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THE ECONOMICS OF ACCIDENT PREVENTION — EXPLOSIONS

by

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SUMMARY

Accident prevention is economically justified if the expected losses due to an accident exceed the cost of preventing it. In this paper, this principle is applied to simple accident situations involving explosions, in order to deduce the amount worth spending on prevention. Loss of life is included by assuming a value of £50 000 for a life. The accidents studied are explosions in chemical storage tanks, gas explosions in dwellings and the progressive collapse of flats following an explosion (Ronan Point).

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INTRODUCTION

The Robens Committee, set up in 1970, points out that 'at national level, resources available for accident prevention are not unlimited, and it is therefore important that they should be used to the best effect', and it recommends that an Authority for Safety and Health at Work should be suitably equipped to pursue research into the economics of accidents and accident prevention[1]. Similar arguments must apply across the whole field of safety and accident prevention. Indeed this has been recognised for many years in assessing the value of accident prevention on roads[2,3].

In the present paper we examine a technique for studying the economic aspects of accident prevention. We take as examples some simple accident situations, evaluate the losses likely to occur and hence assess the value of protection.

The difficulties with such an analysis are twofold:

1) Accidents are comparatively rare events, and hence protection is provided against an accident which may never occur. Clearly, the rarer an accident the less justification for costly protection.
2) To balance economy with safety a value must be placed on safety, and in particular on human life, so that the relative urgency or desirability of safety and economy are adequately expressed, having due regard to the maximum benefit to society. Various values for human life have been derived, and will be discussed below: the main justification for such an evaluation is that people are prepared to risk their lives to attain various benefits, and in so doing they are implicitly placing a value on life.

According to decision theory[4], the rarity or uncertainty of an accident and other uncertainties should be expressed as a probability, the various losses and benefits should be measured by a utility value (cost), and then the course of action chosen which minimises the total expected loss of utility. This theorem is used in the present paper to deduce a criterion for justification of safety expenditure.

LOSS DUE TO ACCIDENTS

Types of Loss

The losses due to an accident are of several kinds:

(i) Financial. These might include

- (a) Damage to equipment, buildings etc.
- (b) The cost of lost production during replacement or repair
- (c) Future orders lost because customers cannot wait for production to be resumed, or because they feel the company is unreliable etc.

(ii) Non-financial

- (a) General alarm and dissatisfaction which it would be difficult to evaluate in monetary terms. The company would have to decide how much it could afford to spend on reducing this anxiety.
- (b) Life-loss

For the purpose of the analysis it is necessary to place a value L^* on life lost. The evaluation of a life presents formidable problems; estimates vary widely according to the methods and ideas applied. For example, the Roskill Commission values a (male) life at £9 300 during their study of the siting of the Third London Airport; £6 000[2] and £17 000[3] are values which have been used in road safety problems, and £30 000 has been used by the Home Office for examining the siting of fire stations[6]. Recent work at the Fire Research Station[7] suggests a figure in the region of £50 000, and this is the value which will be taken for the purpose of this paper. It should be remembered that these are values more appropriate for use by the community than by private concerns, since they have a social rather than financial basis. To a company a worker is not irreplaceable and his value to them is simply the amount they would lose as a result of his death, which might be small (unless, for example, they had to pay a large amount of compensation to his dependents, or in wage increases if these became necessary in order to retain and recruit labour if people felt that the company was an unsafe concern to work for).

To obtain an acceptable level of safety it may be necessary for the community to take a paternal attitude towards its workers, insisting that a high value of life be used to estimate expenditure on safety. Alternatively the community could offer incentives such as insurance rebates to bring the level up to its desired value.

Discounting

It is usual in accountancy to discount future costs and profits. Future loss may be covered by the investment of a suitable sum at the present, this sum being less than the sum of the future loss. If d^* is the expected annual loss, the discounted value d of the total expected loss over n years, which would occur in accidents, is given by

$$d = d^* \int_0^n \exp(-rt)\, dt = d^* \quad (1-\exp(r^n))/r$$

or

$$d^* + \frac{d^*}{1+r} + \frac{d^*}{(1+r)^2} + \frac{d^*}{(1+r)^3} \ldots\ldots + \frac{d^*}{(1+r)^{n-1}}$$

where r is the interest rate. If we are thinking in strictly economic terms, we must treat life loss in the same way as any other financial loss, and discount it. (An argument against the inclusion of life loss in the total amount to be discounted might be that more importance is being placed on the present day population than on those of the future, since the discounted loss is smaller than the actual loss and justifies the spending of less money).

