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THE DEVELOPMENT OF SAFETY CRITERIA FOR USE IN THE NUCLEAR INDUSTRY

by

D.J. HIGSON

AUSTRALIAN ATOMIC ENERGY COMMISSION,
45 BEACH STREET, COOGEE, N.S.W.

SUMMARY

Limits to routine radiation exposure have been laid down in the health regulations of industrial nations and provide a basis for the safe operation of nuclear power stations, uranium mines and other nuclear installations. However, these limits do not take account of the possibility of accidents, which may also be a major concern in the siting and design of plants. In this paper specific limits to fatal accident frequencies are recommended. An indication of the required level of safety has been derived from the records of other industries and human activities which are already regarded as safe.

1. INTRODUCTION

The nuclear industry has always pursued definite aims in the field of safety. This paper discusses the possible need to redefine some of these aims. It does not deal with the technical or administrative achievement of safety, important though these topics may be, and the safety record of the industry is mentioned only briefly.

2. ACCEPTABLE SAFETY STANDARDS

During a recent visit to Australia, Sir Frederick Warner, the well-known British consulting engineer, defined safety as "the reduction of risk to an acceptable level". This is an excellent definition but invites the question, "acceptable to whom?".

The easy answer is to say "acceptable to society", but society consists of many individuals some of whom may accept a particular risk but many of whom may not. Risks which are considered to be high constitute an important factor influencing people's attitues to an activity, but the perception of a risk is only one of many such factors. Individuals have an enormous range of motivations for accepting or not accepting various risks and an enormous range of awareness of risks.

Many people are prepared to accept risks of which they are aware in order to derive financial returns, and this includes some workers in industry. On the other hand, bystanders or members of the general public are entitled to feel that they are (in conventional terminology) exposed to "no risk" at all. Zero risk (or absolute safety) is, of course, unobtainable but there is a level of risk below which most people generally cease to be aware of danger or at least cease to worry about it.

Pressures from public opinion and from workers have had their effects on industrial safety practices and planning decisions. Most existing industrial activities must be regarded as acceptable, otherwise they could not continue. It has been suggested that, in the chemical industry, a fatal occupational accident frequency of two deaths per 100 million man-hours should be regarded as a reasonable aim, based on accepted industrial practice[1]. It has also been suggested (tentatively) that the figure applicable to risks imposed on the general public might need to be a factor of a hundred or so lower[1].

It is important that such criteria be developed. Once a potential hazard is recognised, it is tempting to suggest that there should be no limit to efforts and expenditure to mitigate it. After considering hazards in their own industries, engineers will realise that this is unlikely to be a socially responsible attitude because it would be reflected in high prices and low availability of intrinsically valubable products and services. It might also lead to the adoption of even more dangerous alternatives unless it is consistently applied. For example, should asbestos be discarded in favour of an inflammable building material?

Questions of this nature should not be decided by industry on its own. Potentially hazardous industries and activities should be regulated by responsible authorities, normally government agencies, who in effect decide the acceptable level of risk when they set standards of safety. Regulatory authorities should, of course, take public attitudes into consideration in setting these standards, and they must often work within the constraints of national policy over which they may have little control. For example, it may be policy to develop one source of energy ahead of others for reasons unrelated to safety.

3. RADIATION PROTECTION AND RISK ANALYSIS

The National Health & Medical Research Council (NH & MRC) of Australia has recommended annual dose limits for the controlled use of radiation sources for individual members of the public and for radiation workers[2,3]. These are consistent with the recommendations of the International Commission on Radiological Protection (ICRP)[4] and may be used to derive working limits for radiation exposure and for radioactivity in effluents; for example, from the AAEC's Research Establishment at Lucas Heights[5]. Some or all of the NH & MRC's recommendations are incorporated in the State regulations which are the minimum requirements to be met in the design and operation of nuclear reactors, uranium mines and other nuclear installations.

However, there are no international standards of radiation protection for accidents to nuclear plants and the ICRP has recommended that national authorities should set their own standards[4]. In Australia, the NH & MRC has recommended emergency reference levels of risk for use when an accident has occurred[6], but these are not useful for setting engineering standards or for deciding the design of plant features required to limit the consequences of accidents.

