INSAG-9

Potential Exposure in Nuclear Safety

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A REPORT BY THE
INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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POTENTIAL EXPOSURE IN NUCLEAR SAFETY

INSAG-9

A report by the
International Nuclear Safety Advisory Group

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1995

The International Nuclear Safety Advisory Group (INSAG) is an advisory group to the Director General of the International Atomic Energy Agency, whose main functions are:

(1) To provide a forum for the exchange of information on generic nuclear safety issues of international significance;
(2) To identify important current nuclear safety issues and to draw conclusions on the basis of the results of nuclear safety activities within the IAEA and of other information;
(3) To give advice on nuclear safety issues in which an exchange of information and/or additional efforts may be required;
(4) To formulate, where possible, commonly shared safety concepts.

THIS INSAG REPORT IS ALSO PUBLISHED IN FRENCH, RUSSIAN AND SPANISH

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FOREWORD

by the Director General

The International Atomic Energy Agency's activities relating to nuclear safety are based upon a number of premises. First and foremost, each Member State bears full responsibility for the safety of its nuclear facilities. States can be advised, but they cannot be relieved of this responsibility. Secondly, much can be gained by exchanging experience; lessons learned can prevent accidents. Finally, the image of nuclear safety is international; a serious accident anywhere affects the public's view of nuclear power everywhere.

With the intention of strengthening the IAEA's contribution to ensuring the safety of nuclear power plants, leading experts in nuclear safety were invited by the Agency to form the International Nuclear Safety Advisory Group (INSAG). This group serves as a forum for the exchange of information and for the provision of advice to the IAEA on nuclear safety issues of international significance. INSAG seeks not only to identify such issues, but also to draw conclusions on the basis of research on nuclear safety and operational experience. It advises on areas where additional efforts are required. Where possible, it seeks to formulate common safety concepts.

The present report deals with the concept of potential exposure in nuclear and radiation safety, discussing policy aspects, safety assessments, risk considerations and probabilities. The report is intended for use by governmental authorities and by the nuclear industry and its supporting organizations. It is intended to stimulate discussion and to promote practical action at all levels to enhance safety.

I am pleased to have received this report and am happy to release it to a wider audience.

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1. INTRODUCTION

1. The International Nuclear Safety Advisory Group (INSAG), at its meeting in February 1993, decided to develop a report on potential exposure in nuclear safety with reference to existing and future nuclear plants. The subject has also been treated in the more general context of radiological protection by the International Commission on Radiological Protection (ICRP) in its 1990 Recommendations [1] and in ICRP Publication No. 64, Protection from Potential Exposure: A Conceptual Framework [2]. This INSAG report is intended to help unify the approaches to accident prevention in activities involving exposure to ionizing radiation.

2. The term potential exposure is used to mean an exposure that is not certain to occur or, more specifically, an exposure that could be caused by some departure from normality. In routine conditions for a practice, most exposures of workers and members of the public are the result of normal operating conditions. The magnitude of the exposures will vary with changes in operating conditions and environmental conditions, but the occurrence of the exposures is not in question. Such variations, some of which are due to minor mishaps, are to be expected and are subject to managerial and regulatory control. However, there may sometimes be variations that cannot be regarded as normal. They may result in annual doses that are outside the normal range of values of the annual dose from normal operations, although not necessarily outside any imposed limits. The occurrence of the exposures that could be caused by these variations will then be conditional on the occurrence of the abnormal variations. Such exposures are termed potential exposures.

3. The main aim of this report is to address the principal issues that should complement the IAEA's work on safety standards in the context of potential exposure. As with INSAG-3, there is considerable merit in achieving a uniformity of objectives and strategic policy covering all safety aspects of nuclear activities, from normal operations through to the prevention of accidents and, if accidents should occur, the mitigation of their consequences.

4. Historically, there has been a distinction between 'radiation protection', which has dealt mainly with the assessment and control of normal (i.e. actual) exposures and with the aftermath of accidents, and 'nuclear safety', which has dealt mainly with the prevention of accidents causing substantial damage to a nuclear plant and with the on-site mitigation of their consequences. Extensive medical use was made of ionizing radiation early this century, before it was fully appreciated that radiation could cause harmful effects. Those who became responsible for radiation protection were faced with existing practices and sources and had to make the best of the situation. The techniques of protection were thus concentrated on operating procedures to protect

workers against existing risks, rather than on achieving safety by emphasizing the improvement of equipment and installations. The emphasis in protection shifted only slowly towards the design of facilities and equipment.

5. Nuclear safety became an issue only when large scale industrial processes were introduced. The history of radiation injury among early radiologists and X ray technicians and nurses made it obvious that the safety features of plant and equipment were at least as important as the operating procedures in protecting workers. It also became apparent that large scale operations had substantial potential for major accidents that could put the public at risk. The concepts of protection at the source and accident prevention became intrinsic elements of radiation safety policy in all nuclear activities.

2. ASPECTS OF RISK

6. Most of the health effects of exposure to ionizing radiation are stochastic; that is, the exposure gives rise to a probability of induction of the effect, not a certainty. For potential exposure, the occurrence of the exposure and the occurrence of health effects are both matters of probability. Thus, dealing with any radiation exposure involves the concept of risk, and it is imperative to have a clear understanding of the meaning of that concept. Unfortunately, the word risk has several different meanings. Inherent in all these meanings is the underlying idea of probability. In many publications 'risk' has been used as synonymous with the 'probability of an event with unwelcome consequences'. In nuclear safety 'risk' has often been used to mean a combination of the probability and the consequences, sometimes presented as the product of the probability of an event and the magnitude of its consequence. This product is the mathematical expectation of the consequences.

7. These different interpretations, which have caused some confusion, should be avoided. It should be recognized that the concept of risk involves sets of event probabilities with each event causing several consequences, of which not all are easy to quantify. It is therefore of fundamental importance that a risk should not be represented by a single number but by a full presentation of the potential events and their respective probabilities and consequences.

8. For these reasons, terms such as 'probability', 'consequence' and 'mathematical expectation of consequence' should be used when these concepts are meant and 'risk' should be reserved for the concept that may include all these attributes. It should also be recognized that many people view 'risk' as a threat or a hazard without any quantitative measure.

