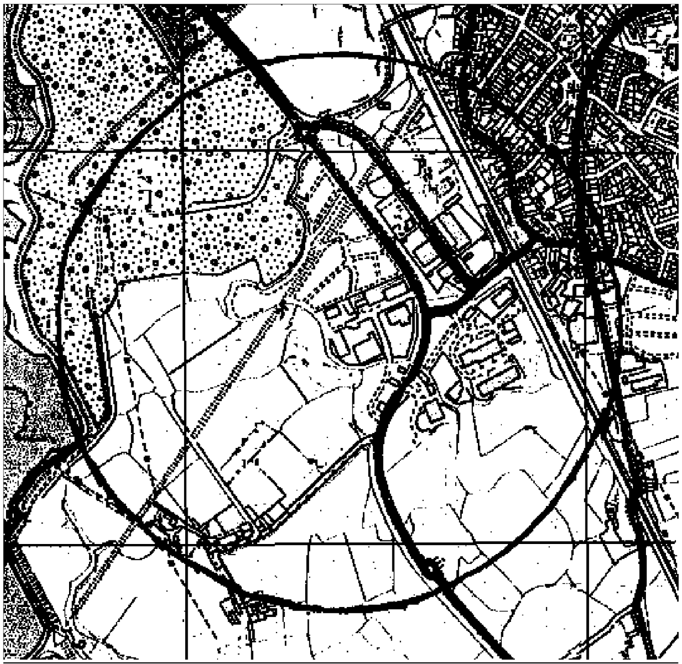

Fig. 5. LPG example.

With $N_{\max} = 500$, $f(N_{\max}) = 10$ cpm per year and an omni-directional consequence, the value of $\mathrm{ARI}_{\mathrm{COMAH}}$ is about 193,000 and the scale-aversion enhancement factor about 5.7.

Compared with the example criteria derived from the *F–N* plots in Fig. 4, this site would be deemed in the "tolerable if ALARP" region and consideration of additional risk reduction measures would be expected.

9. Use of the methodology: example 2—chlorine

The worst case for a bulk liquefied toxic gas installation is a major failure of one of the storage vessels at a time of stable weather and low windspeed.

A (fictitious) site has two vessels each containing 25 t of chlorine in an open air location. For a catastrophic failure of one vessel at a time of F2 weather the LD_{50} contour for an indoor recipient population is calculated to be 1900 m long with a maximum width of 1000 m at a distance of 950 m. Damage causing a large hole near to the base of a storage vessel would have a very similar footprint. Overlaying the footprint on a map of the locality (Fig. 6) and trying different orientations, we find that the maximum number of persons that could be captured within the plume ($N_{\max}$) is about 50.

The worst case event frequency is determined by:

$$\text{failure frequency} = 10\,\text{cpm per year (comprising 2 cpm per year for catastrophic failure} \\ +3\,\text{cpm per year for a large hole, per vessel)},$$

$$\text{conditional plume probability} = \frac{2 \times \arctan(500/950)}{360} = 0.15,$$

$$\text{probability of F2 weather} = 0.14,$$

$$\text{wind rose bias factor} = 1.0\ \text{(no bias)},$$

$$\text{population distribution factor} \\ = 0.2\ \text{(localised population in the far field of the hazard range)}.$$

The worst case frequency ($f(N_{max})$) is the product of the above, about 0.04 cpm per year.

With $N_{max} = 50$, $f(N_{max}) = 0.04$ cpm per year and a uni-directional release, the value of ARI_{COMAH} is about 1000 and the scale-aversion enhancement factor about 2.2.

Compared with the example criteria derived from the *F–N* plots in Fig. 4, this site would be deemed in the "broadly acceptable" region and consideration of additional risk reduction measures would not be expected.

Fig. 6. Chlorine example.

10. Benchmarking of the methodology against a full QRA

The site used in the second example above has been subjected to a full QRA and the whole of its *F–N* curve is, therefore, known. The *F–N* curve is in fact that shown as Fig. 2 of this paper. Knowing the whole of the *F–N* curve allows RI_{COMAH} to be calculated exactly. The value obtained is 836, which compares favourably with the value of "about 1000" derived with our approximate methodology above.

11. Disclaimer

The methods described in this paper are those of MSDU. They have been developed specifically for application to chemical major accident hazard installations. Otherwise the views expressed in this paper are those of the authors alone and are not a statement of HSE policy.

Appendix A. Derivation of the approximate EV and ARI_{COMAH} formulae

Knowing N_{max}, $f(N_{max})$ and the directionality of the worst case consequence we wish to evaluate:

$$EV = \sum_{N=1}^{N_{max}} f(N)N \quad \text{and} \quad RI_{COMAH} = \sum_{N=1}^{N_{max}} f(N)N^a.$$

Two cases must be considered, depending on whether the consequences of the worst case accident are omni- or uni-directional.