A common approach has been to set limits to the potential radiological consequences of certain arbitrarily specified hypothetical accidents, often called "design basis accidents". However, it is difficult to define these accidents and limits consistently for different types of plant. Detailed studies of reactor safety[7,8] have also shown that there are potential accidents of lower probability but greater severity, and of higher probability but lesser severity, which may pose significantly greater risks to the public than the design basis accidents.

This arbitrary approach to potential accidents was developed at a time when the capability for numerical assessment of the probabilities of accidents did not exist. Now, although there are still some major uncertainties in risk assessments, the application of reliability analysis techniques has made possible estimation of the probabilities of a wide range of potential accidents with reasonable confidence. These techniques are also used in other industries, for example the manufacture and operation of aircraft, and are becoming more widely used in the chemical industries.

More than ten years ago, probabilistic analysis was applied by Farmer[7] to the development of a more comprehensive approach to reactor safety. In principle, the probability* of every conceivable nuclear reactor accident and its consequences in terms of iodine-131 release (the dominant hazard) is calculated and plotted on a graph. According to Farmer's criterion the risk presented by the plant is "acceptable" if all the points are below a line as shown on Fig. 1. As an extension of this approach, the criterion is expressed on Fig. 2 as the societal risk for a given site[9], i.e. the probabilities of accidents resulting in various total numbers of casualties. Fig. 2 is based on the most commonly used version of Farmer's criterion, i.e. with a slope of -1 (see Fig. 1). It must be stressed that Figs. 1 and 2 represent upper limits of risks allowed by the criterion, and not assessments of actual risks from any existing plants.

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*The term "probability" is used loosely to denote the average number of events likely to occur in a given time. The fact that it has the units of frequency should not be taken as implying a regular periodicity.

A major problem in using this type of risk criterion in licensing decisions is the reluctance of regulatory authorities to talk in terms of the probabilities of killing people. However, the Nuclear Installations Inspectorate in the UK does base its safety criteria on the probabilities of exposing people to certain levels of radiation dose in accidents[10]. Radiation dose level is directly linked to a risk of death. The Nuclear Regulatory Commission in the USA requires that the probability of an accident which is likely to kill people outside a nuclear power station should be less than 10^{-6} per reactor per year[11].

4. INDIVIDUAL RISKS FROM "ACCEPTABLE" ACTIVITIES

When formulating safety criteria, it may be instructive to examine, in an objective and quantitative form, the current risks to workers and to society as a whole from industrial and other hazards[1,8,12-16]. Tables 1 to 4 give this experience in terms of probabilities of death. Other consequences could be examined, such as non-lethal illness and injury, but it would be necessary to take into account the duration and severity of disabilities. Death, on the other hand, is a completely definable event.

For comparative purposes all risks are expressed in terms of deaths per person per year, the figure given being as far as possible an average for those at risk. In applying these data to the development of safety criteria, no distinction will be drawn between immediate death and delayed or latent effects leading to death, although:

(i) the average loss of life expectancy is of course quite different in the two cases; and

(ii) some delayed health effects are similar to naturally occurring illnesses (such as cancer) and distinguishable from them only as an increased incidence of disease.

Some very high risk occupations, e.g. professional boxing, must be regarded as separate cases consciously undertaken for special reasons, such as large financial reward. Such risks are omitted as irrelevant to the present study. On the other hand, some occupational risks, e.g. those associated in the past with asbestos working and uranium mining, would not now be regarded as acceptable and special measures are taken to control them[17].

Tables 1 to 4 give clear data on the risks that many people actually run in their daily lives. Most of these are avoidable or controllable to some extent. For currently encountered conventional hazards, workers are not normally exposed to occupational risks of death greater than about 10^{-3} per person per year. (This is equivalent to the death of about 4% of the workforce from occupational causes.) Uninvolved members of the public become quite concerned if they find they are exposed to risks of death greater than about 10^{-4} to 10^{-5} per person per year. If risks are greater than either of these levels, then the industry may reasonably be described as "dangerous".

If risks of death are less than about 10^{-5} per person per year for workers in an industry or about 10^{-7} per person per year for members of the general public, the activity would usually be described as "safe" and there would usually be little incentive to reduce the risks still further. However, an activity may still be regarded as dangerous at the lower levels of individual risk if there is a significant potential for disasters killing many people (consider, for example, air travel compared with road travel).