9. Much use is made of the terms 'event' and 'consequence'. It is usually clear from the context that an event is intended to mean an accident or failure of plant or equipment and that the resulting effects, such as radiation exposures or injuries, are consequences. This is the distinction used in this report. On this basis, it is clear that a risk cannot be adequately described without dealing with at least two aspects: the probability of the event, and a description, preferably quantitative, of the consequences. In reality, the event and the consequences represent a series of events, each event having a series of consequences. In particular, the consequences may be related to an individual or, more generally, to a society as a whole.

2.1. PROBABILITY AS A COMPONENT OF RISK

10. Probability is a key feature of risk. An account of the main features of probability is given in the Annex and some basic issues are summarized here. It is necessary to consider in turn the definition, the estimation, and the application of probability.

11. It is difficult to define the quantity probability without reference to specific situations or to the methods of estimating the quantity. This is because any statement of probability requires a model; that is, a formalized description of the situation in which the probability of an outcome is to be estimated. The classical definition of probability concerns games of chance with defined winning and losing outcomes. These games are themselves models of reality. In short, any statement of probability is dependent on the existence, whether explicit or implicit, of a model.

12. There are several ways in which probability can be estimated. If the situation modelled is simple enough, the probability of a particular outcome can be derived logically. This is the case for simple games of chance with several equally probable outcomes. The probability of each outcome is determined by the number of possible outcomes. The probabilities of combinations of outcomes can be calculated from logical principles. There are no uncertainties in the estimated probabilities if the model accurately represents the real situation. Such simple situations are rare, but they provide a useful basis for the logical use of the probability of failure of simple systems in the estimation of the probability of failure of complex systems.

13. In practical situations, estimates of probability usually start from information about the observed frequency of events. Provided that the observed events are independent of each other and that the mean frequency is constant with time over the period of observation and prediction, there is a direct relationship between the mean frequency f and the probability that an event (one or more events) will occur in a time interval t. These provisos are not always met in practice. For example, successive

earthquakes in a single area are not independent events, and faults in equipment often appear at frequencies that show variations with time after its installation.

14. Given the provisos, the product ft of the mean frequency and the time interval is the mathematical expectation of the number of events occurring in the interval. If the expectation is small relative to unity, say less than 0.1, ft is also a close approximation to the probability that an event will occur in the interval. In most of these situations, the distribution of events will be Poissonian and the true probability that an event will occur in the interval t is given by $(1 - e^{-ft})$. The mathematical link between frequency and probability is discussed in more detail in the Annex.

15. In many cases, probability can be estimated only on the basis of expert judgement. Indeed, probability is sometimes defined as the degree of belief in a predicted outcome. This definition is sometimes seen as leading to a different kind of probability, but it is simpler to regard it merely as a different method of estimating probability. As is shown in the Annex, the two methods, based on frequency and judgement, can give very different results. Usually, the judgement is based on experience and, when it represents a broad consensus, it plays an important part in safety assessment. Nevertheless, it should be treated with caution, because it may well be distorted by the expert's individual appreciation of the available data.

16. Whichever method is used to estimate a probability, including in some situations the combination of both methods, the existence and the definition of the underlying model become vital when the estimate is used for making predictions or decisions.

17. One important type of probability is the conditional probability. The conditional probability is the probability that an event will occur, given the occurrence of an earlier defined event. For example, the probability of dying as the consequence of an exposure to radiation is conditional on the occurrence of the exposure and on its magnitude. Conditional probabilities must be used with care, since they can be manipulated and combined only if the conditions applying to them remain unchanged.

2.2. CONSEQUENCES AS A COMPONENT OF RISK

18. The consequences of an accident are of several different kinds. They include the health effects of the radiation exposures caused by the accident, the probability, severity and number of which are directly linked to the potential exposures associated with the accident. Some consequences are linked only indirectly to an accident. These include the effects of the countermeasures taken to limit the health effects of

the accident. Local areas may have to be temporarily evacuated, consumption of food may have to be restricted, communities may have to be relocated, and areas of land may have to be declared unfit for occupancy or for agriculture. These consequences are linked to the potential exposures, but only in an indirect way through regulatory or social decisions about countermeasures. Finally, some consequences, such as the loss of the plant's power output and the costs of repairing or decommissioning the damaged plant, are linked to the scale of the accident but are independent of the potential exposures associated with the accident. The present report is concerned only with those radiological consequences that are linked to the scale of the accident and the magnitudes of the resulting exposures.

19. The consequences of an accident affect both individuals and society as a whole. The primary consequences of concern in nuclear and radiation safety are the exposure of people to radiation and the resulting biological effects on health. These biological consequences are of obvious concern to the individual. The concerns of society are more general. They include society's reaction to observable, as opposed to predicted, numbers of deaths and other health effects, and the economic consequences of measures such as restrictions on the use of land and the loss of use of the plant concerned. The biological effects of radiation on humans are regularly reviewed by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and by the ICRP. Details are given in the 1993 and 1994 UNSCEAR Reports to the UN General Assembly [3, 4] and in the 1990 Recommendations of the ICRP [1].

20. The health effects of exposure to radiation are of two kinds: deterministic and stochastic. Deterministic effects are certain to occur if the dose received is high enough. For doses below some threshold level, they never occur. If vital tissue is exposed to high levels of radiation and is severely damaged, the result will be death within weeks or months. The occurrence of stochastic effects, notably cancer, is statistical in character. The probability that a cancer will result from irradiation usually increases with increments of dose. The occurrence of the effect in the exposed individual will be delayed, often by several decades, from the time of the exposure.

21. The difference between deterministic and stochastic effects of radiation is important in the specification of risk because it affects both the probability and the time of occurrence of an effect. It is often assumed that death and the probability of causing death are simple concepts for use in the specification of risk. In fact, the implications differ of a death at different times after an exposure. For exposures spread over a lifetime or delivered in mid-life, the loss of lifetime due to a death from cancer is on average about 15 years. The corresponding loss of lifetime due to a death resulting from a deterministic effect is about 35 years. Furthermore, the lifetime probability of death from all causes is unity. Thus any increase in the lifetime probability

of death due to an exposure to radiation (that is, the probability that the exposure will be the eventual cause of death) necessarily implies a decrease in the probability of death due to other causes. In short, the probability of death attributable to an exposure is not an adequate measure of the risk associated with that exposure.

