AUSTRALIAN ATOMIC ENERGY COMMISSION

NUCLEAR POWER PLANT SAFETY - THE RISK OF ACCIDENTS

by

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ABSTRACT

Although it is physically impossible for any nuclear plant to explode like an atom bomb, an accidental release of radioactive material into the environment is conceivable. Three factors reduce the probability of such releases, in dangerous quantities, to an extremely low level. Firstly, there are many safety features built into the plant including a leaktight containment building to prevent the escape of such material. Secondly, the quality of engineering and standards used are far more demanding than in conventional power engineering. Thirdly, strict government licensing and regulatory control is enforced at all phases from design through construction to operation.

No member of the general public is known to have been injured or died as a result of any accident to a commercial nuclear power plant. Ten workers have died as a result of over-exposure to radiation from

experimental reactors and laboratory work connected with the development of nuclear plant since 1945. Because of this excellent safety record the risk of serious accidents can only be estimated. On the basis of such estimates, the chance of an accident in a nuclear power reactor which could cause a detectable increase in the incidence of radiation-induced illnesses would be less than one chance in a million per year. In a typical highly industrialised society, such as the USA, the estimated risk of an individual being killed by such accidents, from one hundred operating reactors, is no greater than one chance in sixteen million per year.

There are undoubtedly risks from reactor accidents but estimates of these risks show that they are considerably less than from other activities which are accepted by society.

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COMPARATIVE EVALUATIONS; FORECASTING; NUCLEAR POWER PLANTS; RADIATION HAZARDS; REACTOR ACCIDENTS; REACTOR SAFETY; SABOTAGE; SAFETY ENGINEERING

SUMMARY AND CONCLUSIONS

The object of this paper is to review the public risks that could be involved in potential accidents in commercial nuclear power plants of the type now in general use throughout the world. The safety record of commercial nuclear power plants is excellent and no member of the general public is known to have been injured or died as a result of any accident. However, despite its successful development and widespread acceptance, nuclear power is now meeting highly vocal public opposition on a number of counts, one of which is the fear of accidents.

Although it is physically impossible for a nuclear power station to explode like an atomic bomb an accidental release of radioactivity from the fuel into the environment is conceivable. The problem is therefore defining the risks of such releases in terms of the consequences to the public health and their probability. The conclusion of this paper is that these risks are very small, for the following reasons.

The designs of nuclear power plants provide many safety features preventing the escape of radioactivity into the environment. The main source of this radioactivity is the radioactive fission products arising in the fuel as a result of the fission process. Three barriers prevent the escape of this material; a metal cladding encasing the fuel, the reactor coolant boundary consisting of a high quality steel pressure circuit, and finally a leaktight containment building. Designs also include several protective systems, independent of the basic plant equipment, and with high degrees of redundance and diversity. These systems prevent overheating of the fuel following any conceivable reactor fault, and provide automatic shutdown (scram) capable of dealing with any power transient or operator fault. Furthermore, all currently designed nuclear power reactors have inherently self-regulating nuclear characteristics which further reduce the chance of failure.

A major and possibly essential contributing factor to the excellent safety record of nuclear power reactors is the strict government licensing and regulatory control exercised over these plants in all countries using nuclear power on a commercial scale. In addition to a very detailed review of designs to ensure that all relevant codes, standards and safety criteria are correctly applied, regulatory bodies carry out surveillance during construction and operation to ensure compliance with all safety requirements. In cases of non-compliance, penalties are applied including refusal to permit operation.

Because of their excellent safety record the risks of serious accidents to commercial nuclear plants can only be estimated. Such estimates have recently been made by Professor Rasmussen of the Massachusetts Institute of Technology, for light-water power reactors of the type commonly used in the USA and throughout the world. His studies assumed that these plants would continue to be built under properly regulated conditions and would comply with all licensing requirements. The results of his study show that for these reactors the consequences of potential accidents are no larger, and in many cases, are much smaller than those of non-nuclear accidents. Even the largest conceivable accident to a nuclear power plant would not be as catastrophic as many people have suggested and would be less disastrous than the failure of some dams in hydroelectric schemes and other potential risks to which some members of the public are already exposed.

