THE DEVELOPMENT AND APPLICATION OF QUANTITATIVE RISK CRITERIA FOR CHEMICAL PROCESSES

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Some activities of the chemical industry are concerned with the handling of toxic and flammable materials. This paper describes why and how quantitative risk criteria have been developed and indicates how they are applied in assessing risks to which employees are exposed. It is considered that similar criteria need to be developed in regard to the general public to ensure that the risks do not exceed tolerable levels.

INTRODUCTION

Any activity which we undertake involves a risk of injury or death. We might imagine that the home is an oasis of safety where we can shelter from the harsh risks associated with the roads, the air, the mountains and the sea. If we did, we would be disturbed to learn that each year in Britain, about seven thousand people die in accidents in the home. Wherever we are, whatever we do, we cannot escape risk.

Those who work in the chemical industry encounter a level of risk which on average is very similar to the level encountered in their private life. Over the last three years, we have begun to apply quantitative risk criteria mainly to new chemical plant, in an effort to ensure that our safety performance in the future will measure up to the best which we have achieved in the past.

It is a logical development that we should seek to apply appropriate quantitative criteria in deciding whether or not risks experienced by the general public as a result of our operations are tolerable.

The Development of Quantitative Risk Criteria for Chemical Industry Employees

Within recent years, chemical plants have begun to grow larger, run at higher temperatures and pressures and operate nearer to critical limits. As these changes took place, the potential risks associated with the processes became more apparent, and we realised that we would have to adopt more rigorous methods of ensuring safety. As a first step, we instituted detailed critical examinations at the design stage, where we sought to identify all significant hazards, and minimise or eliminate them on qualitative grounds depending on the views of those conducting the examination. We realised that

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if we were to deal consistently with questions of safety, we must adopt a quantitative approach, expressing the magnitude of hazards on an absolute scale, and somehow deciding whether or not action should be taken to reduce their effect. We had discovered the need for quantitative risk criteria.

The reasoning behind the setting up of quantitative risk criteria has already been elaborated (Kletz, 1971) but is briefly repeated here for completeness.

We generally use as our index of risk a measure of the number of fatalities which occur during 10^8 man-hours of exposure in an occupation. We call this the fatal accident frequency rate (FAFR). FAFR's have been calculated for various industries and occupations (Sowby, 1964). These are listed below in Table 1.

TABLE 1 - FAFR for various occupations

Chemical Industry	3.5
British Industry	4
Steel Industry	8
Fishing	35
Coal Mining	40
Railway Shunters	45
Construction Workers	67
Air Crew	250
Professional Boxers	7000
Jockeys (National Hunt)	50000

FAFR's have also been calculated for some non-industrial activities, which are listed in Table 2. These are due to Sowby with the exceptions of the FAFR for staying at home which has been calculated by Kletz, and the FAFR for skiing which has been calculated from data in a paper by Starr, 1969.

TABLE 2 - FAFR for some non-industrial activities

Staying at home	3
Travelling by bus	3
Travelling by train	5
Travelling by car	57
Skiing	71
Pedal cycling	96
Travelling by air	240
Moped riding	260
Motor scooter driving	310
Motor cycling	660
Canoeing	1000
Rock climbing	4000

A spectrum of risks as we might experience is illustrated by the histogram of Fig.1, which is intended to represent accident risks which might be met in a typical day. In the histogram the letters represent the following activities:

a Sleeping time
b eating, washing, dressing, etc. at home
c driving to or from work by car
d the day's work
e the lunch break
f motor cycling
g communal entertainment, eg. pub

The histogram shown is, in fact, imposed on top of another histogram of risks which are mainly medical. Thus, for example, including the average risk of committing suicide would have increased all the FAFR figures by one. If our "typical man in the street" had been a West Berlin worker in 1966, the suicide risk would have been increased all the FAFR figures by 6.3 (Guiness Book of Records, 1971).

