CALIBRATING HAZOP STUDIES

G. C. Stevens and A. M. Humphreys
Arthur D. Little Limited, Science Park, Milton Road, Cambridge CB4 4DW

Risk identification is the corner stone of most Risk Mitigation activities. If important sources of risk are overlooked then any mitigation is likely to have a disappointing outcome. Employing a rigorous methodology such as HAZOP provides a systematic approach to risk identification and may generate a long list of items for attention. Still it is reassuring to cross check that the potential accidents lead to a loss expectation in line with past data. More important is the ability to rank the risks in order of contribution to the overall loss so that actions can be effectively given priority.

This paper uses the concept of a Loss Profile, the relationship between size of Loss per Year and probability of occurrence, to demonstrate the completeness of risk identification developed from either a HAZOP or a protocol based site safety survey. The method is illustrated using a summary of casework from Storage Depot studies.

Keywords: HAZOP; Risk Analysis; Loss Profile

APPROACH

The HAZOP (Hazard and Operability) study is a well known and widely used method for risk identification in the process industries (1,2). Deviations from design intent which have the potential for hazardous outcomes are identified and listed in a worksheet which records the discussions of the HAZOP team. A study of one or two weeks needed to evaluate a complex plant may easily give rise to several hundred recommendations. Each will have an implication for safety but obviously some will give rise to a bigger loss expectation than others, either because they are more likely to occur, or have serious consequences if they do.

The priority for attention to each risk can be assessed using a ranking matrix (3). The frequency and consequence ranges are set up and each hazardous event is allocated to one cell of the matrix. For simplicity, the matrix cells can be assigned priority codes such as "Immediate Attention" or "Plan Action eg next turnaround", as illustrated in Figure 1 (4).

Although a 4 x 4 matrix has been proposed for the assessment, there is no reason why a greater number of divisions could not be used provided, of course, it is possible to discriminate between the narrower frequency or consequence ranges. With broad ranges, the expert can make a reasonable judgement based on his experience, but this becomes harder if narrower bands are used. Of course, the issue can be investigated in greater detail where necessary using a full QRA (quantified risk analysis) technique (5).

Looking back over a number of years' casework in QRA, it becomes apparent that similar potential hazards are encountered quite commonly. Fault trees drawn in one study have a close resemblance and produce top event frequencies close to values found in other work on facilities of a similar type. While the circumstance of each plant will be different, it is clear that generic top events will appear as similar hazards are identified in successive studies. The use of such generic top events permits assignment to a narrower range of frequencies in the matrix ranking table.

Once completed, the matrix table can be used in several ways:

- The average value of loss and the average value of frequency can be multiplied for each cell and summed to give the average loss for all the items in the matrix.

- An F-N curve (5) can be drawn showing the frequency of suffering a loss of a given size. This is a fairly crude representation for a 4 x 4 matrix.

- A simulation approach can be used (3,4) in which the occurrence of a loss is sampled from its frequency range and the size of loss sampled from the consequence ranges. If the sampling is done iteratively, (eg using a Monte Carlo approach), then a cumulative probability curve can be built up showing probability against annual loss.

The mean of the cumulative probability distribution obtained by the simulation (option 3) should be close to the average determined by the first option. This paper compares the conventional F-N curve to the Loss Profile and shows how the latter can be used directly in the interpretation of insurance deductibles and excess of loss policies.

The Loss Profile predicts the size of loss expected from a particular facility. The part of the curve dealing with the more frequently occurring events can be compared directly to the actual loss history of the plant and a significance test used to check that the HAZOP based risks have been assessed to give a reasonable account of the loss expectation. In a sense, this is a calibration of the HAZOP.

If a more general approach is taken, items identified in a number of HAZOP studies on plants of a particular type can be compared against the loss history for the industry. This paper looks at Storage Facilities and compares the loss expectation derived by a ranking method against published records of accidents which have occurred.