Rasmussen shows that the risks to individual members of the public from power reactor accidents are negligible compared with risks from other accidents which society currently accepts. On the basis of 100 power reactors in the USA he concludes that the chance of an individual dying of cancer as a result of any reactor accident would be no greater than 1 in sixteen million per year and might probably be much less. By comparison, the average chance of an individual being killed in an air crash in the USA is one chance in one hundred thousand per year.

Provided strict controls are enforced over the construction and operation of nuclear power plants, many fears currently being expressed over the consequences and likelihood of serious accidents to these plants appear to be unfounded. There is undoubtedly a risk, as in all similar human undertakings, but estimates show that these risks are considerably less than from other activities which are accepted by society.

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INTRODUCTION

In the 30 years since the first demonstration of controlled nuclear fission, many nations have devoted substantial effort to developing nuclear energy into a practical source for generating electrical power. Today energy from this source is available at a competitive cost, and most of the major energy consuming nations (and many less developed nations) are coming to depend upon it for future supplies of electricity. It may be regarded as fortunate that this has been achieved just when uncertainty regarding the supply of oil and its rapidly rising cost are causing a world wide reappraisal of energy resources. Yet, despite its successful development and widespread acceptance, nuclear power is now meeting highly vocal opposition on a number of counts.

One issue, discussed in this paper, is the fear of an accident causing exposure to radiation. Although it is physically impossible for any nuclear plant to explode like an atomic bomb, a release of radioactive material is conceivable. During operation a reactor generates radioactive substances, mostly as by-products of the fission process, and although the mass of this material is quite small, its potentially damaging effects are large. However there are many other potentially hazardous industries operating in a manner which the community accepts. The problem is therefore not so much the existence of a potential risk as the nature and extent of the risk. The questions about nuclear plant safety should perhaps be phrased:

- What are the risks of public injury by a nuclear accident?
- How do the chances of injury compare with other risks of modern life?
- Are these risks justified by the benefits they bring?

The possibility of accidents is present at all stages of the nuclear power generating process (e.g. fuel reprocessing plants, interim high-level liquid waste storage plants, and transportation) but the greatest potential for a major accident involving a large release of radioactive materials exists in the reactor itself. An objective appraisal of this risk needs to take into account the effectiveness of measures taken in the design and operation of nuclear plants to ensure that no significant fraction of these radioactive substances can be accidentally released into the environment.

SAFETY RECORD OF NUCLEAR POWER

The history of nuclear power cannot be held to justify the fear of accidents. Between 1945 and 1968, ten workers died as a result of over-exposure to radiation from experimental reactors or in laboratory work connected with the development of nuclear power. There have been no such accidents since 1968. Several accidents have occurred in which fission products were released causing contamination of the surrounding districts, but not a single member of the general public is known to have died as a result of these accidents. During 20 years of operation of commercial and military power-producing reactors, several thousand reactor-years of experience have been accumulated. No member of the general public is known to have been injured by their operation. Compared with other industries, this is an outstanding record and reflects the fact that no other technology has been developed from its conception with as much attention to safety questions.

Reporting of all abnormal occurrences in commercial nuclear power stations is a legal requirement in most countries. For example, 861 incidents were reported in nuclear plants in the USA during 1973. Many of these were trivial and none of them came anywhere near to causing harmful release of radioactivity. This fact is testimony to the effectiveness of the measures adopted by the nuclear industry to protect against such events.

Notwithstanding the excellent safety record of nuclear power, public opinion has become polarised in a debate in which some opponents of nuclear power appear to be demanding assurances of absolute safety. This is an irrational demand because it is impossible to eliminate all chances of failure. The real issue is whether operating plant has demonstrated a low enough risk to be acceptable.