The figures which have been quoted demonstrate that the average risk of chemical industry employees lies at the low end of the risk spectrum. We have taken as our criterion that in new capital projects, no individual employee should be placed at greater risk than the average risk in ICI during the safest ten consecutive years of operation which we have recorded. Application of this criterion should bring about an improvement in our fatal accident statistics as new plant replaces old, despite the fact that in many cases the new plant can be potentially much more dangerous than the previous generation of chemical plant if the necessary precautions are not taken.

An examination of all the accidential fatalities which have occured in ICI reveals that roughly half of them resulted from incidents such as road accidents, tripping and falling. We seek to control risks in these categories by the application of the relevant codes of practice and statutory instructions such as the Factory Act and Building Regulations, and also by internal Company standards which aim to promote good engineering practice. An important influence in this field is the Safety Officer who maintains a general awareness of potential risk situations through regular Company safety publications and by special safety compaigns. He also monitors the application of standards and statutory instructions and advises on their effective implementation. These are qualitative controls, and we do not believe that our techniques of quantitative hazard analysis can have much influence over accidents which arise in these categories: we term such accidents the "background risk". The other half of the fatalities occurred as a result of incidents such as gassings and explosions. These are the specific risks of the chemical industry and we believe that we can significantly influence their frequency of occurrence by the application of hazard analysis. Thus our criterion can be practically applied if we express it by saying that the specific risks which any employee experiences on a new plant should not exceed one half of the average FAFR recorded in ICI during our safest ten consecutive years of operation.

Inevitably situations are liable to occur where it proves impossible to reduce risks to this specification. Thus, for example, we have employees who work as railway shunters and miners. Sowby's statistics show that the FAFR associated with these jobs is an order of magnitude greater than the average for the chemical industry, and while we are constantly seeking to improve our safety record, it is clearly unrealistic to expect a factor of ten safety improvements in these traditional occupations at a stroke. It has been decided that where this situation arises, the facts will be placed before the Division Board for a decision on whether or not a higher level of risk can be tolerated in the particular circumstances. In practice, most of the new projects which we have examined have involved the construction of chemical plant and we have found it possible in situations where the risk has been greater than our criterion, to make alterations at the line diagram stage which result in very little change in the overall project cost, and allow us to meet our criterion. We anticipate that very few situations will have to be referred to our Board for decision.

We believe that the financial resources which we devote to safety should be allocated in a manner which achieves the greatest possible improvement in safety per £1 spent. Since we can quantify the risk before and after safety expenditure, we can estimate the value which that expenditure implies for a life. Using this technique we have calculated the values implied for a life by a number of past cases of safety expenditure where the safety improvement could be quantified. The range of values found covered five orders of magnitude from tens of thousands of pounds to hundreds of millions of pounds. These calculations showed us that by financial standards we have used our resources in an inconsistent manner in the past, since where the implied life value was hundreds of millions of pounds, each £1 of expenditure achieved only one ten thousandth of the improvement in safety achieved by £1 spent in situations where the implied life value was tens of thousands of pounds. There may also be cases in our history where proposed safety expenditure has been rejected on qualitative grounds even though a calculation today would indicate a comparatively low implied life value, and therefore a good case for proceeding with that expenditure.

It is clear that we would increase the safety improvement obtained if we concentrated the bulk of our recourses in situations where the implied life value is, say, £1m or less. Our current feeling is that this should be our secondary criterion to be applied, for example, in situations where the FAFR criterion cannot be met, to indicate to our Board how much money should be spent if we are to improve safety in these situations in a consistent manner. This is an established technique which is used, for example, in the allocation of road safety expenditure (HMSO, 1967).

An example is now presented to show how these two criteria can be applied.

Application of these Criteria - The FAFR Criterion

As has already been stated, we mainly restrict application of the FAFR criterion to new chemical plant at the design stage. This is a practical decision in the light of our experience showing that in the region of 500 engineer hours of analysis are required for each £1m of capital. We are accepting that we cannot analyse all of our plant overnight: we can only move towards this target progressively.