LOSS RECORDS

Large losses occurring over 33 years from 1958 to the present were collected from a variety of sources, some published (6,7) and others available as a result of casework. The database is not a complete record of all losses occurring in terminals but is believed to represent a comprehensive listing of those events causing losses over about $10 million. These represent the relatively infrequent "catastrophic cases".

A total of 52 incidents with losses amounting to over $1.6 billion have been included in the analysis.

An F-N curve was derived from the data by counting the number of losses exceeding given loss values. Frequency per year was calculated by dividing the number above a certain loss value by the number of facility years.

A Loss Profile was derived by working out the size of loss occurring in each year. The number of losses up to a particular size was divided by the total number of losses to obtain the probability of occurrence (see Figure 1).

HAZOP STUDIES

A list of general risks was drawn up by examining a number of HAZOP studies which had been performed on storage installations. The list is necessarily general and will be influenced by:

- the type of storage vessels (floating roof, fixed roof, spheres, bullets, etc)
- loading facilities (road tanker, marine tanker or barge, railcar)
- extent of drum storage and drum or bottle filling plant
- flare
- neighbouring facilities
- pipeline connections

The design standards applied for its construction will also be crucial. With these reservations the following list

includes the main generic top events identified in storage facility HAZOP studies. This in no way represents all the risks which could be present in any single storage facility.

Tank, sphere or railcar overfilled	Frequency depends on instrumentation, eg high level alarm or high level switch to stop feed pump. Consequence depends on inventory and proximity to source of ignition.
Fire in spillage in pipe trench	Spillage can occur from flange or fitting leaks or maintenance activities which release flammable liquids to the pipe trench. If not drained and intercepted, the spill can be ignited, eg if nearby welding.
Leak at flange, fitting or pump seal which cannot be isolated	Prompt isolation of large inventories is often crucial to limiting the consequences of a small incident. If isolation valves do not exist or may be hard to reach, motorised valves should be considered.
Rupture of flow lines	High surge pressures caused byu valve actuation or high pump discharge pressure eg on ship. Frequency depends on number of loading cycles and consequence on pump and piping design. Liquid lines which can be blocked in should be provided with relief for thermal expansion. Rupture can also result from terrorism.
Small bore fittings	Impact, vibration etc causes higher frequency of damage to fittings and lines below 1" diameter.
Hot rundown causes vapour release	In process operations, eg to slop tank with fixed roof hot rundown or rundown of volatile components can lead to vapour release and possible ignition. If the tank is heated, accidental inclusion of volatile components can lead to large release. Rupture of the steam line can lead to boilover or explosion.
Relief valve sizing	Relief valves may not be sized for full discharge rate, eg of ships pumps. If valve or vent has potential for blockage, eg from solid deposition or polymerisation, special precautions needed.
Lightning strike	May ignite flammable mixture, eg if inert blanketing has failed or cause structural damage to tank. Location sensitive.
Hurricane or earthquake	Structural damage depending on location
Fire on floating roof tank	Mechanical failure of rim seal or overfilling can cause leak which can ignite in rim of tank. Frequency related to tank contents and maintenance level.
Spill from loading arm	Frequency depends on instrumentation, eg position sensors, interlocks and high level alarms/switches
Maloperation of drains	Releases due to drain freezing, eg LPG spheres, or to being left unattended.
Ignition during cleaning	Proper procedures needed when working on "empty" tanks which may contain hydrocarbon vapour.
Tanker explosion	Ignition of flammable vapours.
Rupture due to movement during loading	Collision between tankers or rail cars leading to rupture vessel or line.

Accident records provide instances for each of the above occurrences and some have occurred several times, leading to catastrophic loss:

- overfilling
- fire on floating roof tank
- lightning
- pipe rupture
- tanker collision
- vapour release or explosion in heated tank

FAULT TREE ANALYSIS

Many of the incidents listed in the previous section have been analysed and fault trees drawn to portray the build up of the top event from its initiating base events. The fault trees have been quantified to give top event frequency, sometimes using site specific failure rates, but more commonly by choosing appropriate figures by reference to published databases. The top event frequency in any one location will be influenced by a number of factors including management and operating practice which influences the human error rates which should be applied. Maintenance and testing programmes will also directly affect the observed rate of failure.