SAFETY BY DESIGN

In most of the nuclear power stations currently proposed or under construction, the fuel is a ceramic oxide of uranium in the form of cylindrical pellets stacked into rods and sealed into metal cladding, usually zirconium alloy tubes. The reactor core is made up of a large number of these rods. Heat generated by the fission process is removed by the circulation through the core of a high pressure coolant which may be either water or gas, depending upon the reactor type. Most of the fission products are retained within the crystal structure of the fuel material although the highly volatile and gaseous species may diffuse very slowly to the surface. The metal cladding provides a barrier to this release.

Two further barriers prevent the release of fission products into the environment. The first is provided by the reactor coolant boundary, usually consisting of a high quality steel pressure circuit. The final barrier is usually provided in the form of a leaktight containment building designed to withstand the highest internal pressure and other loads likely to be generated from a reactor accident. Systems are provided to limit and subsequently reduce the pressure, and to clean up radioactive contamination inside this building.

An accident of sufficient severity to cause a major hazard outside the reactor site boundary would therefore need to damage the fuel material sufficiently to release substantial quantities of fission products and at the same time breach all three barriers to provide an escape route into the environment.

One accident in the water-cooled type of reactor which could conceivably cause such a train of events would be a large break in the reactor coolant boundary leading to a rapid loss of coolant. Although this would automatically shut down the reactor power, the radioactivity in the fuel continues to generate heat which, if not removed, could cause the fuel and its cladding to melt; this would release substantial quantities of fission products which would then escape into the containment building. Further mechanisms exist such as missiles generated as a result of the accident which might conceivably breach the containment itself.

Nuclear power plants incorporate many features in their design to prevent such a sequence of events. The piping and pressure vessels which together make up the reactor coolant boundary are manufactured to very stringent code requirements which reduce the probability of such a catastrophic failure to well below one chance in 10,000 years per reactor. Missile barriers are also provided to protect the containment. In addition all plants are equipped with a number of systems capable of removing heat from the core and the containment in the event of a loss of primary reactor coolant. One such system, designed to cope with the most serious loss of coolant accident, is the emergency core cooling system which has received so much attention in recent years. Hence the chain of events postulated could only occur if these systems fail in addition to the occurence of the initial accident causing the break.

Another possible mechanism for causing a release of fission products would be a very rapid and uncontrolled increase in power level. This could cause fuel melting and failure of the primary coolant boundary owing to overpressurisation and overheating. Reactors therefore have highly reliable protection systems to detect any fault condition and provide automatic corrective action. Furthermore, all currently designed nuclear power reactors have inherently self-regulating nuclear characteristics which, together with the protection system, would reduce the probability of such an accident to a negligible level.

In any engineering system, components will fail in service and human errors will occur. These facts are recognised and allowed for in the design of all nuclear plants, their protection systems and their engineered safety features. Redundancy of components and systems is provided wherever possible so that, if a failure occurs, their functions will still be performed. Furthermore, a multiplicity of different safety features are provided. Their overlapping functions provide diverse modes of protection againstunforeseen circumstances. As a final general principle, the redundant and diverse protection systems and engineered safety features are designed, as far as practicable, to be independent of each other and of the reactor systems in order to reduce the possibility of common modes of failure.

A major part of the design process involves the incorporation of well-established engineering principles by extensive use of appropriate nuclear standards and codes of practice. Codes and standards provide a base of established and proven technological practices which, when fully implemented, provide a general degree of conservatism in the overall design of the plant and hence in its operational safety margins.

It is of equal importance to ensure that these standards are complied with in the design, construction and operation of plant. Considerable emphasis is therefore placed on quality assurance programs intended to provide evidence or proof that requirements for safety have been met. In practice this means that all tasks, starting from the very conception of the design, which might ultimately have any bearing on plant safety are carried out according to planned and logical procedures. The culmination of this program is the compilation of comprehensive and authenticated records as proof that all tasks have been successfully completed.