CHEMICAL TANK EXPLOSIONS

There is a certain risk to life from explosions in fixed-roof chemical tanks containing volatile hydrocarbons. This risk may be much reduced by the blanketing of tanks with inert gas.

One measure of a risk is the fatal accident frequency rate, (FAFR). This is th number of fatalities which result from an activity during 10^8 exposed hours (1000 working lifetimes). In the chemical industry as a whole the FAFR is about 3.5. Kletz[5] proposed as an arbitrary guide line that no single hazard should exceed one tenth of the total average hazard, and that therefore any activity in the industry whose FAFR exceeds 0.35 should be made safer as a matter of priority. This criterion, however, takes no account of the cost of reducing the hazard, nor the property damage caused by an accident.

Data[5], covering 500 fixed-roof tanks containing volatile hydrocarbons over a period of 20 years, show that the annual probability of an explosion or fire is one in 883 per tank[5].

A man might need to be on the roof dipping, sampling, maintaining relief valves, etc. for 100 hours a year, and if he is there when an explosion or fire occurs, he will be killed.

From these figures Kletz obtained an FAFR value of 0.13 which seems acceptabl However, an accident is more likely to occur when a man is working on the roof than when he is not; figures suggest that the hazard is increased 20 times. Therefore, if Kletz's criterion is accepted this risk is unacceptable and some preventive action is desirable.

Inert gas blanketing is the method which will be examined in this paper; there are other measures, such as the provision of non-ferrous boots, which would presumably have been taken already, and without which the initial risk would have been higher.

Expected loss

If T is the total loss in the event of an accident, and P_e is the annual probability that an accident will occur in one tank, then the annual expected loss per tank is defined as P_eT.

The probability of an explosion incorporates two different ingredients in this case; the probability of explosion per unit time when the operator is absent, (P_a), and the probability of explosion when he is present. If his presence makes an accident n times as likely, this probability may may be denoted by nP_a. The risk of an accident will be affected by the length of time for which the operator is present. If he is present for proportion m of the time, and therefore absent for proportion $(1-m)$,

$$P_e = (1-m)P_a + m.\ nP_a \qquad (1)$$

If mnP_a is the annual probability that someone will be killed, the expected annual value of life which might be expected to be saved is mnP_aL^*.

The annual probability of damage D^* occurring is P_e or $(1-m)\ P_a + mnP_a$. The total annual expected loss is therefore

$$(1-m)\ P_a\ D^* + mnP_a\ (D^* + L^*)$$

from (1) $$P_a = \frac{P_e}{1-m+mn}$$

and the expected total loss is

$$\frac{P_e}{1-m+mn}\left[D^*(1-m) + (D^* + L^*)\ mn\right] \qquad (2)$$

The expected discounted loss due to accidents is

$$\frac{P_e}{1-m+mn}\left[D\ (1-m) + (D + L)\ mn\right] \qquad (3)$$

(As used here, D is the discounted material loss, and L the discounted life loss which would result from one accident per year).

The amount worth spending on protection

The value of protection (and thus the amount worth spending on it) is equal to the reduction in expected losses which is achieved as a result. This will depend on the reliability of the protective installation. If we suppose that the use of inert gas blanketing is completely effective in preventing explosions, its reliability will depend on the amount of time during which it is in working order.

To eliminate the risk entirely, the installation would have to be completely reliable, ie. in working order all the time. However, Kletz suggests that, for various reasons, the blanketing equipment might be out of use for 10 per cent of the time. So 10 per cent of the original hazard would remain, ie. the reliability would be 90 per cent.

If we denote by K the proportion of time which the equipment is ineffective, then by its use the risk of explosion would be reduced to KP_e.