22. The individual fatality risk associated with an exposure to radiation can be more effectively specified as the conditional probability of causing a death with an average loss of lifetime of 15 years for a death from a stochastic effect or 35 years for a death from a deterministic effect. Also, for potential exposures, there is a probability of less than unity for the occurrence of the exposure. The complete statement of fatality risk thus requires at least three components: the probability of the exposure, the probability of the attributable death and any weighting to be attached to that death.

2.3. AGGREGATION OF THE COMPONENTS OF RISK

23. There would be obvious advantage in introducing a method of aggregating the components of risk, either to individuals or to society, into a quantity with only one dimension, a simple index of potential harm. However, the disadvantages of such an aggregation are substantial. The most serious disadvantage is the loss of information available to the user of the aggregated risk. In most cases, the user will also need the unaggregated risk data. The most obvious step for aggregating individual risk is to amalgamate the probability of the exposure and the conditional probability of the consequential death. If all deaths can be treated as equal, this amalgamation provides a statement of the overall probability of an attributable death. However, the user of the risk statement will not always regard changes in the probability of the exposure and changes in the conditional probability of death as being of equal importance. When a low probability, high magnitude exposure of an individual occurs, there will be administrative and regulatory consequences that would not occur if the exposure were smaller but of higher probability. There is thus no simple trade-off between the probability of the exposure and the probability of biological consequences from it. However, if the exposures, should they occur, are not large enough to have regulatory or administrative consequences, then the aggregated probability of an attributable death may well be an adequate representation of risk of fatality.

24. The aggregation of individual risks to give a measure of societal risks is much more difficult. Societal risks are more complex than the simple sum of individual risks. Society tends to regard the reduction of the consequences of an accident as more important than the reduction of the probability of the accident, possibly because the reduction of consequences is more readily appreciated. Society also reacts more acutely to several observable deaths associated with a single event than to a larger total number of deaths due to separate events. Almost all the deaths resulting from

accidental exposure to radiation are not individually identifiable as being attributable to the accident.

25. Further problems are introduced by the different kinds of consequence that may follow an accident. The health effects, the reaction to countermeasures and the economic consequences must be considered separately. Clearly, the simple aggregation of societal risks of different kinds is not a viable objective. The problems are set out in more detail in Section 3 in the context of safety policy.

26. One form of aggregation is worth discussing in some detail, because it is used fairly commonly in the treatment of societal risk and because it is often seriously misleading. In this form, the probability per unit time (probability rate) of an event, such as an accident, is multiplied by the average number of deaths that will result from the event should it occur. This gives the mathematical expectation of the number of deaths per unit time. However, this mathematical expectation is very different from the value that is likely to occur. For example, an accident with a probability rate of 10^{-3} per year and an average consequence of 1000 deaths produces a mathematical expectation of one death per year. However, the only possible outcomes in a year are either no deaths or about 1000 deaths, with the most likely outcome in any one year being no deaths. The mathematical expectation is of use only if the time period of interest is much greater than the mean time interval between events, and then only if the mean death rate is of interest.

27. To sum up: the aggregation of measures of the consequences of accidents is of limited value. In most circumstances, it must be supplemented by more detailed unaggregated information that would otherwise be concealed. The unaggregated information includes many features requiring a wide range of different judgements. There is no single criterion by which the whole range of consequences could be judged.

3. POLICY FOR NUCLEAR AND RADIATION SAFETY

28. No human activity is completely free from the risk of causing adverse effects to humans. Accidents can be made unlikely, but they cannot be completely prevented. Exposures to harmful agents can be kept low, but they cannot be reduced to zero and it cannot be guaranteed that exposures will always be harmless. It follows that absolute guarantees of safety are not valid, and that some risks will have to be tolerated, even if they are unwelcome.

29. Most, perhaps all, human decisions involve a balancing of costs (including risks) and benefits. Decisions about nuclear activities are no different. All nuclear activities give rise to some radiation exposure in normal operating conditions and to some probability of accidents. Both normal and potential exposures must therefore be considered in the development of a safety policy. For any activity causing normal or potential radiation exposure to be 'justified' in radiation safety terms, it must produce sufficient benefits to offset the radiation detriment. Society's decision to adopt such an activity depends on many other aspects and goes far beyond considerations of radiation safety. For the purposes of this report, it is presumed that the choice has already been made to adopt nuclear activities.

30. Since safety cannot be absolute and knowledge of how to enhance it is never complete, responsible action includes a continuing process of looking for possible improvements and possible deficiencies in both design and operation. This process applies in the control of normal situations and in the prevention of accidents and the mitigation of their consequences. It provides the essential basis for all aspects of safety. For potential radiation exposure, both the probability and the magnitude of the exposures should be subject to assessment and control.

31. Source related considerations now play a major part in radiation safety. The term 'radiation safety' is used here because it describes the intention more appropriately than does 'radiation protection'. There still remains a historical distinction between nuclear safety and radiation safety, but the conceptual similarities between the two are now more important than the differences. It is notable that in both disciplines the concepts have led to practical control systems based on the concept of defence in depth.

32. The current INSAG safety policy is described in INSAG-3 [5], which sets out three safety objectives for nuclear power plants. The first, termed the General Nuclear Safety Objective, reads:

> "To protect individuals, society and the environment by establishing and maintaining in nuclear power plants an effective defence against radiological hazard."

The second safety objective, termed the Radiation Protection Objective, reads:

> "To ensure in normal operation that radiation exposure within the plant and due to any release of radioactive material from the plant is kept as low as reasonably achievable and below prescribed limits, and to ensure mitigation of the extent of radiation exposures due to accidents."

The third safety objective, termed the Technical Safety Objective, reads:

> "To prevent with high confidence accidents in nuclear plants; to ensure that, for all accidents taken into account in the design of the plant, even those of very low probability, radiological consequences, if any, would be minor; and to ensure that the likelihood of severe accidents with serious radiological consequences is extremely small."