Subsequently,over the operational lifetime of the plant a quality assurance program is implemented to ensure efficient operation, effective maintenance and periodic inspection. Authenticated documentation of the success of these activities creates a high degree of confidence in the continued safe operation of the plant.

THE IMPORTANCE OF LICENSING AND REGULATION

The low level of risk which both analysis and experience lead us to expect from a nuclear power industry depends upon effective supervision of the industry by an independent regulatory organisation. All countries with significant nuclear power programs have such organisations to license plant and plant operators and to enforce the high standards which the licences require. As with many other potentially hazardous industries (e.g. civil aviation), the system of licensing and regulation is essential to guarantee continued safe operation; the success of this policy is evident in the results which have been achieved.

Licensing authorities are responsible directly to governments and play no part in the development, design, construction or operation of plant. Their functions in nuclear power programs include:

- Formulation of safety criteria and approval of standards and codes of practice.
- Approval of all proposed sites, plant designs and operating procedures for nuclear installations.
- Approval of operators.
- Independent inspection at all stages of manufacture, erection and operation to ensure compliance.
- Imposition of penalties for non-compliance.

A requirement generally imposed by a nuclear plant licence is that emergency countermeasures be planned to control the hazard if an accidental release of radioactivity occurs. Possible countermeasures include evacuation, control of contaminated foodstuffs, and administration to exposed persons of stable, non-radioactive iodine in order to block the uptake of radioactive iodine into their bodies.

A necessary condition for the approval of a site for a nuclear installation would therefore be the feasibility of emergency action in the areas adjacent to the site.

RISK ANALYSIS

Despite all the precautions taken in design, construction and operation of nuclear installations, no responsible person in the industry claims absolute safety. The important questions therefore are 'How safe is nuclear power? What are the risks to life, health and property from possible accidents?'

All the well-informed and objective studies carried out to date lead to the conclusion that nuclear power is very safe indeed. Until recent years these studies have generally centred around a range of hypothetical accidents called Design Basis Accidents, the worst of which is sometimes called the Maximum Credible Accident. There are a number of deficiencies in using this approach for risk analysis, namely:

- it diverts attention from other accidents which may be of greater concern, either because of greater frequency (though less serious consequences) or greater consequence (though very improbable);
- it may lead the layman to conclude that these specified accidents are going to happen, regardless of probability: and
- the definition of Design Basis and Maximum Credible Accidents is arbitrary and subjective.

In recent years a new approach to risk analysis has been introduced in which the consequences and the probabilities of all conceivable accidents are evaluated. These two factors may be taken together to measure the risks from hypothetical accidents. This approach was first developed in the UK (ref. 1) and recently has been applied to nuclear power stations in the USA by Professor Rasmussen at the Massachusetts Institute of Technology (ref. 2).

Another recent independent study of reactor safety in the USA, by the American Physical Society, recognised the importance of probability in determining the risk of an accident but its authors lacked the resources to evaluate this aspect (ref. 3).

The first step in the analysis of risks from nuclear installations is to identify every combination of conceivable component failure which could lead to an uncontrolled release of radioactivity into the environment. This is done by a meticulous process of logic called 'event tree methodology' in which hypothetical accident sequences or chains are traced from the initiating fault through every possible state of performance of relevant equipment. Each alternative represents a 'branch' in the event tree. Next a probability is estimated for each branch in each sequence and the overall probability of arriving at the end of that sequence of events is computed. Naturally the highest probability at each step is that the equipment will function properly, but failures cannot be set aside as impossible and, in almost every case, the probability of failure can be predicted from experience of failures in similar equipment.

Event tree methodology is now widely used in the nuclear and aeronautical industries as a tool of safety and reliability analysis.

Recent major accidents in chemical plants, such as the Flixborough disaster in England, have led to official recommendations that such techniques should be more widely used to improve safety in the chemical and other industries. In the space industry, event tree methodology is considered an effective technique, which is capable of producing valuable numerical estimates if there is a sufficient data base for determining the probabilities of failure. However, in the space industry such a data base rarely exists.