Risks are identified by an exhaustive hazard study where a group of engineers under the guidance of a hazard study engineer examine the proposed line diagrams pipe by pipe with the aid of check lists which require answers to questions such as "What happens if there is high flow/temperature/pressure? " This is a mechanistic exercise which depends on the commitment of the team if it not to become tedious. With this in mind, we have recently looked for methods of hazard analysis which would be more generally acceptable. Computerised methods of hazard analysis which are currently under development at Loughborough University and the Massachusetts Institute of Technology look promising for the future, but in general we have concluded that the effort which we apply at present can easily be justified even by the spin-off design improvements which result from such an intensive examination of the plant line diagrams: it is our experience that many minor design errors come to light during the hazard study. At this stage, corrections can be made at negligible cost saving production losses and hardware modification when the plant comes on-stream.

As a simple example of the procedure, refer to Figure 2, which is a line diagram of a hypothetical process. Let us imagine that discussions in the hazard study have revealed that if the ratio of chlorine to the gas becomes too great, there is liable to be a detonation. This then is the potential hazard, but it is necessary to go more deeply into the cause of detonations before the detonation frequency can be quantified. Figure 3 shows a fault tree drawn for this situation. As a first step it is possible to write down that a detonation will occur if the ratio of chlorine to the gas rises and the gas ratio protective system fails to operate. A rising chlorine to gas ratio will occur either if there is a high chlorine flow or if there is low gas flow. At this stage, it is still not possible to quantify frequencies. Investigating the causes of high chlorine flow and low gas flow does, however, yield causes which can be quantified. From past experience it is estimated that the chlorine flow will rise out of control about once every 5 years, mainly due to over-pressure in the chlorine vaporiser. Experience also gives us estimates for the frequency with which the gas supply pressure is liable to drop dangerously, or the gas line to block. A quantitative assessment of the flow ratio protective system indicates that it will fail 1.2 times per year to a condition where it is incapable of operating on demand. Since it is proposed to proof test the protective system monthly, this means that its fractional dead time, generally abbreviated to FDT, equals 0.05 (FDT = one half x fail danger fault rate x proof test interval). The other frequencies required are estimated by referring to available data. Combining these frequencies logically through the fault tree predicts 0.071 detonations per year, equivalent to a detonation about every 14 years, on average.

The next step involves assessing the risk to life.

It is intended that the plant represented by the line diagram of Figure 2 should be supervised by one shift process operator, and it is estimated that he will be in the vicinity of the reactor for about one sixth of his shift, logging, taking sample, and so on. During this time he will clearly be at risk from a detonation. If we can assume that the operator's presence has no influence on the occurrence of detonations, then when a detonation takes place the probability that he is present is equal to the fraction of time for which he is in the danger area. If the operator is unfortunate enough to be involved in a detonation, the best estimate which can be made of the likelihood of consequential death, taking account of the energy released, and the layout of the plant is that 1 in 20 detonations would be fatal.

We are now in a position to calculate the FAFR. In general, to do this we identify the individual who is at greatest risk from the hazard, on the grounds that if the risk is acceptable for him, it will usually be acceptable for all others. In this instance, it will be any one of the four shift operators who individually supervise the plant. Picking an individual operator who supervises the plant for one quarter of the year, it follows that on average one quarter of the detonations will occur during his shifts, and on the basis of the time which he spends in the vicinity of the reactor, he will be involved on average in one sixth of these detonations. Thus his chance of death in one year = $0.071 \times \frac{1}{4} \times \frac{1}{6} \times \frac{1}{20}$.

Since he works 2200 hours each year, his chances of death per worked hour =

$$0.071 \times \frac{1}{4} \times \frac{1}{6} \times \frac{1}{20} \times \frac{1}{2200}$$

Thus the number of deaths per 10^8 worked hours (the FAFR) =

$$0.071 \times \frac{1}{4} \times \frac{1}{6} \times \frac{1}{20} \times \frac{10^8}{2200} = 6.8$$

It now becomes apparent that about a factor of ten reduction in risk is required for the calculated FAFR to come into line with our criterion FAFR, since the operator will also be exposed to other risks such as gassing, which are to be treated separately.