The following table gives the ranges of values quoted for the main top events identified in the HAZOP studies:

	Annual Frequency	
	Low	**High**
Tank overfilling(/tank)	2.7E-06	1.0E-03
Fire in spillage in pipe trench	1.0E-04	5.0E-04
Pump seal leak (single seal)	5.6E-03	1.1E-02
Pump seal leak (double seal)	2.9E-03	4.2E-03
Rupture of flow lines (/km)	1.0E-05	2.0E-03
Small bore fittings	4.0E-05	2.0E-04
Hot rundown release	1.5E-05	5.0E-03
Fire on floating roof tank	1.4E-03	1.6E-02
Spill from loading arm	1.2E-03	6.0E-03
Maloperation of drains	1.0E-03	1.6E-02
Rupture due to movement	4.1E-04	4.0E-02

There is considerable range due to variation between facilities and standards of operation and maintenance.

MATRIX RANKING

A ranking matrix was constructed using order of magnitude ranges for frequency and consequence:

Frequency (/yr)					
1 to e-1	e-1 to e-2	e-2 to e-3	e-3 to e-4	e-4 to e-5	e-5 to e-6

Consequence					
A To $10,000	B To $100,000	C To $1 million	D To $10 million	E To $100 million	F +$100 million

The matrix may be represented as follows with the higher frequency, higher consequence combinations appearing as the higher risk (see Figure 2).

The figures in the matrix show the number of risks identified in the HAZOP assigned to each cell of the matrix for one particular facility. The assignment of frequency was based on the ranges shown for the top events and the consequence was estimated from the size of the inventory and the estimated cost of refurbishing the plant likely to be affected.

The ranking matrix can be used as the basis for developing either an F-N curve (which is necessarily approximate because of the few numbers of contributing points) or a simulation can be used to provide a loss profile. The following results obtained are shown in Figure 3.

Comparison between the curves derived from the Loss Records and these curves shows sufficient measure of agreement to give confidence that the HAZOP study and the estimate of frequency and consequence for the top events which have been identified is in broad agreement with experience. The mean of the Loss Profile from the historical loss is $48.1 million which compares to the simulated profile mean of $53.9 million and is well within the error of the mean as indicated by the histogram. The Loss Profile is a more sensitive measure than the F-N curve. The shape of the latter is very dependent on the number and magnitude of events in the lowest frequency category. This is the hardest to estimate. However, the Loss Profile can be adjusted on the basis of the mean which is responsive to the entire range of data. Measurement of the error about the mean as indicated by the histogram indicates the significance of any difference between the historical loss and the study curve.

The simulation can be used to estimate the probability of losses occurring in excess of specific levels. This can be useful when assessing excess of loss coverage. The expected loss can be compared to the premium sought for the coverage. For example, in the current case the mean loss occurring above certain limits is as follows:

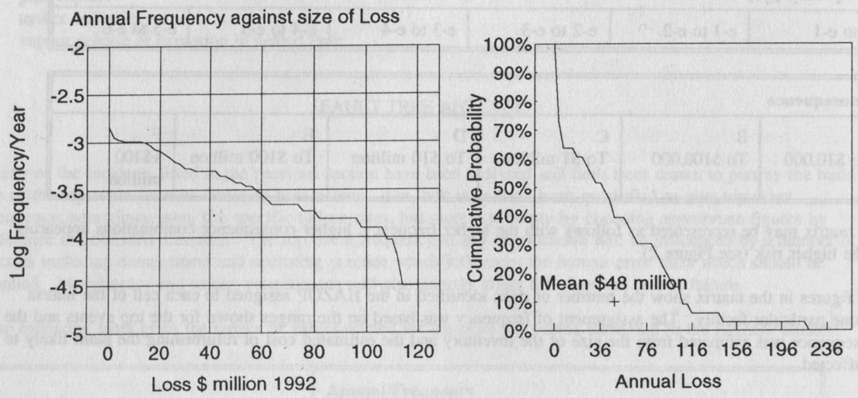
Threshold	Mean Loss	Premium as % of Line
$100 million	$4.18 million	4.2%
$150 million	0.93 million	0.6%