33. Subsequently, the IAEA published its own more general policy on nuclear safety as a Safety Fundamentals publication, The Safety of Nuclear Installations [6]. The document closely followed the INSAG policy, slightly edited to reflect the wider application to all nuclear installations. However, it also differed in slight but significant ways from INSAG's Technical Safety Objective[1]. INSAG has concluded that these changes are detrimental and recommends the retention of its version.

34. A very similar policy has also been set out in relation to both normal and potential exposure by the ICRP [1]. The relevant paragraph reads as follows:

> "(a) No practice involving exposures to radiation should be adopted unless it produces sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes. (The justification of a practice.)
>
> (b) In relation to any particular source within a practice, the magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures where these are not certain to be received should all be kept as low as reasonably achievable, economic and social factors being taken into account. This procedure should be constrained by restrictions on the doses to individuals (dose constraints), or the risks to individuals in the case of potential exposures (risk constraints), so as to limit the inequity likely to result from the inherent economic and social judgements. (The optimisation of protection.)
>
> (c) The exposure of individuals resulting from the combination of all the relevant practices should be subject to dose limits, or to some control of risk in the case of potential exposures. These are aimed at ensuring that no individual

[1] The Technical Safety Objective in Safety Series No. 110 is as follows: "To take all reasonably practicable measures to prevent accidents in nuclear installations and to mitigate their consequences should they occur; to ensure with a high level of confidence that, for all possible accidents taken into account in the design of the installation, including those of very low probability, any radiological consequences would be minor and below prescribed limits; and to ensure that the likelihood of accidents with serious radiological consequences is extremely low."

is exposed to radiation risks that are judged to be unacceptable from these practices in any normal circumstances.... (Individual dose and risk limits.)"

35. The ICRP principles relate mainly to the protection of individuals, but they make clear that the number of individuals exposed is also important. The references to potential exposure make clear that the principles are also aimed at reducing the probability of accidents. The nuclear safety objectives of INSAG and IAEA give more direct emphasis to the prevention of accidents and the mitigation of their effects.

36. When all the doses to individuals are well below the thresholds for deterministic effects, for protection purposes a general linearity is assumed to exist between the exposure, the probability of a health effect in an individual and the total radiation health detriment to the community. In many accidents and cases of potential exposure, this linearity still applies; however, in serious situations it no longer applies. This loss of linearity is partly because the doses may be high enough to cause deterministic effects, but mainly due to consequences that are not simply related to the potential exposure (see Section 2.2). There is currently much discussion on possible methods of presenting non-linear situations and on how best to judge their acceptability. It seems likely that use will have to be made of complex presentations of all the relevant components of risk with judgements being aided by the use of non-linear utility functions. No clear-cut policy consensus has yet emerged.

4. SAFETY ASSESSMENTS AND RISK CONSIDERATIONS

4.1. SAFETY ASSESSMENTS AND SAFETY GOALS

37. The achievement of safety, including the control of potential exposure in nuclear power plants, is based on the concept of defence in depth. The first priority is the prevention of accidents. Provision is made for mitigating the radiological consequences of accidents should they occur. The defence in depth ranges from the prevention and control of minor events and deviations from normal operating conditions, which are inevitably associated with routine operations, to the management of accidents causing major damage to a plant.

38. Judgements of what constitutes acceptable levels of prevention and mitigation ('how safe is safe enough?') are based on established procedures for safety assessments with associated acceptance criteria or guidelines. A safety assessment is a structured review of the performance of the components of a plant, its operating

systems, its safety systems and its personnel and management under a wide spectrum of anticipated events and situations. Deterministic methods of assessment start by specifying scenarios in terms of initiating events and component failures that are assumed to occur. The scenarios are specified to include even highly unlikely events, and acceptance criteria (including safety margins) are specified in such a way that the end result can be shown to meet national safety objectives. For a probabilistic assessment, realistic quantitative information about the occurrence of various events and conditions and about the reliability of components is used to assess the probability of failure of the operational and safety systems of the plant. In this way, the probabilities of the various potential sequences of events and their consequences can be assessed. A general account of probabilistic safety assessment is given in INSAG-6 [7].

39. The quantitative estimates of the probabilities and consequences of possible accidents that are provided by probabilistic safety assessments can be used as indicators of the safety level achieved and may be compared with safety goals given in probabilistic terms. A probabilistic safety goal is usually expressed in terms of the annual probability of some specified adverse event, such as severe damage to a reactor core or a specified radiological impact due to accidental exposure of members of the public. The intended purpose of a safety goal needs to be made clear when the goal is being specified. This has not always been done and some confusion has resulted. When a safety goal, expressed in probabilistic terms, is used as a design and operational objective, it is best interpreted as a desirable figure of merit for the reliable performance of plant safety functions, with the limitations of probabilistic methods of safety assessment kept in mind. With these same limitations kept in mind, a safety goal may also be used as a basis for estimates of and judgements on the risk associated with the operation of a nuclear power plant, the level of risk being expressed as both a probability and a statement of consequences.

40. What constitutes an acceptable level of safety for a nuclear power plant should be judged mainly by an evaluation by deterministic methods of the quality of defence in depth, complemented by probabilistic safety assessment. In a separate report, INSAG-8 [8], INSAG discusses a common basis for judging whether the level of safety at a plant is acceptable. There is widespread agreement that, also for plants complying with these criteria for an acceptable level of safety, the aim should be a safety level as high as reasonably achievable, in view of the cost–benefit aspects of various safety improvement measures, for example. This corresponds to the radiation protection principle of optimization cited in para. 34(b). INSAG-3, in para. 25, gives guidance in probabilistic terms on safety levels that should be reasonably achievable for existing plants and for new designs. In line with INSAG-3, and to be useful, a probabilistic safety goal should be expressed in terms of a probability and a statement of consequences. These must correspond to a level of safety which is clearly better than the just acceptable and which is reasonably achievable. However, it must not be

so demanding as to remove all incentives to make further improvements on the basis of operating experience and technical developments. The application of the concepts of 'an acceptable level of safety', 'reasonably achievable levels of safety' and probabilistic safety goals, as discussed here, to the licensing of nuclear power plants is within the realm of national regulatory decisions and hence outside the scope of this report.