5. THE IMPORTANCE OF ACCIDENT SIZE

Society generally views the large single accident less favourably than the total of small accidents having the same average risk, viz. 10,000 deaths in a single event with a probability of 10^{-4} per year is less acceptable than a steady rate of one death per year. The slope of Farmer's original safety criterion line (Fig. 1) was intended to take this into account[7].

This aversion is expressed most vociferously immediately after a catastrophe but diminishes as memory fades and particularly as costs and inconvenience of counter-measures become evident. Over a period, acceptable levels for the risk of recurrent events are reflected in regulations such as building codes in earthquake and hurricane prone areas and certification requirements for aircraft. In recent years, predictive techniques, in some cases similar to those used in the nuclear power industry, have been used to estimate the risks of rare or potential accidents and to assist in deciding whether any action to mitigate them is required. An outstanding example relates to planning approval for the Canvey Island petrochemical complex in South East England[16].

Table 5 shows data on risks of major disasters throughout the world, including both recorded observations and authoritative estimates based on experience[8,15,16,18-20]. For most of these risks, the potential number of fatalities is much greater than in any disaster actually recorded. There is direct evidence that events of the necessary physical magnitude have occurred, although fortunately not in areas of high enough population density to have the effects indicated as possible.

Fig. 3 shows how accident size is related to frequency. This figure is similarly based on world experience, but is restricted to some types of major disaster that are direct results of human activities. The risks have been scaled to represent the current situation in the USA[8]. It appears reasonable to enclose the curves on Fig. 3 within two lines A and C a factor of approximately 100 apart. The area above line A represents risks which are unacceptable ("dangerous"), and the area below line C represents risks generally ignored ("safe"). For a risk to be allowable in the range between A and C, the activity should be justified by being of some benefit to the people exposed to risk.

6. APPLICABILITY OF NON-NUCLEAR RISK DATA TO NUCLEAR SAFETY CRITERIA

It is now necessary to consider whether data on risks which are accepted for non-nuclear activities are applicable to formulating safety criteria for the nuclear industry. Four questions arise:

(i) Are the uncertainties in assessing nuclear risks significantly greater than the uncertainties in assessing other risks? Not generally. In fact, in some important respects the uncertainties are much less. Radiation can be detected and measured more easily than many other hazards, for example the presence of some toxic gases and vapours in air. Experience has already demonstrated beyond dispute the greater probability of fatal accidents in non-nuclear industries (often the energy industries) including accidents killing tens and even hundreds of people. The greatest number of deaths recorded in a single radiation accident is three, and the total for the industry is ten (all workers in research or developmental aspects). There are obvious difficulties in evaluating the probabilities of hypothetical accidents, whether nuclear or non-nuclear, and when the basis of evaluation is seen to be uncertain it is advisable to be conservative. Much attention has been given to the potential hazards of nuclear plants, but the potential also exists for severe accidents in many "conventional" plants and is often ignored. Much more is known about the behaviour and effects of radioactive materials in the biosphere than about most chemical poisons. In both cases the effects of low levels of exposure are not fully understood. For some chemical poisons this ignorance is profound; however, on the basis of current informed opinion, the method of evaluation recommended by the ICRP[21] does not underestimate the effects of radiation.

(ii) Are the potential consequences of accidents in the nuclear industry much greater than in other industries? It is completely impossible for any commercial nuclear installation or any assembly of material in the commercial nuclear fuel cycle, to explode like an atomic bomb. Nevertheless, nuclear plants may be potentially large sources of hazard, but this is also true of dams, chemical plants and many other industrial installations. For both nuclear and non-nuclear accidents, the worse the consequences the lower the probability. The estimated number of casualties from some potential non-nuclear accidents is at least as high as has ever beeen authoritatively estimated for nuclear plant accidents.

(iii) Is the nature of the hazard from the nuclear industry so different from that of other industries that comparisons are not supportable? Some people undoubtedly fear ionising radiation more than other hazards giving the same probability of death, because of the risk of delayed effects such as cancer and genetic damage. However, the risk from radiation in the nuclear industry is not unique and is often grossly overstated in comparison with radiation from medical and natural sources. For example, coal contains naturally occurring radioactivity which is therefore present in the effluents from coal burning power stations. Depending on the coal*, the potential hazards from long-lived radioactivity in ash, and in the waste produced by the equivalent generation of energy from uranium fission, may be of the same order of magnitude within a thousand years. Furthermore, there are many potentially carcinogenic and mutagenic non-radioactive agents handled in industry and present in industrial effluents. This is particularly true of the energy industries which burn fossil fuels.