Possible ways of achieving a reduction are by reducing the proportion of his shift which the operators spends in the vicinity of the reactor, by reducing the frequency of demands on the protective system, or by improving the protective system. In this situation, the first two options prove to be impractical, but conveniently the protective system can be improved, reducing its FDT and hence also the operator's FAFR by a factor of fifteen, for an additional expenditure of £2,000.

After the line diagram has been modified, the detonation frequency therefore becomes $\frac{0.071}{15}$ /year = 0.0047 per year, which is equivalent to a detonation on average about every 210 years, and the operator's FAFR becomes $\frac{6.8}{15} = 0.45$.

This is less than our criterion value, and we find that when it is added to the FAFR's appropriate to the other specific risks which the operator will experience, the total remains below our criterion value. We therefore conclude that with the modification to the protective system the risk from detonations is now acceptable.

THE FINANCIAL CRITERION

Application of the second subsidiary financial criterion can be demonstrated by using figures from the previous example, where we saw that an FAFR reduction from 6.8 to 0.45 was achieved by a capital expenditure of £2000.

If we take account of maintainance costs, depreciation and return on capital, the capital sum of £2000 can be equated to an annual cost of about £500. Our technique is to equate this annual cost to the fraction of a life which is saved each year, and thereby calculate the implied value of a life.

In this situation, a total of 4 shift operations all will have their FAFR reduced by (6.8 - 0.45), ie. 6.35 deaths per 10^8 worked hours.

In one year they work 4 x 2200 hours, hence the fraction of a life saved each year = $\frac{4 \times 2200}{10^8} \times 6.35$

Hence the implied value of a life = £ $\frac{10^8 \times 500}{4 \times 2200 \times 6.35}$ = £900,000.

Referring back to the section of this paper where the financial criterion was introduced, we see that the increase in the plant capital cost which the hazard study has produced leads to an implied value of a life which is consistent with our criterion.

THE DEVELOPMENT OF QUANTITATIVE RISK CRITERIA FOR THE GENERAL PUBLIC

In the preceding sections of this paper, I have described why we developed quantitative risk criteria for our employees and have demonstrated briefly how they are applied. In this section I shall describe why we seek to develop quantitative risk criteria for operations which affect the general public. In developing these criteria we are perhaps at the stage we had reached two or three years ago in the development of criteria for our employees. Hence this section does not cover the application of criteria.

Perhaps I can demonstrate the need for criteria by two examples.

Our society depends on transport for its survival. Food is distributed from ports to the cities: goods move from the factories to the ports: fuel is transported to our power stations: we travel to and from work, and not least, travel provides us with an opening for leisure. To set against these benefits, every year seven or eight thousand people die in road accidents, during the same year two or three members of the general public die in fires following accidents involving petrol road tankers distributing the fuel on which our transport depends. Each death in the latter category will receive as much publicity in the press as a thousand or no "normal" road deaths.

This example illustrates one point clearly: we tolerate a very much higher level of risk if we can relate the source of the risk to something in which we voluntarily participate - in this case driving. But if we are unable to relate the risk directly to our own activities - as individuals we are not involved in petrol distribution - we are far less tolerant of that risk. How do we decide whether the existing fatality rate in road accidents is tolerable? Should we bring public pressure to bear on the petrol distributors to strengthen their road tankers? How do we formulate the balance between the benefits of travel and the disbenefits of the different kinds of injury and death incidents on the roads? To answer these questions, it would clearly help to have some standards against which to judge our current performance.

A second example can be drawn from our own industry. Society derives increasing benefits from the use of chlorine. As a constituent of plastics it has led to major advances in the construction of homes. It is used in the manufacture of dry-cleaning solvents and modern, highly efficient fire extinguishants. As a sterilant it is used in our swimming pools and reservoirs not forgetting our 'babies' bottles, killing "<u>all</u> known germs". Yet chlorine is a poisonous gas and obviously its manufacturer and use result in a risk of gas escapes. There is no way of eliminating the possibility of these accidents other than by abandoning the use of chlorine with the wide-spread consequences not least a loss of employment. How do we decide, therefore, a standard against which to judge existing or future risks?