4.2. INDIVIDUAL RISK

41. There are many operations whose conduct is a matter of choice by society. The operations are judged to provide a benefit to society, but they also impose some risk on individuals.

42. For normal radiation exposure, the ICRP recommends annual dose limits that correspond to an annually committed probability of premature death of a few $\times 10^{-5}$ for members of the public. This is the implied limit of the probability of death from the normal use of all regulated sources affecting the same individual. It represents the ICRP's judgement of the threshold of the region of unacceptable risk imposed by these sources. More restrictive constraints are usually applied to single sources of risk. The corresponding restrictions on the annual individual risk from potential exposure should be of similar magnitudes to the restrictions for normal exposures. The requirement to take all reasonable steps to reduce risks results in risk levels substantially lower than the limiting requirements. It seems appropriate that for members of the public a risk for potential exposure, expressed as the annual probability of death attributable to a single installation, should not exceed 10^{-5}.

43. There have been some suggestions that a higher probability could be acceptable for the late deaths resulting from stochastic effects than for early deaths resulting from deterministic effects, but the difference in detriment is not large, a factor of less than three. The suggestions seem to depend primarily on the late deaths being less apparent and they have not been followed here. In any event, most accidents causing early deaths will have other major societal consequences. Individual risk will then not be the principal cause of concern.

44. On the assumption that the individual risk for the total of the sources of potential exposure in an entire plant would be limited so that in any single year there would be a committed unconditional death probability of 10^{-5}, exposures causing low radiation doses could be permitted at a substantially higher probability because of the low conditional probability of attributable death given the exposure. For example, a predicted effective dose of 100 mSv would carry a probability of attributable death of 5×10^{-3}. The annual probability of such a dose could be up to 2×10^{-3} without infringing the criterion for individual risk.

45. However, in the range of doses of 10–100 mSv, there will be other considerations in addition to considerations of individual risk. The regulatory authority will have become involved and intervention (the use of countermeasures) will probably have been indicated. It is then necessary to consider the acceptability of these consequences. If the annual probability of an accident causing these consequences is 2×10^{-3}, the probability that such an accident will occur at some time in the life of the plant (40 years) is about 0.1, or one chance in ten. This would probably not be tolerable and it seems reasonable to expect that accidents that require simple, local countermeasures should have an annual probability of not more than about 10^{-4}.

46. A similar calculation can be made for more severe accidents causing an individual effective dose of 1 Sv. This dose will probably not produce serious deterministic effects, but the probability of stochastic fatality will approach 0.1. In order that the individual risk does not exceed 10^{-5} in a year, the annual probability of exposure should not exceed 10^{-4}. Such an accident will require substantial intervention, probably including temporary evacuation and widespread disruption of agriculture. It is likely that these interventions will have more influence on the acceptability of plants similar to the one concerned than will the individual risks. An annual probability of such an accident of 10^{-5} is likely to be required because of the societal consequences.

47. From these arguments, it seems that individual risk expressed in terms of potential exposure would only be the determining factor for the safety of nuclear power plants for doses, should they occur, of less than about 10 mSv. For larger doses, the individual risk of attributable death (which is the combination of the probability of the exposure and the conditional probability of attributable death) will be inappropriate (see para. 24). The potential exposure will still play a part, but societal consequences, especially of intervention, will increasingly prove to be more limiting. Intervention is to be initiated if the dose that can be averted by the available countermeasures exceeds predetermined intervention levels. This serves to emphasize the importance of setting the intervention levels realistically.

4.3. SOCIETAL RISK

48. In judging what steps are reasonable for reducing risks, decisions based on individual risk alone are insufficient. The number of individuals at risk and the economic and social implications of the accident are also relevant. These issues are often grouped together and termed societal risk.

49. For the purposes of this report, the term societal risk is used to represent the total impact of an accident. As indicated in Section 2.2, this impact includes the risk

to individuals, the number of individuals at risk, the economic impact of such things as the countermeasures needed to protect individuals, including food bans, and the loss of production and of the capital value of the installation.

50. The use of societal risk in decision making for protection is problematic. For normal exposures, for which the probability of occurrence is essentially unity, the collective dose is an adequate indicator of the collective health detriment and it is used in the optimization of protection. For high probability, low dose events, with, say, annual probabilities of about 10^{-2} and doses of a few millisieverts, the collective potential dose could be used as a simple measure of the societal risk. This approach is not widely used, however. It follows from the discussion in Section 2.2 that, for low probability events, the societal risk, even in the limited sense of the probability of death, cannot be represented by the mathematical expectation of consequence.

51. In general, it is necessary to deal with events of both high and low probability. It is then necessary to take account of both the event probabilities and the full description of the potential consequences in judging the level of safety. The necessary techniques are in principle available and are used in reaching decisions in other fields. Their use in nuclear safety has proved difficult, however, largely because of the complexity of the societal consequences of accidents and the complexity of plants themselves.

52. In view of these complexities, it is also worth considering whether a simpler, if cruder, criterion of collective risk might be selected. Collective risk is some combination of the individual risk and the number of individuals at risk. It is only part of the societal risk and, as with individual risk, it would have to be supplemented by other criteria. One historical way of presenting the consequences of severe accidents is the curve of the frequency of accidents each causing more than a stated number of deaths, the so-called f–N curve. Similar curves can be predicted for new plants from the results of probabilistic safety assessments. They are useful for making comparisons between different types of accident and natural disaster, but such comparisons are of limited value in making judgements about the level of societal risk that should be treated as unacceptable. The use of the absolute values in f–N curves for these judgements is even more difficult, because the selection of an f–N profile to serve as a criterion seems always to be arbitrary.

53. Another approach to societal risk is that which has been adopted for individual risk. It is apparent that for some accidents the need for intervention becomes a more limiting feature with regard to accident prevention than does the individual risk. Similarly, for severe accidents, the societal risks directly associated with the radiation doses become less important than other societal consequences.

54. In the context of potential exposure, the severity of an accident must relate to the impact on public health and the scale of intervention in the public domain, irrespective of the degree of damage to the plant. One option is to base the definition of severity on the likely magnitude and character of the radioactive release, and thus on the scale of the intervention necessary if such an accident occurs. This approach is already in use to supplement the consideration of individual risk.