(iv) Should a new industry, with a clearly identified hazard, aim at a higher level of safety than a familiar existing industry? Yes, it probably should. Instead of allowing attitudes to develop by trial and error, the level of "unacceptable" risk should be deliberately set lower than for existing industries.

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* NSW coal has a relatively high radioactive content.

On the basis of currently recommended risk coefficients[21], the ICRP's dose limit for occupational exposure to radiation appears to imply a mortality risk of 5×10^{-4} per person per year. However, this figure should be determined statistically for the total group. The average exposure of radiation workers is inevitably lower than the limit, and on the basis of current experience is a factor of ten lower[22]. The estimated risk to be compared with figures in Table 1 is therefore 5×10^{-5} per person per year. The average for non-occupationally exposed people living near nuclear plants is a factor of at least ten lower again even if some individuals experience routine doses up to the relevant limit, which is highly unlikely.

In the case of accidents, the risks must take into account the probability of the accident as well as the probability of harm from the consequent exposure to radiation. There are good reasons why the risk limits for accidental exposure to radiation, particularly for members of the general public, should be more conservative than the limits for routine exposure. Radiation risks at and below recommended routine limits are estimated by extrapolating from high dose and dose-rate effects (the so-called "linear hypothesis"). However, there is yet no evidence to demonstrate that radiation has caused cancer to workers routinely exposed within the ICRP limit in the course of their occupations* (although there have been a number of claims to this effect). The limit for members of the public is a factor of ten lower than the limit for radiation workers, and is within the range of variation of natural background dose. However, the doses experienced in accidents could be in the range at which health effects have actually been observed.

Upper individual limits to fatal accident frequency of 10^{-4} and 10^{-6} per person per year are therefore proposed for occupationally and non-occupationally exposed persons respectively. For comparison, a British gas-cooled reactor which just complied with Farmer's criterion (Fig. 1) would give rise to an average mortality risk of about 10^{-7} per person per year at a distance of 450 metres[23], which might be outside the site boundary.

To allow for the size of accidents, Curve B (a factor of ten lower than A) on Fig. 3 is proposed as the upper limit for nuclear plant accidents. Fig. 3 represents the risk to the public in the USA. On Fig. 4, Curves A, B and C have been scaled down to the size of population of the United Kingdom and are compared with the upper limit of risks from the British nuclear power program, estimated on the assumption that all twenty eight British nuclear plants meet Farmer's criterion on rural-industrial sites (Fig. 2), and the risk from chemical plants on Canvey Island as estimated for the UK Health and Safety Executive (HSE)[16]. Nuclear power stations now supply more than 10% of Britain's electricity. The author understands that Canvey Island contains a similar but somewhat larger percentage of the nation's petrochemical production capacity.

7. CONCLUSIONS

1. The quantitative evaluation of risks described in this paper provides a reliable and consistent gauge of safety. This approach should be used explicitly in setting standards and criteria.

2. Standards set by health authorities for routine exposure to radiation and radioactive materials imply risks which are well within the limits regarded as acceptable in relation to other environmental hazards.

3. There should be a high degree of confidence that potential fatal accident frequencies for nuclear plants do not exceed 10^{-4} and 10^{-6} per person per year for occupational and non-occupational exposure to risk respectively, and do not exceed Curve B of Fig. 3 scaled in proportion to the size of the population at risk (Fig. 3 is based on the population of the USA).

4. There is no incentive for reducing these fatal accident frequencies (identified in Conclusion No. 3) below 10^{-5}, 10^{-7} and Curve C respectively unless the cost of doing so is trivial. On this basis, Farmer's criterion (Fig. 1, line with a slope of -1) appears to be conservative.

5. Between the limits identified in Conclusions 3 and 4, risks should be made as low as reasonably achievable taking economic and social factors into account, which would be consistent with the recommendations of the ICRP[3].

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*Most lung cancers in uranium miners date from exposure incurred before the radon problem was understood and taken into account in regulations.