The discounted loss due to explosions in a protected tank would therefore be (from 3)

$$\frac{KP_e}{1 - m + mn} \left[D (1 - m) + (D + L) mn \right]$$

The maximum amount worth spending on protection, C, is equal to the reduction in losses resulting from the use of the protection, and is given by

$$C = (1 - K) \quad \frac{P_e}{1 - m + mn} \left[D (1 - m) + (D + L) mn \right] \qquad (4)$$

The Cost of installing protection[8]

The capital cost per tank might be £1000 if nitrogen is already available on site.

The usage of nitrogen can vary widely depending on the throughput of the tank, but if we suppose that a tank has a volume of 1000 m^3 and is emptied once weekly, the annual usage will be 50 000 m^3.

The cost of nitrogen is about £5 per 1000 m^3 if supplied by pipeline but £20 per 1000 m^3 if brought in as liquid. Depreciation, maintenance and return on capital ≏ £250 p.a.

Assuming the nitrogen is piped, the total yearly cost will be £250 + £(5 x 50) = £500. If nitrogen were not available on the site and a system had to be installed, the cost could be very much higher.

Discussion

Firstly, the blanketing of tanks will be considered solely as a method for reducing fatal accidents, and all other losses will be ignored ($D = 0$).

If we substitute into equation 4 the following values suggested by Kletz:[5]

$$P_e = \frac{1}{883}, \quad K = 0.1, \quad m = \frac{100}{8766}, \quad n = 20$$

and take the exptected life of the project to be 25 years, we find that if a life is valued at £50 000 it is worth spending only about £10 per tank per year. Clearly then, inert gas blanketing at £500 p.a. is not an economic proposition.

In practice, the decision may be made the other way round; a tank will cost a certain amount to protect, which will imply a value of L. The operation is economic if the implied value of L is £50 000 or less. In this case the implied value of L is about £2 500 000.

If protection is considered as an insurance against damage and consequential losses ($L = 0$) then from equation 4 we find that a yearly £500 spent on blanketing a tank would cover about £500 000 worth of damage. However, the losses due to tank fires are not often very high, and so it is unlikely that gas blanketing would be an economic means of insurance against monetary loss.

GAS EXPLOSIONS IN DWELLINGS

About 60 per cent of town gas explosions in dwellings, where the cause is known, are due to faulty installations, and about 40 per cent to mishandling by users[9]. We shall assume that a similar ratio exists for those accidents where the cause is not known.

It is possible that, for example, a programme of house to house calls, for the purpose of inspecting gas fitments, replacing them if necessary and ensuring that house-holders known how to use them safely, would reduce the frequency of these accidents, but such a campaign would be costly. Also, its effectiveness may be reduced with time, because

a) The public memory may be short
b) New households are being set up all the time
c) Gas equipment is continually being replaced.

For the purpose of calculation, it has been assumed that the beneficial effects of a safety programme would last for five years, and although this is probably an over-estimate leading to an over-estimate of the money worth spending it is an error on the side of safety.

It has been estimated that the annual frequency of explosions involving town gas is approximately 8 per million (8×10^{-6}) per dwelling[10].

We require to estimate the proportion of domestic gas explosions causing accidental death, but the information necessary for this calculation is drawn from a variety of sources[11,12,13], and is not strictly comparable. However, it has been calculated that in 1970 there was about one death per 17 accidental explosions.

Figures for 1969[14] indicate that the average value of material damage in domestic explosions is about £520, say £600 today. The discounted expected damage per dwelling over five years taking a rate of discount of 10 per cent per annum

$$= 8 \times 10^{-6} \times £600 \times 3.93$$

$$= £0.02$$

where 3.93 is the discount factor.

Given that a life is worth £50 000 and its value is also to be discounted at 10 per cent p.a. the life loss per dwelling over five years

$$= £50\ 000 \times \frac{1}{17} \times 8 \times 10^{-6} \times 3.93$$

$$= £0.09$$

So, on the basis of the figures used, the total expected damage per dwelling over the next five years is about 11p. Even assuming that safety campaign would be 100 per cent effective, it would not be worth spending more than this amount on each dwelling (unless there were widespread public alarm which would justify the spending of more money).