4.4. RISK TARGETS

55. In INSAG-3 the target that is set for existing nuclear power plants is a likelihood of occurrence of severe core damage below about 10^{-4} events per plant operating year. Application of all safety principles at future plants should lead, according to INSAG-3, to the achievement of an improved goal of not more than about 10^{-5} such events per plant operating year. Severe accident management and mitigatory measures should reduce by a factor of at least ten the probability of major external radioactive releases requiring off-site response in the short term.

56. The probability of a given individual receiving a dose as a result of an accident is less than unity, and the risk of harm to that individual were the dose to be received would also likely be less than unity. Therefore the fatal risk to the individual posed by existing plants that meet the INSAG-3 target should be much less than 10^{-5} per plant operating year, and that posed by future plants much less than 10^{-6} per operating year.

5. THE IMPLICATIONS OF LOW PROBABILITIES

57. Regulators are often concerned with very low probabilities. Some potential exposures will have such low probabilities that they will be of no regulatory concern. Further study of such exposures is unwarranted, mainly to avoid the diversion of resources to nugatory activities.

58. There have been numerous proposals to define a radiation dose, or an activity of a radioactive substance, that could be considered, from all practical points of view, to be negligible. There is also a desire to specify an event probability so low that it can be ignored, irrespective of the potential consequences. These magnitudes would then be below regulatory concern, so that a source or a practice could be exempted from certain regulatory requirements such as notification, registration or licensing. Advice on radiation sources or practices that can be exempted from such

requirements because of the minuteness of the radiation dose is given in Safety Series No. 89, Principles for the Exemption of Radiation Sources and Practices from Regulatory Control [9] and the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Interim Edition [10]. The recommended requirements relate to both individual and collective doses.

59. With regard to potential exposure, there could never be a similar exemption of a source that could cause a serious, albeit very unlikely, consequence. The potential for large consequences can only exist for radiation sources of high activity and it is inconceivable that high activity sources would be exempted from regulatory concern. A more relevant issue is the appropriateness of cut-off values for low probability sequences or scenarios in the probabilistic safety assessment. Very low probability scenarios, or branches within scenarios, may well be of no regulatory concern and require no further analysis.

60. Some of the sequences making up a scenario may be presented by a probabilistic safety assessment as having a very low probability. This will certainly occur in computerized assessments. However, this probability is often the result of a combination of probabilities of failure of subunits that have moderate individual failure rates and that are assumed to be completely independent. This independence must not be taken for granted. It can be validated only by critical studies of the system. If no critical studies have been carried out, it is usual to ignore sequences only if their estimated annual probability is very low, so that a substantial allowance is left for unsuspected dependences and for the possibility of there being many such sequences.

61. A further problem is presented if the total annual probability of an accident is claimed to be less than about 10^{-6}. It is then very difficult to be sure that there are no unsuspected sequences of similar improbability. It is wise to refrain from claiming total annual accident probabilities of much less than about 10^{-6}. Claims for total annual probabilities of less than 10^{-7} are usually very difficult to demonstrate as being correct.

62. A common question is whether there might be events with consequences so severe that the operation of an installation would not be acceptable however low the probability of the event, unless the probability could be shown to be zero. A positive answer would rule out many human activities that we already accept. The worst possible consequence of allowing aircraft to fly over cities with sports stadiums is many thousands of deaths in one accident. We could avoid the risk but we choose not to. People live in valleys below major dams despite the risk. The benefits are perceived to be sufficient to justify the combination of consequences and probability. The feasibility of preventing the risk is also a factor in forming our attitudes. The

question is less easily dealt with when the benefits are less obvious or are controversial. Nevertheless, whatever we do, or decide not to do, we can concoct a scenario, albeit extremely unlikely, which would lead to a postulated extreme disaster. If a 'worst case' is presented, it is generally possible to postulate an even worse, but less likely, outcome. If we did not neglect such extreme events with such minute probabilities, we should not be able to take any action and, indeed, we should have to accept that non-action could also result in a similarly unlikely scenario. Clearly, we do not make decisions on the basis of such extreme situations. Furthermore, it is wrong to argue that we should select some human activities to which this extreme policy should be applied. If an activity is to be prohibited, the grounds for that decision should be consistent with the way in which we deal with other safety issues.

6. BALANCING POTENTIAL AND NORMAL EXPOSURES

63. The possible conflict of interest when, for example, normal radiation exposures are increased for the purpose of reducing potential exposures from accidents is a problem in both radiation safety and nuclear safety. This situation could occur when increased safety inspections and maintenance lead to increased normal occupational exposures in order to reduce potential public exposures. The inverse situation may also arise, when normal releases of radioactive material are reduced at the cost of storing waste on the site. This transforms the public exposure to an occupational exposure with both potential and normal components. These situations involve trade-offs between public and occupational risks and between normal and potential exposures. For the trade-off between occupational exposure and public exposure, the ICRP has recommended that the collective doses from the two types of exposure should be equally weighted. The Commission has not yet given guidance on ways of combining potential and normal exposures in this context.

64. These problems are essentially of the same nature as the problems found in optimizing safety overall by giving preference to particular options. The same types of decision aiding technique may be used. Both potential and normal exposures give rise to probabilities of harm to individuals as well as societal impacts. Achieving the optimum balance in the trade-off between these risks is not straightforward, since the situations have to be described in terms of several attributes and the judgements depend on the preferences used in defining the necessary utility functions. In practice, the necessary judgements are reached on a case by case basis by a structured appraisal of the available options, without necessarily quantifying this procedure.

7. CONCLUSIONS

65. The term potential exposure is used for an exposure that is not certain to occur. Unusual events in operations and environmental conditions may result in annual doses that are outside the normal range of values of annual doses from normal operations. Exposures that could be caused by these events are termed potential exposures.

66. In conditions of potential exposure, individual risk can be expressed in terms of the probability of the exposure and the conditional probability of death resulting from the exposure. It is not always appropriate to combine these probabilities, even when the exposures, if they occur, are small. Societal risk is more than the sum of individual risks. This report explores the relationship between individual risk and societal risk and the relevant criteria. For accidents causing serious damage to a nuclear power plant or having off-site consequences, individual risk is not sufficiently limiting because of the many aspects of societal impact.