In quantifying fatality risks which affect the general public, we generally express them as risks per person per year. Table 3 lists some risks experienced by the general public where involvement in the source of the risk is not direct.

TABLE 3 - Some risks affecting the general public (fatality risk per person per year)

Falling meteorite	6×10^{-11}	(Wall, 1969)
Cosmic Rays	$10^{-11} - 10^{-10}$	(" ")
Explosion of pressure vessel	5×10^{-8}	(" ")
Accidental release from UK atomic power station at 1 km	1×10^{-7}	(Farmer, 1971)
Lightning (UK)	1×10^{-7}	(from RoSPA statistics)
Major US storms	8×10^{-7}	(Starr, 1969)
Falling aircraft (close to an airport)	1×10^{-6}	(from data in Wall, 1969)
Californian earthquakes	1.7×10^{-6}	(Starr, 1969)
US Midwest tornadoes	2.2×10^{-6}	(" ")
US Floods	2.2×10^{-6}	(" ")

For comparison, the UK fatality risk from road accidents is about 1.5×10^{-4} per person per year, and in our middle years, our fatality risk from all causes including accident and disease is about $12. \times 10^{-3}$ per person per year.

Considering the figures in Table 3, we can suggest that if the risks which the general public experience as a result of individual operations are to be regarded as acceptable when compared with those listed, then the great majority of individual risks should be less than 1×10^{-6} per person per year. We should be concerned about risks which exceed this level.

Ultimately, an acceptable level of risk could be expressed in economic terms, since we can calculate the value implied for a life by any safety improvement in exactly the same way as was shown for chemical employees. Figures vary from a few hundred pounds by screening established smokers for lung cancer (Leach 1972) through the range £10,000 - £100,000 for road safety improvements. A few early calculations of the value implied for a life by safety measures taken by our industry to protect the general public, lead to figures in the range of £1m - £10m.

Some authors have attempted to outline methods of financially optimising safety expenditure (Starr, 1969: Sinclair, 1972: Melinek, 1972: amongst others) in the extreme, by spending money on safety only where it can be economically justified against the "true" value of lives saved. Assessing the "true" value of a life is, to say the least, difficult. Is the value to society of a retired person negative, since he is a net consumer? Should our leisure time be valued at 10p per hour or £10? What is the value of a composer whose music is not appreciated during his life-time? These are some of the questions which have to be answered. Sinclair has listed values which have been derived by various methods, and in general the implied value of a life is several tens of thousands of pounds. Thus, if we were to financially optimise safety expenditure we would use our resources only where the implied value of a life was less than this sum. If we were to follow this philosphy in our industry, safety expenditure on measures to protect the general public would be cut to a very small proportion of the existing budget, and we would hand over large sums of money, probably to the medical profession for the purchase of mobile cancer screening clinics, artificial kidneys, and so on.

This course of action has the merit of being logical, but we do not believe that it could be practically applied in our present social system. To cite one situation where the difficulties become obvious: should society seek a greater sacrifice of men by our fire service, since it is almost certain that a much higher level of risk-taking would be cost effective when a fireman's life is valued at only several tens of thousands of pounds? There is something inadequate about an argument which is wholly economic.

Nevertheless, while a national optimisation of safety expenditure seems to us impractical, we know that we have a technique which at least will allow us to locally optimise safety expenditure in seeking to achieve a level of risk which would be deemed tolerable for chemical process hazards affecting the general public.

You will have gathered that at the present stage in the development of criteria for the general public, our conclusions are far from finalised. Our interim conclusions are that we require to develop a primary criterion - an acceptable level of risk, which may possible be supplemented by a secondary financial criterion. We have recently appealed for the involvement of other responsible bodies in the debate which will culminate in the setting of these criteria (Gibson, 1973). May I use this opportunity to renew our appeal for such involvement?