The major potential source of hazard in nuclear reactors is the radioactive products of fission which are retained, during normal operation, within the fuel elements. Therefore the main accidents of concern are those which include failure of the fuel elements, through overheating of the reactor core, coupled with failures in systems designed to contain such releases. Data on the failure of components in the nuclear industry and conventional industries are used to compute the probabilities of these significant accidents. Great care is required in this process to allow for possible 'common-mode failures', where several failures could occur from the same cause, or where one failure could result from another failure. Great care is also taken to include all independent modes of failure, even those which are very unlikely.

The final step is to calculate the consequences of the releases of radioactivity. The main hazard is usually from airborne releases, and the consequences are therefore affected by the prevailing weather conditions, the density of population in the region downwind from the reactor and the land usage. Using weather records and population statistics for the region around the reactor site, the number of injuries and fatalities can be calculated and related to the overall probability of accidents.

The most comprehensive analysis so far undertaken is Rasmussen's study of light water reactors of the type widely used in the USA and other countries. A draft report of this study is available (ref. 2) and the publication date of the final report was expected to be late in 1975. Rasmussen now believes that his prediction of delayed cancers should be increased by a factor of three, and the final report will be adjusted accordingly. The figures quoted below from Rasmussen's study incorporate this factor of three to bring them into line with the final report. Rasmussen's study shows that accidents to nuclear power stations, like all other types of accidents, have a wide range of possible consequences. The following table, which is based on Rasmussen's paper, illustrates this point and gives upper limits of casualties for a range of hypothetical accidents:

Chance per year per reactor	Latent cancer (20 years)	Thyroid abnormalities	Genetic effects	Acute effects (within a few weeks) Fatalities	Illness
1 in 17,000*	1	12	1	1	1
1 in 1 million	1300	36,000	450	70	170
1 in 10 million	4000	130,000	1300	450	900
1 in 1000 million	10,000	250,000	3000	2300	5000

* *This is the predicted chance of melting of a reactor core.*

It is important to note that the predicted casualty figures for latent cancers, thyroid abnormalities and genetic effects are based on the assumption of a linear response to dose, with no threshold - that is no minimum harmful dose. This assumption is almost certainly pessimistic.

The table shows that even the large and highly improbable nuclear plant accidents would not be as catastrophic as many people have suggested. The population at risk in these studies was about 2 million persons downwind of the release. Within this population about 64,000 fatal cancers would be expected over 20 years from natural causes compared with an upper limit estimate of 10,000 from the largest conceivable accident. Similarly 100,000 genetic defects would be expected in one generation from natural causes compared with 3000 from the same hypothetical accident. Thyroid illnesses that might result from a large accident are the formation of nodules on the thyroid gland that can be treated by medical procedures and rarely lead to serious consequences. There might be a measurable increase in the incidence of thyroid cancer but this would be relatively small and is rarely fatal, assuming normal medical care. Rasmussen does not give figures in his draft report for the number of thyroid cancers.

Accidents with a chance less than one in a million per year would be so unlikely that many persons are prepared to consider them incredible. The consequences of accidents which could be considered credible are therefore unlikely to cause a detectable increase in diseases.

COMPARISON WITH OTHER RISKS

(a) Single Accidents

When discussing risks from accidents, both the consequences and the probabilities should be taken into consideration. On this basis it can be fairly claimed that the risks to the public from single potential reactor accidents as discussed in the previous section are very small. The potential consequences of reactor accidents are no larger , and in many cases are smaller than those of non-nuclear accidents, some of which can occur in alternative methods of generating electricity. For example, the failure of certain dams in hydroelectric schemes could have even more disastrous effects than the worst conceivable reactor accident. Weinberg, quoting estimates made by Professor David Okrent of the University of California (4), states that the probability of failure of dams is between once in a hundred years and once in a thousand years per dam. He further states that possible deaths from dam failures in the USA could be as high as 250,000 (e.g. the Folsom dam near Sacramento).