67. In these cases, the existing goals of INSAG-3 for existing and future plants provide more restrictive targets since severe accident management and mitigatory measures further reduce the probabilities of harm to individuals from the suggested core damage probabilities. This means that for plants applying all the safety principles of INSAG-3, the annual probability of individual fatality would be much less than 10^{-5} per plant operating year for existing plants and much less than 10^{-6} per operating year for future plants.

68. There still remains the historical distinction between nuclear safety and radiation safety or radiation protection; however, the similarities are more important than the differences. The approach to dealing with potential exposures in nuclear safety results in risks that are consistent with or more stringent than the ICRP's recommendations in its recent publications.

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Annex

PROBABILITY THEORY AND ITS APPLICATION IN PROBABILISTIC SAFETY ASSESSMENT

ESTIMATION OF PROBABILITY

In general, probability is the degree of belief that a certain statement is true or that some event will occur. This degree of belief is always conditional on some postulated model or assumption, although this is often not recognized.

Since different individuals, because of their different knowledge, experience and information, may make different assumptions and use different models, all statements on probability are subjective, in the sense that someone using a different model or assumption may state a different probability. In some cases, the validity of the model or assumption may be verified by observations, in other cases this is not possible.

However, because they may use different models and assumptions, different experts may state different probabilities for one and the same event. There is then a distribution of the estimates of probability, as there is for estimates of any quantity. It is sometimes possible to assess the uncertainty of an estimate of probability.

Since probability is a concept that is mainly of use as a basis for decisions, it is the decision maker's view on what the probability is (i.e. his or her degree of belief in the estimate) that is relevant. If the decision maker is faced with a distribution of probability statements from a number of experts, this set of data will be used to derive the probability that is used as an input to the decision procedure. This is rarely the average of the statements, since the decision maker should also judge the credibility of the various experts in order to derive a weighted average and use that as the appropriate value.

The decision maker may have more or less confidence in that value, depending on whether the experts make similar or widely different probability statements. We may therefore speak about more or less *robust* probability statements.

The extent to which the choice of model may influence the conclusions about an estimate of probability can be seen from a simple example. If a coin is known to be unbiased and can be tossed in an unbiased way, there are only two possible outcomes, heads or tails. Each has a probability of 0.5. However, if nothing is known about the coin and if, in five tries, it produces five heads, the interpretation of the data depends on the model. Many gamblers will believe that the next try is more likely to produce a tail than a head. Mathematicians will reject that model and choose another. Two extreme models are available. The first is that the coin is unbiased, in which case the probability of another head is still 0.5. The second is that the coin has two heads, in which case the probability of another head is unity.

PROBABILITY AND MATHEMATICAL EXPECTATION OF FREQUENCY

In the case of N repeated trials, where the probability of a certain outcome (desired or feared) is p, the mathematical expectation λ of the total number n of such outcomes is $\lambda = p\, N$.

In games of chance, what matters is λ rather than p, although the estimate of p on logical grounds, e.g. from symmetry conditions (such as one in six for each side of a die), presents a theoretical way of assessing λ.

In cases where we speak about frequentistic probability, we have access to observations of $n = n_0$ in total for a number of sets of altogether N_0 repeated trials. We have then directly observed outcomes and may have reasons to believe that, next time, after N_x trials, the outcome will be about n_x in proportion to N_x so that:

$$n_x = n_0\,(N_x/N_0)$$

This is simple *regula de tribus* based on the number of trials and the observed number of desired or feared outcomes. There is no obvious need to bring in a probability. However, if this is done, it is conventional to say that $p \approx n_0/N_0$ and that, strictly, p is the value that n_0/N_0 would approach as N_0 tends to infinity. This means that we may alternatively speak about either (a) a probability, $p \approx n_0/N_0$, which we can use in our assessment of the mathematical expectation of n as $\lambda = p\, N$, or (b), directly, a mathematical expectation of relative frequency, being approximately n_0/N_0.

THE LIMITATION OF THE USEFULNESS OF THE EXPECTATION VALUE

If $p \ll 1$ and $N \gg 1$, the probability of n turning out as a specified number x is given by the Poisson formula:

$$P(n = x) = e^{-\lambda}\,\lambda^x/x!$$

where $\lambda = p\, N$ is the mathematical expectation of the number of outcomes (events). It follows that the probability of having zero events is:

$$P(n = 0) = e^{-\lambda}$$

and the probability of having at least one event is:

$$P(n > 0) = 1 - e^{-\lambda}$$

The nearest integer to λ is a number that is rather likely to occur, i.e. it is a central value in the outcome distribution. If $\lambda < \ln 2$, the most likely outcome is $n = 0$.

When the outcome is a number of events, it is obvious that non-integer values of λ cannot occur. However, the exclusion of some values of the expectation is less obvious when instead of each event its *consequence* is used and the mathematical expectation of consequence is calculated.

It is of interest to compare the mathematical expectation of n (i.e. λ) with the standard deviation σ of the distribution. Since $\sigma = \sqrt{\lambda}$, it follows that $\sigma/\lambda = 1/\sqrt{\lambda}$. This means that the uncertainty of the outcome is larger than the expectation if $\lambda < 1$. In this case, the mathematical expectation should not be used to guide decisions. 'Risk' in that case has to be presented as the probability of the event together with a description of the consequence of the event should it occur.

PROBABILITY AND FREQUENCY

Since probabilities are often assessed on the basis of observed frequencies, there is sometimes confusion with regard to the two concepts. It may be helpful to consider the case of the observed number of events $n_0(T, t)$ over the period from time t to time t + T. This may be compared with the mathematical expectation of the number of events n over the same period of time, assuming that the event probability per unit time is constant and equal to dp/dt. This is $\lambda = (dp/dt)T$.