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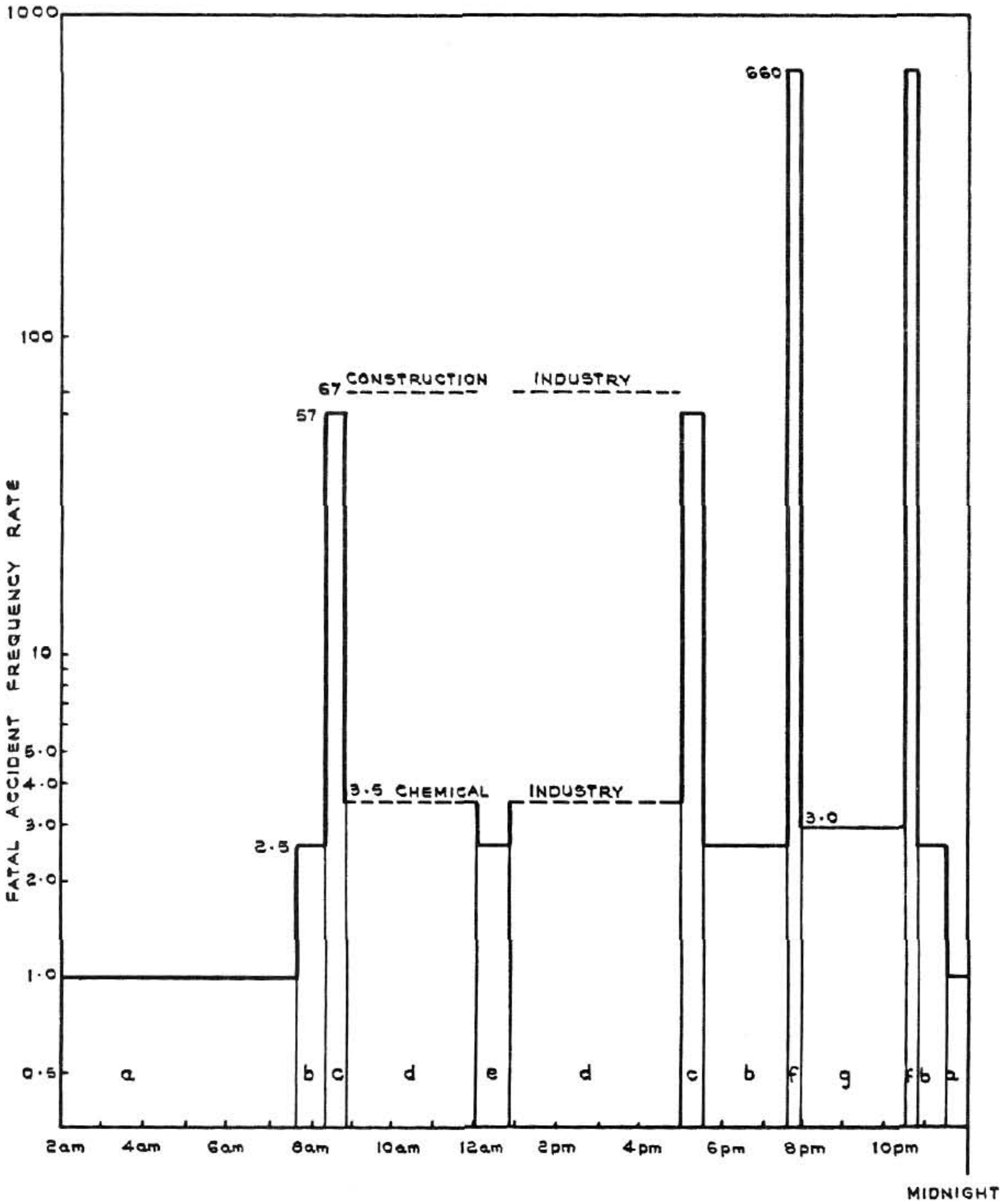

a SLEEPING TIME
b EATING, WASHING, DRESSING ETC AT HOME
c DRIVING TO OR FROM WORK BY CAR
d THE DAYS WORK
e THE LUNCH BREAK
f MOTOR - CYCLING
g COMMUNAL ENTERTAINMENT, e.g. PUB.

FIGURE 1.