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TABLE 1

OCCUPATIONALLY INDUCED INDIVIDUAL RISKS OF DEATH (REFS. 1,12,13,14,16)

Industry	No. of deaths per person/yr
Coal mining (underground - pneumoconiosis	4×10^{-3}
Asbestos workers (smokers) - lung cancer	3×10^{-3}
Coal mining (UK and NSW) - pneumoconiosis	2×10^{-3}
Air - crew	2×10^{-3}
Fishing	2×10^{-3}
Uranium miners (underground) - lung cancer	1.5×10^{-3}
Mining and quarrying (US)	1×10^{-3}
Construction workers	8×10^{-4}
Wood machinists - nasal cancer	7×10^{-4}
Coal mining (UK) - accidents only	6×10^{-4}
Agriculture	6×10^{-4}
Steel industry	2×10^{-4}
Shipbuilding and marine engineering (UK)	2×10^{-4}
Metal workers (France and Germany)	1×10^{-4}
Shoe industry (press and finishing) - nasal cancer	1×10^{-4}
Chemical industry	1×10^{-4}
Timber, furniture, etc.	6×10^{-5}
Engineering and electrical goods	2×10^{-5}
Clothing industries (France)	2×10^{-5}
Clothing and footwear (UK)	3×10^{-6}
Average for all industry (UK)	6×10^{-5}

TABLE 2

INVOLUNTARILY ACCEPTED INDIVIDUAL RISKS OF DEATH (REFS. 1,12,13,14,15,16)

Risk	No. of deaths per person/yr
Lung cancer (Merseyside, UK)	6×10^{-4}
Lung cancer (average UK)	4.4×10^{-4}
Lung cancer (Australia)	2.6×10^{-4}
Influenza (UK)	2×10^{-4}
Estimated risk from petrochemical plant accidents (Canvey Island, UK) assuming improvements recommended	1.4×10^{-4}
Leukaemia (Australia)	6×10^{-5}
Run over by road vehicle	6×10^{-5}
Air pollution from 1000 MW(e) coal fired power station (average within 80 km)	10^{-5} to 10^{-7}
Floods (US)	2.2×10^{-6}
Earthquakes (California)	1.7×10^{-6}
Storms (US)	8×10^{-7}
Lightning (UK)	1×10^{-7}
Bites of venomous creatures (UK)	2×10^{-7}
Flooding of dykes (Holland)	1×10^{-7}
Falling aircraft (US)	1×10^{-7}
Explosion of pressure vessels (US) (public, not employees)	5×10^{-8}
Transport of petrol and chemicals (US)	5×10^{-8}
Meteorite strikes	10^{-9}

NOTE: Although most of these risks have been described as "involuntarily accepted" by students of risk acceptance, it is clear that the element of choice is rarely absent entirely. For example: people may in principle choose not to live in areas of high air pollution and natural hazard potential; society may choose to limit air pollution and construct buildings to withstand natural hazards; in view of the correlation between lung cancer and smoking, many lung cancers must be regarded as self-inflicted.

TABLE 3

VOLUNTARILY ACCEPTED INDIVIDUAL NON-OCCUPATIONAL RISKS OF DEATH (REFS. 1,8,13)

Activity	No. of deaths per person/yr
Motor cycling	2×10^{-2}
Smoking (20 cigarettes/day)	5×10^{-3}
Rock climbing	1.2×10^{-3}
Travelling by car (US)	2.2×10^{-4}
Travelling by car (UK)	1.3×10^{-4}
Staying at home (UK)	1.2×10^{-4}
Drinking (1 bottle wine/day)	7.5×10^{-5}
Playing football (UK)	4×10^{-5}
Taking contraceptive pills	2×10^{-5}
Travelling by air (US)	9×10^{-6}
Travelling by rail (US)	4×10^{-6}

NOTE: Although most of these risks have been described a "voluntarily accepted" by students of risk acceptance, it is clear that the element of choice is not always strong. For example, travelling may often be a virtual necessity and a choice between methods of travel is frequently absent.

TABLE 4

OTHER INDIVIDUAL RISKS OF ACCIDENTAL DEATH (US DATA, REF. 8)

(Combined occupational and non-occupational, voluntary and involuntary, etc.)