The premium required to cover the expected loss can be measured as a percentage on the excess of loss threshold. The market will, of course, price the excess of loss coverage in an entirely different way so the premium derived from the technical considerations in the study can be directly compared to market quotations.

The simulation represents annual losses worldwide rather than losses from any individual site.

FIGURES

Figure 1



F-N Curve : Historical Data

Loss profile: Historical data

Figure 2

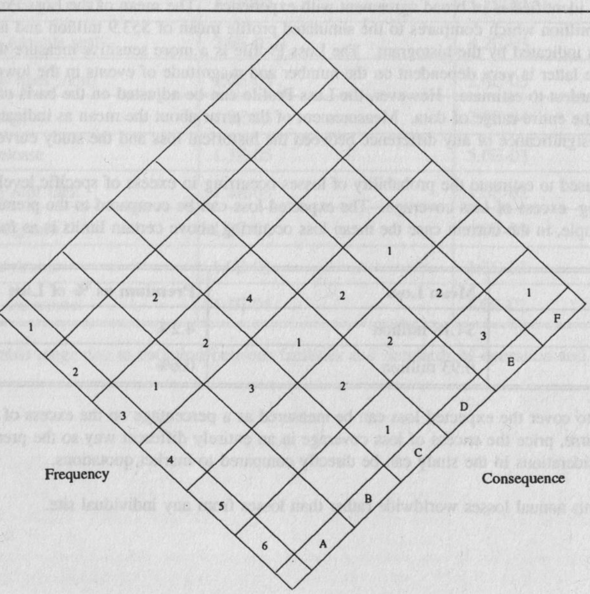
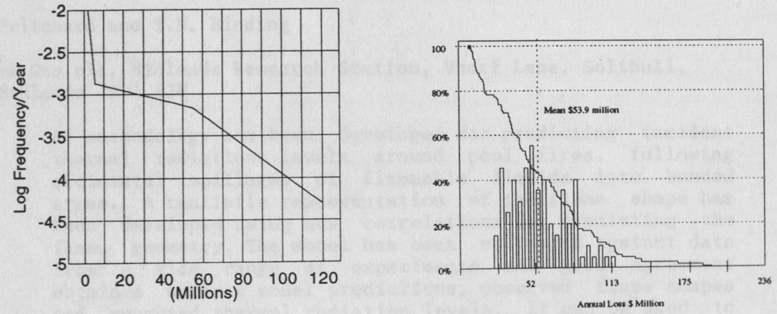


Figure 3



F-N Curve : Study data

Loss profile : Study data

REFERENCES

1. CCPS AIChE, 1985,"Hazard Evaluation Procedures"
2. CIA, 1990, "A Guide to Hazard and Operability Studies"
3. G. C. Stevens and R. P. Stickles, AIChE, Orlando 1992, "Prioritisation of Safety Related Plant Modifications using Cost Benefit Analysis"
4. G. C. Stevens, A. Mohktar and P. Legrand, International Symposium on Loss Prevention, Taoromina 1992, "Cost Effective Implementation of Safety and Environmental Projects"
5. CCPS AIChE, 1989, "Chemical Process Quantitative Risk Analysis"
6. W. G. Garrison, M&M Protection Consultants, 1988, "100 Large Losses"
7. Schadenspiegel, 1/91, "Major Losses in the Chemical and Petrochemical Industries"