First, for the omni-directional case we assume that the *F–N* curve can be approximated by:

$$F(N) = \frac{F(1)}{N} \text{ for } N = 1, 2, \dots, N_{max} \quad \text{and} \quad F(N) = 0 \text{ for } N > N_{max}.$$

One point on the curve is $F(N_{max}) = F(1)/N_{max}$, from which we can isolate $F(1)$ and eliminate it from the above equation, making it:

$$F(N) = \frac{F(N_{max})N_{max}}{N} \text{ for } N = 1, 2, \dots, N_{max} \quad \text{and} \quad F(N) = 0 \text{ for } N > N_{max}.$$

Now, by definition

$$F(N) = f(N) + f(N+1) + f(N+2) + \cdots \text{ for all } N \text{ and}$$

$$F(N+1) = f(N+1) + f(N+2) + \cdots \text{ for all } N.$$

So, by subtraction, $f(N) = F(N) - F(N+1)$ for all *N*.

Plugging in the definition of $F(N)$ and $F(N+1)$ from the equation of the F–N curve gives, after manipulation:

$$f(N) = F(N_{\max})N_{\max}\left[\frac{1}{N(N+1)}\right] \text{ for } N = 1, 2, \ldots, N_{\max} - 1,$$

$$f(N) = \frac{F(N_{\max})N_{\max}}{N} \text{ for } N = N_{\max} \text{ and}$$

$$f(N) = 0 \text{ for } N > N_{\max}.$$

Plugging these values of $f(N)$ into the equations that define EV and RI_{COMAH}; recognising that we have made an approximation; and recognising that $f(N_{\max}) = F(N_{\max})$, we obtain finally, for the omni-directional case:

$$\text{approximate EV} = f(N_{\max})N_{\max}\left[\sum_{N=1}^{N_{\max}-1}\frac{1}{N+1} + 1\right],$$

$$ARI_{COMAH} = f(N_{\max})N_{\max}\left[\sum_{N=1}^{N_{\max}-1}\frac{N^{a-1}}{N+1} + N_{\max}^{a-1}\right].$$

Secondly, for the uni-directional case we assume that the f–N curve can be approximated by:

$$f(N) = \frac{f(1)}{N^2} \text{ for } N = 1, 2, \ldots, N_{\max} \quad \text{and} \quad f(N) = 0 \text{ for } N > N_{\max}.$$

One point on the curve is $f(N_{\max}) = f(1)/N_{\max}^2$, from which we can isolate $f(1)$ and eliminate it from the above equation, making it:

$$f(N) = \frac{f(N_{\max})N_{\max}^2}{N^2} \text{ for } N = 1, 2, \ldots, N_{\max} \quad \text{and} \quad f(N) = 0 \text{ for } N > N_{\max}.$$

Plugging these values of $f(N)$ into the equations that define EV and RI_{COMAH}, and recognising that we have made an approximation, we obtain finally, for the uni-directional case:

$$\text{approximate EV} = f(N_{\max})N_{\max}^2\sum_{N=1}^{N_{\max}}\frac{1}{N},$$

$$ARI_{COMAH} = f(N_{\max})N_{\max}^2\sum_{N=1}^{N_{\max}}N^{a-2}.$$

Appendix B. Software for evaluating the approximate EV and ARI_{COMAH} formulae

The BASIC routine shown below calculates ARI_{COMAH}. It also calculates the approximate EV and the scale-aversion enhancement factor. Outputs from the two example cases follow: they may be used to verify implementation of the software.

```
CLS: PRINT "Program ARICOMAH"
a = 1.4: aev = 0: aricom = 0
PRINT "INPUTS"
INPUT "Value of Nmax"; Nmax
INPUT "Value of f(Nmax) in cpm per year"; efNmax
DO
INPUT "Omni-directional (O) or Uni-directional (U)"; typ$
typ$ = UCASE$(typ$)
LOOP WHILE typ$ <> "O" AND typ$ <> "U"
IF typ$ = "O" THEN
FOR I = 1 TO Nmax − 1
aev = aev + 1/(i + 1): aricom = aricom + i^(a − 1)/(i + 1)
NEXT
aev = efNmax * Nmax * (aev + 1)
aricom = efNmax * Nmax * (aricom + Nmax^(a − 1))
enhanc = aricom/aev
ELSE
FOR i=1 TO Nmax
aev = aev + 1/i: aricom = aricom + i^(a − 2)
NEXT
aev = efNmax * Nmax^2 * aev
aricom = efNmax * Nmax^2 * aricom
enhanc = aricom/aev
END IF
PRINT "RESULTS"
PRINT USING "Approx EV = ##,###,###"; aev
PRINT USING "Approx RI(COMAH) = ##,###,###"; aricom
PRINT USING "Enhancement factor = ##.##"; enhanc
END
```

Outputs from the two example cases:

```
Program ARICOMAH
INPUTS
   Value of Nmax? 500
   Value of f(Nmax) in cpm per year? 10
   Omni-directional (O) or Uni-directional (U)? O
RESULTS
   Approx EV = 33,964
   Approx RI(COMAH) = 192,766
   Enhancement factor = 5.68
Program ARICOMAH
INPUTS
   Value of Nmax? 50
   Value of f(Nmax) in cpm per year? 0.04
   Omni-directional (O) or Uni-directional (U)? U
```

RESULTS
Approx EV = 450
Approx RI(COMAH) = 1,005
Enhancement factor = 2.23

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