Fewer figures are available for the frequency of natural gas explosions and their effect in comparison with those caused by town gas; we are in a changeover period and the frequency of natural gas explosions, at present apparently greater than that of town gas explosions[15], might be expected to diminish in the future.

There might still be room for improvement in the design of gas installations, and perhaps it would be possible to pool available resources to this end. Alternatively the money might be used to publicise safety on television, etc. which would perhaps have the effect of reducing accidents caused by the mishandling of appliances. A campaign through broadcasting media and posters could have the advantage of being continuous, although its effectiveness would also depend on the size of the audience reached.

Assuming that there are 18M dwellings at risk[10], the total discounted expected loss due to gas explosions over the next five years will be 18M x 11p = £2 000 000.

Only 40 per cent of these explosions will be due to user faults, and so the total damage which might be prevented by publicity

$$= £2\ 000\ 000 \times 0.4$$
$$= £800\ 000$$

That is the maximum amount it would be worth spending on publicity if the campaign were to be completely effective. The effectiveness of publicity is difficult to assess, but if we assume - and this is pure guesswork - that half the householders take notice of the campaign and as a result that three quarters of their accidents are avoided, then the total amount of damage prevented would be

$$£800\ 000 \times {}^{1}/2 \times {}^{3}/4$$
$$= £300\ 000$$

This is the discounted value. Assuming that it is worth spending this quantity on publicity campaigning over five years, then about £80 000 per year would be justified.

Much more information is required on the effects of publicity and the decay of beneficial effects to obtain more reliable estimates for safety programmes. It is likely that the figures derived here are over-estimated.

THE PROGRESSIVE COLLAPSE OF HIGH RISE FLATS AS A RESULT OF GAS EXPLOSIONS

The accident at Ronan Point, Canning Town on May 16 1968 demonstrated the existence of a new hazard - the progressive collapse of system built blocks. The essential structural components of these buildings are precast concrete wall and floor panels. The report of the accident inquiry[10] states that when a gas explosion occurred in Flat 90, three loadbearing panels of the flank wall were blown out, and 'the joints between the wall panels in the next storey above, and between them and the floor slabs, were not strong enough to secure the structure above Flat 90 as a cantilever over the vacant space resulting from the explosion. In the event, most of the corner structure above Flat 90 collapsed, and the force with which it fell upon the corner flats below caused a progressive failure right down to podium level'.

The Report of the Official Inquiry recommended that existing and future buildings of similar pattern should be strengthened, and that gas supplies to existing buildings should be disconnected until this work had been done. In fact local authorities decided to remove town gas supplies from existing blocks altogether and to strengthen the blocks to withstand a pressure of 17 kN/m^{-2}. This has been justified on risk grounds[16] as follows:

The Frequency of Progressive Collapse

Piped gas and the presence of volatile liquids would probably be the main explosion risk in a block like Ronan Point where it is unlikely that there would be open grate or LPG explosions.

In the ten years from 1957 to 1966 there were in the UK 393 town gas explosio on domestic premises which caused structural damage, ie. to walls and ceilings. The inquiry based its calculations on this figure, but it was estimated later[17] that only 152 of these had caused damage of a level of severity which might have led to a progressive collapse in a system-built block.

If 12M dwellings in the UK are supplied with gas[10], the annual probability of severe explosion per dwelling

$$= 152/\ 12000\ 000 \times 10^{-1}$$

$$= 1.3 \times 10^{-6} \qquad (5)$$

There were also 71 explosions attributable to liquids which caused structural damage, of which perhaps 35 could be classed as severe[16].

If there are 18M dwellings at risk[10], the annual probability of severe explosion per dwelling due to this cause

$$= 35/\ 18\ 000\ 000 \times 10^{-1}$$

$$= 1.9 \times 10^{-7} \qquad (6)$$

$\therefore$ Total risk per flat

$$= 1.5 \times 10^{-6}$$

If there are 110 flats, the annual risk per block

$$= 1.7 \times 10^{-4}$$

Risk per block per lifetime of 60 years

$$= 10^{-2}$$

So one block in 100 might be expected to suffer progressive collapse during its lifetime; with 200 blocks at risk during the time of the inquiry, one disaster would be expected every 30 years, on average.