It then follows that the observed number of events per unit time, the observed frequency, is $f_0 = n_0/T$, while the mathematical expectation of frequency is dp/dt. The mathematical expectation of frequency in time and the probability per unit time (the probability rate) are therefore identical quantities. The frequency, like the probability rate, is not dimensionless but has the dimension $(\text{time})^{-1}$. Its numerical value, therefore, depends on the time unit chosen. The probability of at least one event over the period T, however, is dimensionless and cannot exceed unity. It can be calculated as:

$$P(n \geq 1) = 1 - e^{-(dp/dt)T}$$

Instead of frequency, the inverse expectation of frequency, i.e. $(dp/dt)^{-1}$, is sometimes given, having the dimension time. However, this may mislead lay people. The statement that the frequency is 'one in a thousand years' may be misunderstood to mean that a thousand years have to pass before any event will happen. It is preferable to say that the frequency is '10^{-3} per year' (which strictly means that the event probability in any one year is $1 - e^{-0.001} = 0.999 \times 10^{-3}$).

PROBABILITY IN UNIQUE CASES

In the case of games of chance, where a probability is derived on the assumption of some symmetry, each event for which the probability applies truly relates to the same stochastic mechanism, for example: in throwing dice, each die and its throwing are identical to the others.

In the case of frequentistic probability, this could still be the case, but usually the observed outcome is in a heterogeneous population of individuals (or items), be it of humans, animals, valves or ball-bearings. It is not so much a matter of stochastic events in the population as in stochasticity when the population was created. That valves are found to malfunction with a certain frequency may reflect a certain frequency of valves not produced with the same quality as others. That a certain type of cancer is found at some frequency in a population may be because some individuals in that population, either by habits, environment or inheritance, are more disposed to develop that cancer.

This presents no interpretation problem as long as the estimates involve the expectation of event frequency in the population. However, if this assessment involves a quantity called the 'event probability', there may be misunderstandings. In that case, the probability relates only to an *average* individual in the population in the statistical sense. It may well be that very few individuals are average individuals; they may differ either upwards or downwards with regard to the event frequency that would be found in subpopulations of individuals of the same sensitivity. Therefore, the frequentistic probability found from observations on the population as a whole says rather little in each individual case.

The probability, which is based on frequentistic information and therefore only relates to the average individual or item (again either human or technical component), includes the uncertainty as to whether the individual belongs to one or the other of subpopulations for which the frequentistic information would differ, were it known. In some cases, the relative proportions of the subpopulations may be known, for example the frequency on the market of components that may then be assumed to have been selected (purchased) at random. If, in a probabilistic safety assessment, the question arises of the probability of failure of such components, there is a case of a set of different probabilities depending on which subpopulation the component belongs to, and, in that sense, a distribution of probabilities from which a probability for the component of unknown origin may be derived.

The magnitude of the probability in the individual case would depend on the information available to whoever states a probability. Different experts will therefore give different probabilities depending on how much they happen to know about the particular individual.

A 'true' probability in the individual case only exists if there is complete lack of information as to whether the individual in any respect deviates from the average in the population. There is also undoubtedly a true conditional probability once some assumptions have been made and a model has been defined. But each additional piece of information on the characteristics of the individual provides a new foundation for a model. What model is then truly correct, describing exactly how randomness enters into the picture? As an increasing amount of information removes more and more of the uncertainty, the actual outcome in the individual case tends to approach a deterministic result, i.e. with certainty either 'event' or 'no event'. Along the road towards determinism, it is arbitrary where to stop and define the 'true' basis for a model.

To escape this problem, which borders philosophical thinking about determinism and randomness, it is sometimes said that, even though there is no repetition in the individual case, one might think of a conceptual experiment where identical individuals are put at risk and that this would be expected to yield a frequency that would give the true probability. However, this presupposes a model for the experiment, and there is an infinite number of models that could be used. Which one is the model to use? The experimental individuals cannot be identical in a deterministic sense, because the outcome would then always be the same. There must be some degree of stochasticity involved, but at what level? The choice is arbitrary and therefore so is the outcome.

The practical conclusion is that, although there is no true model, the decision maker must adopt a model on the basis of the available information, knowledge and experience, and on that basis express a probability.

The validity of the model could be given a subjective probability by the decision maker and, if so, it becomes one component of the final probability. But there is no model for assessing the likelihood of the validity of the probability model, it is not a stochastic quantity and the degree of belief in the assumptions is entirely subjective[2]. The fact that any probability assessment is conditional on some model and some assumptions is often not recognized. Once a model is stipulated, both exact and low probabilities may be derived, but the question always remains: is the model valid?

THE SIGNIFICANCE OF SCARCE OBSERVATIONS

We may assume that the conditions for a Poisson distribution apply and that we are interested in the probability of at least some future event (assuming that all probabilities relate to observation periods of the same length). This probability is then:

$$P(n > 0) = 1 - e^{-\lambda}$$

Let us then assume that we have some past experience where we have observed $n = 1$. It might be tempting to assume that λ is then also 1, but we must recognize the

[2] It is of interest to note that people who give high odds (e.g. 1000 : 1) of being correct in their assumptions have been found on the average to be wrong in more than 10% of instances and not much more correct than those who give substantially lower odds (50 : 1) of being correct. See FISCHHOFF, B., SLOVIC, P., LICHTENSTEIN, S., Knowing with Certainty: The Appropriateness of Extreme Confidence, J. Exp. Psychol.: Human Perception and Performance 3 4 (1977) 552–564.

possibility that the outcome n = 1 is possible for an infinite number of values of λ. Since there is no non-arbitrary a priori distribution of λ that we can use to give us a weighted mean conditional on the observation of n = 1, the value of λ is not known to us. In classical probability theory it has to be accepted that λ is just an unknown constant and not a stochastic quantity with a probability distribution. With a Bayesian approach, however, we may choose to assume some a priori distribution of the possible values of λ and adjust our assumptions if more information becomes available. We may always assume that λ is larger than the observed value of n since λ = 1 is not the only value of (the unknown) λ that could give us n = 1. The only reasonable conclusion is then that it is more likely than not that there will be another event within a time period of the same length as the one for which the observation was made.

If, instead, we observe n = 0, this will not permit us to assume that λ = 0. In fact, λ = 1 would give a 37% probability of observing n = 0, and λ = 0.1 would give a 90% probability. So, the zero observation does not make a future event within a similar observation period very unlikely.

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