Risk	No. of deaths per person/yr
Falls	9×10^{-5}
Fires and hot substances	4×10^{-5}
Drowning	3×10^{-5}
Poison	2×10^{-5}
Firearms	1×10^{-5}
Machinery	1×10^{-5}
Falling objects	6×10^{-6}
Electrocution	6×10^{-6}
All accidents	6×10^{-4}

TABLE 5

RISKS OF MAJOR DISASTERS

Disaster	Worst on Record (Deaths)	Estimated Risks		
		No.of Deaths	Order of Probability	Ref.
Commercial aircraft crashes, including crashes into sports stadia, shopping centres, hotels, etc.	nearly 600	8,000 30,000 (maximum)	10^{-5} per year per major metropolitan airport. Not estimated.	19
Hurricanes	about 6000	10,000	10^{-2} per year (whole world)	8
Dam failures	over 1000	Up to 260,000	10^{-4} per year per dam*.	19,20
Petrochemical plant accident	about 2000	18,000	3×10^{-5} per year at Canvey Island assuming improvements	16
Earthquakes	over 100,000**	100,000 to 1,000,000	10^{-3} per year (whole world)	8
Meteorite strike	no confirmed deaths	City of 100,000 to 1,000,000	10^{-10} per year per city.	15
Cosmic radiation from a supernova explosion	geological evidence only	The whole human race.	10^{-8} per year.	18

* There are of the order of 10,000 major dams in the world. The estimated consequences of failure would vary from 0 to 260,000, depending on the dam.

**Newspapers reported one series recently in China to have killed over 600,000

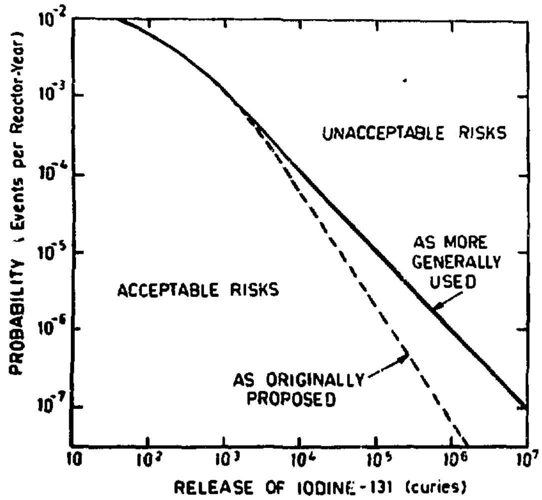


FIG. 1 FARMER'S CRITERION OF NUCLEAR PLANT SAFETY

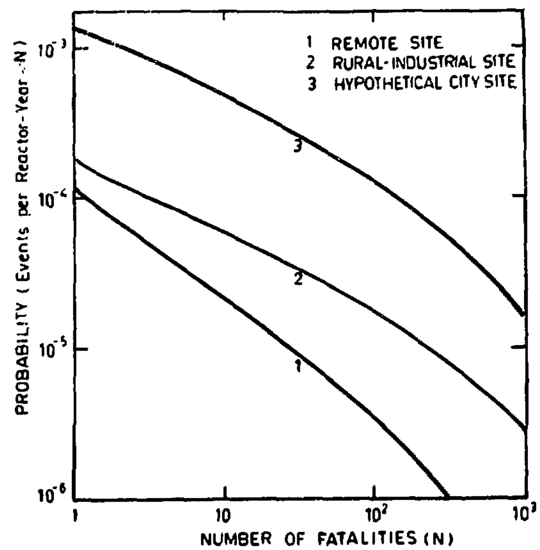


FIG. 2 PROBABILITIES OF REACTOR ACCIDENTS CAUSING LARGE NUMBERS OF FATALITIES AT NUCLEAR PLANTS WHICH JUST MEET FARMER'S CRITERION ON VARIOUS STANDARDISED SITES IN THE UK