HISTOGRAM OF FATAL ACCIDENT RISKS

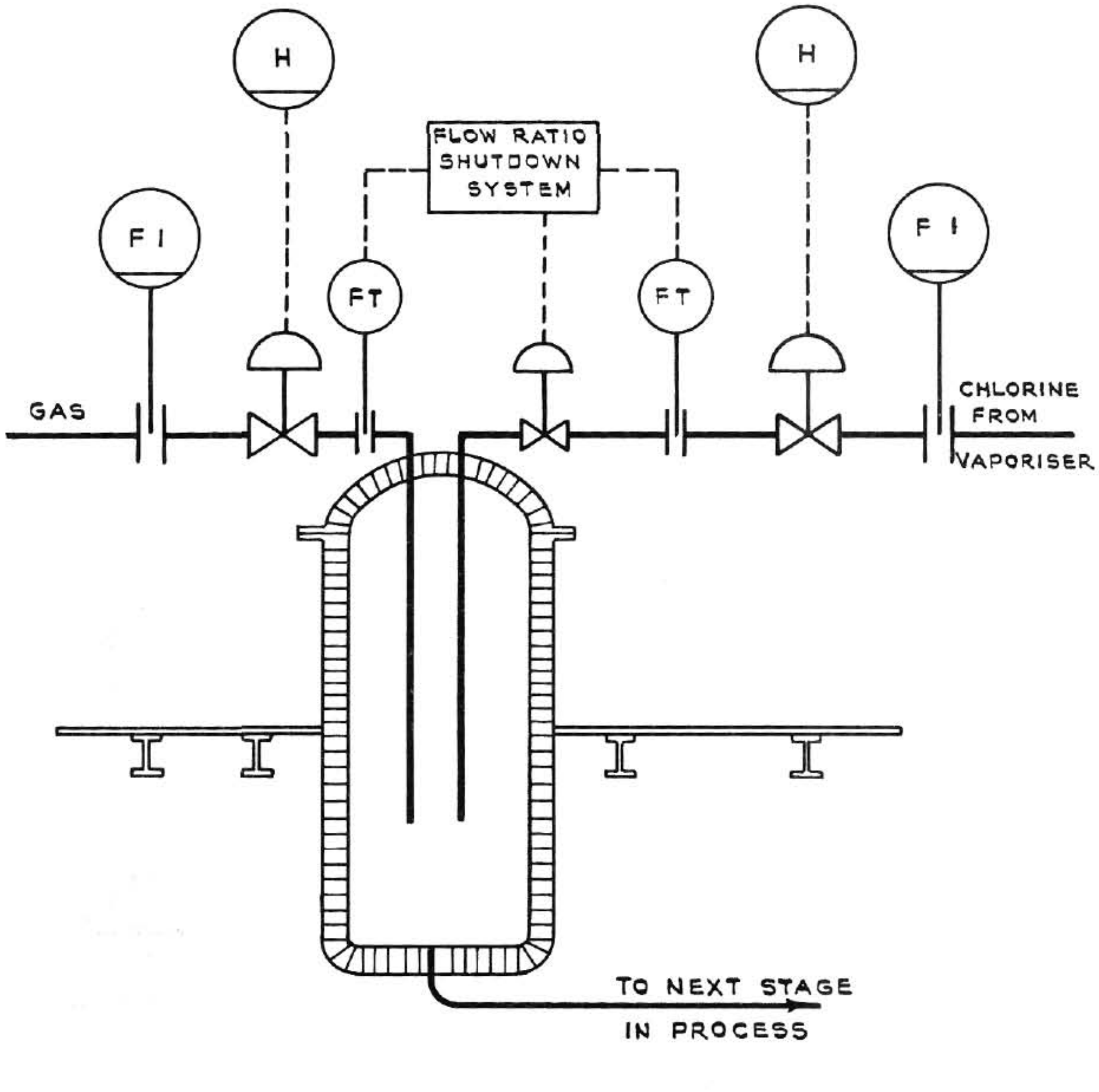

FIGURE 2

LINE DIAGRAM OF A