If the gas supply is removed, the annual explosion risk per block

$$= 1.9 \times 10^{-7} \times 110$$

$$= 2.1 \times 10^{-5} \qquad \text{(see equation 6)}$$

Annual risk among the existing 200 blocks

$$= 4.2 \times 10^{-3}$$

= 1 disaster every 240 years on average

If, in addition to this, the block is positively strengthened to withstand a pressure of 17 kN/m^{-2} over and above the frictional force required to move one panel, it is thought that the risk might be reduced by an unknown factor, probably of the order of two to ten[16]. There would thus be approximately 1000 years between disasters.

If gas supplies were removed, the annual reduction in risk per block

$$= 110 \times 1.3 \times 10^{-6} \qquad \text{(see equation 5)}$$

$$= 1.4 \times 10^{-4}$$

If strengthening a block reduces the remaining risk of progressive collapse (due to the explosion of volatile liquids) to 20 per cent of its value, then the residual risk

$$= {}^{1}/_{5} \times 2 \times 10^{-5}$$

corresponding to a reduction in risk due to this cause of ${}^{4}/_{5} \times 2 \times 10^{-5}$

$$= 1.6 \times 10^{-5}$$

$\therefore$ Total reduction in risk

$$= 1.6 \times 10^{-4} \qquad (7)$$

The cost of converting existing blocks varied widely. At a Moscow symposium on tall buildings, Rodin[18] stated:

> 'Where buildings were not yet occupied, strengthening could be done easily and cheaply. In some occupied buildings, however, the resulting upheaval to the tenants, the disturbance of fixtures and fittings and the replacement of gas added considerably to the cost which rose, it is reported, to as much as £1000 per flat'.

Remain
Amoun
1828 on
7
9

1800
7400

9900
1500
11400

7400
2500
9900

9400
1500
10900

No analysis has been done so far on the total value of damage, consequential and social losses resulting from Ronan Point.

If a disaster occurred, damage and consequential losses might, at a guess, be £1M. It is possible that 20 lives would be lost. ie. one per flat.

Value of lives lost

$$= £50\,000 \times 20$$

$$= £1\ \text{M}$$

$$\therefore \text{Total loss} = £2\ \text{M}$$

Total annual reduction in expected loss by conversion of a block

$$= £2\ \text{M} \times 1.6 \times 10^{-4} \quad \text{(see equation 7)}$$

£300

Over the lifetime of a block, therefore, the total value of reduction in expected loss, discounted at 10 per cent, would be about £300 x 11 (where 11 is the approximate discount factor)

$$= £3300$$

or about £30 per flat.

Modification at the design stage might cost £40–200 per flat[18]. Since the figure for expenditure of £30 per flat has been based on an uncertain estimate of £1M for damage and consequential losses, modification at the design stage could be justified in view of this uncertainty.

The extra strengthening is also desirable to cover marginal risks which have not been considered eg. collapse due to direct impact and occasional explosions due to leakage from small stored bottles of LPG such as are used for camping.

The implied value of a life assuming the expenditure of £1000 to convert an existing flat would be about £3M, and this action is not justified economically.

An argument against the removal of gas supplies from the blocks was that electric cookers cause more fires than gas cookers. But it can be demonstrated that the risk to life is nevertheless reduced[16].

It has been shown that per unit quantity used, LPG is ten times as likely to cause explosions as piped gas[19] and so on no account should this fuel be considered as an alternative.

RISK LEVELS ATTACHED TO TOWN GAS EXPLOSIONS

Figures for 1966 show that there were about 8 explosions per million dwellings supplied with town gas[10]. If we assume that this frequency is typical, and that one explosion in 17 causes a fatality.