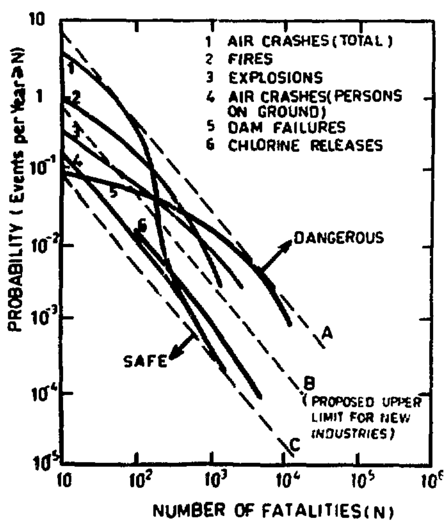


FIG. 3 PROBABILITIES OF ACCIDENTS CAUSING LARGE NUMBERS OF FATALITIES RESULTING FROM HUMAN ACTIVITIES IN THE USA. THE LINES A, B & C REPRESENT PROPOSED INDUSTRIAL SAFETY CRITERIA

CORRECTION

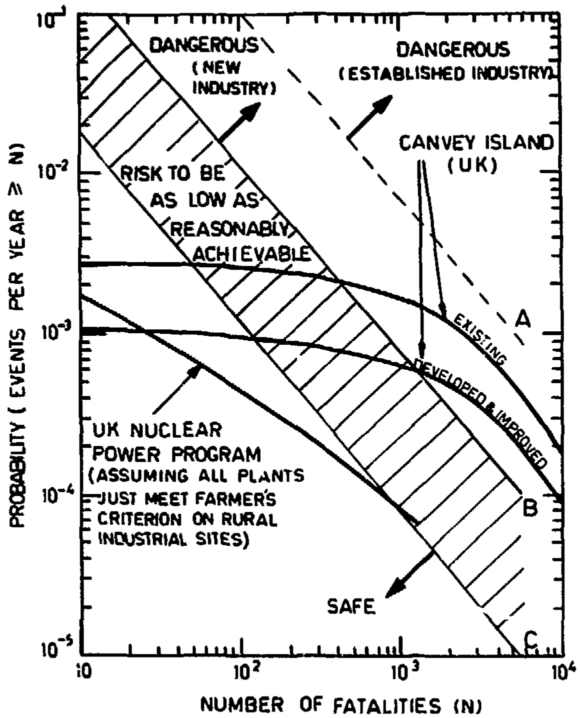
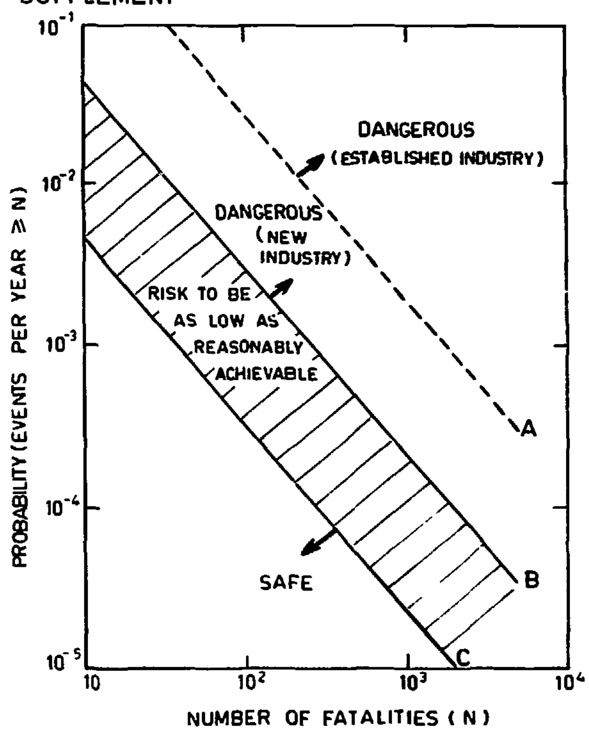


FIG. 4 THE PROPOSED SAFETY CRITERIA SCALED TO THE UK AND COMPARED WITH THE ESTIMATED PROBABILITIES OF ACCIDENTS CAUSING LARGE NUMBERS OF FATALITIES AT CANVEY ISLANDS PETROCHEMICAL COMPLEX AND IN THE UK NUCLEAR POWER PROGRAM

SUPPLEMENT



THE PROPOSED SAFETY CRITERIA SCALED TO AUSTRALIA

FOR GEOGRAPHICALLY SEPARATE CONCURBATIONS, REDUCE IN PROPORTION TO POPULATION

(e.g. BY A FACTOR OF ABOUT FOUR FOR SYDNEY & IT'S ENVIRONS)