HYPOTHETICAL PROCESS

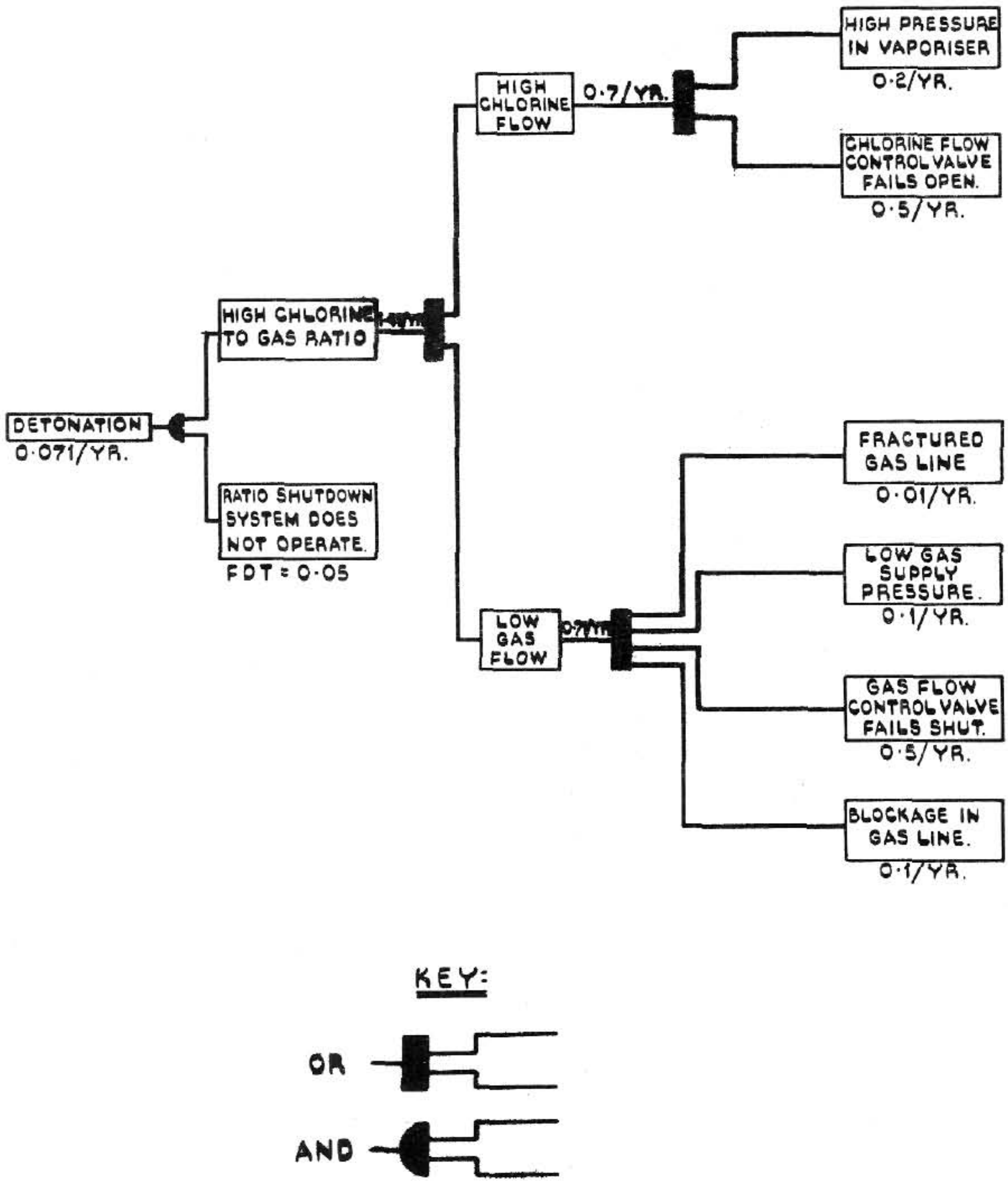

FIGURE 3 - FAULT TREE FOR THE PLANT OF FIG.2.