Number of fatalities per million dwellings per year

$$= \frac{8}{17}$$

$$= 4.7 \times 10^{-1}$$

Number killed per dwelling in 10^8 hours

$$= \frac{4.7 \times 10^{-1} \times 10^{-6} \times 10^{8}}{24 \times 365}$$

$$= 5.4 \times 10^{-3}$$

If we assume that people are in their homes for half the time and that there are three people per dwelling, then 10^8 dwelling-hours will account for $3 \times 0.5 \times 10^8$ dweller-hours. If there are 5.4×10^{-3} fatalities per $3 \times 0.5 \times 10^8$ dweller hours then there will be approximately 3.6×10^{-3} fatalities per 10^8 dweller hours due to gas explosions, ie. the FAFR is 3.6×10^{-3}.

The fatal accident frequency rate for a dwelling in a block of flats like Ronan Point is considerably higher. The dwelling will have the FAFR of 3.6×10^{-3} calculated above, plus an additional risk due to explosions elsewhere in the block. Most of these might not be fatal, but for the fact that they cause a progressive collapse of the building.

Annual probability of an explosion in the block likely to cause collapse

$$= 1.3 \times 10^{-6} \times 110 \qquad \text{(see equation 5)}$$

Frequency per 10^8 hours

$$= \frac{1.3 \times 10^{-6} \times 110 \times 10^{8}}{24 \times 365}$$

$$= 1.6$$

Ronan Point had 22 floors, with five flats per floor. If we assume that one flat on each floor will be damaged by a progressive collapse, then the probability of a given dwelling being damaged in the event of an explosion

$$= \frac{22}{110}$$

$$= 0.2$$

$\therefore$ Probability of a single dwelling being damaged in 10^8 hours

$= 1.6 \times 0.2$

$= 0.32$

If we assume that a person present in a damaged dwelling has a 50 per cent chance of being killed then the FAFR due to the collapse of the block after a gas explosion is 0.16.

Since the FAFR for fire in the home is only 0.1 an additional 0.16 due to progressive collapse seems too high. Fry[20] and Baldwin[21] have shown that the FAFR due to fires in hotels is 1, ten times greater than in houses, and public opinion demonstrated that this risk was unacceptable.

CONCLUSIONS

Two methods of assessing the value of accident prevention have been applied to accidents involving explosions.

a) Bayesian Decision Theory

b) The Fatal Accident Frequency Rate (FAFR)

In the first method the costs, losses and risks involved are combined to calculate the total expected losses both with and without protection, and that course of action which minimises this sum. In the second method, widely used in the chemical industry, action is recommended if the rate of accidents, expressed as the number of deaths per hour of exposure, exceeds a threshold value, representing the maximum acceptable risk, but this method takes no account of the cost of reducing the hazard and the property damage resulting from an accident.

These methods of evaluation have been applied to accidents involving explosions in chemical tanks, domestic gas explosions, and explosions leading to the progressive collapse of blocks of flats. In the case of chemical tank explosions, the FAFR is sufficiently high to warrant the consideration of extra protection. Examination of the costs, losses and risks involved in the example given reveals that materisl damage would rarely justify protection, and neither would life loss, unless a life were given a higher valuation than suggested in this paper, ie. about £2.5M.

In the case of blocks of flats liable to progressive collapse, the cost of reducing the hazard at the design stage is probably justified. The cost of converting an existing flat may be as high as £1000, a cost which would imply a value of £3M for a human life; but the special circumstances of the relatively high risk from explosion to occupants of these flats which is 1½ times as great as the risk from death by fire, and the fact that a fairly small and therefore partially identifiable population is at risk, might justify a higher valuation for a life.

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GLOSSARY OF TERMS USED

L^*	Monetary value placed on a life.	
d^*	The expected annual loss due to accidents.	
d	The discounted value of the total expected loss over n years.	
r	The interest rate	
T	The total loss in the event of an accident	
P_e	The annual probability of an explosion in one tank (P_eT therefore the expected annual loss per tank)	
P_a	The annual probability of an accident to one tank in the absence of an operator	
m	The proportion of time for which the operator is present	
D^*	The value of material loss	which would result from one accident per year
D	The discounted value of material loss	
L	The discounted value of life loss	
K	The proportion of time for which a safety installation is ineffective (therefore 1-K is the reliability of the installation)	

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