It should be noted that certain other risks such as earthquakes and aeroplane crashes into crowded areas have caused very large losses of life from single events and also have the potential for producing more deaths than the largest conceivable reactor accident. Air crashes causing more than about 200 fatalities have a probability of once in ten years in the USA and earthquakes causing more than 10,000 fatalities about once in 100 years.

(b) Total Risks from all Accidents

In addition to the risks from single accidents, it is useful to consider the average risk to the community from all accidents, both nuclear and non-nuclear. The following figures,based on US data, are typical for modern industrial societies. The figures for reactor accidents are based on all potential accidents including the worst conceivable events.

In the following table the chances of death from non-nuclear accidents refer to acute injuries leading to loss of life in a short time. The directly comparable figure for nuclear accidents is therefore 1 chance in 300,000,000 years which does not include the chance of latent cancers.

Some of the conventional accidents, particularly motor car accidents, will also be associated with a long term risk of death as a result of physical injuries and their associated diagnostic X-rays. The later point is of interest since, if the same criteria are applied as have been used in determining the number of cancers from reactor accidents, then this risk might be significant.

The figures in the table are averages for the whole population except the nuclear accidents. These have been averaged over the population within 20 miles radius of the reactor since, from the Rasmussen study, these would be exposed to the major risks. If nuclear risks were averaged over the whole population, the average risk would of course be lower. However, it is already clear from these figures that the risk to the individual from nuclear power is negligible compared with the risks society currently accepts.

Accident type	Average chance of death per year per individual
Motor vehicle	1 in 3,000
Fires and hot substances	1 in 25,000
Drowning	1 in 30,000
Air travel	1 in 100,000
Electrocution	1 in 160,000
Railways	1 in 250,000
Lightning	1 in 2,000,000
Hurricanes	1 in 2,500,000
Nuclear reactor accidents (Based on 100 reactors on 66 sites in the USA)	
(a) Within a few weeks	1 in 300,000,000
(b) Within about 20 years	1 in 16,000,000

THE RISK OF SABOTAGE

It would be very difficult for saboteurs to cause sufficient damage to a nuclear power station to produce a harmful release of radioactivity to the environment. Expert knowledge and unrestricted access to several parts of the plant would be minimum requirements. It would be impossible for saboteurs to cause more serious consequences than the worst reactor accident, and the most likely effects of their actions would be much less serious. If infringement of public safety were their intent it would be possible to achieve greater effects more easily by other methods.

Nevertheless it is conceivable that a determined and knowledgeable group of saboteurs could cause severe damage and the owner of a nuclear plant should obviously provide the security necessary to make sabotage very difficult.

A number of countries have studied the possible sabotage of nuclear plants. The results of most of these studies are not published in order to avoid suggesting courses of action to would-be agents. However, the conclusion has been reached that effective action is possible to deter and prevent sabotage. In an unclassified study (ref. 3) the American Physical Society examined several possible improvements of current physical security at nuclear power plants and concluded 'that significant countermeasures to sabotage could be implemented at reasonable cost and without interfering with normal operations.'

QUESTIONS AND ANSWERS

As an appendix to this paper some questions that arise in the consideration of nuclear plant safety are answered.

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APPENDIX A

NUCLEAR PLANT SAFETY : THE RISK OF ACCIDENTS

SOME QUESTIONS ANSWERED

Index to Questions

SOME QUESTIONS ANSWERED

1. *Has there ever been a reactor accident?*

Yes, there have been several, most of them in experimental and prototype reactors, and most of them more than ten years ago. Four laboratory workers have been killed by reactor accidents and two by accidents in experimental critical assemblies. No member of the general public is known to have been harmed.

The worst accident in terms of injuries occurred in 1961 when a violent release of steam from a small experimental military reactor (the SL-1) at the National Reactor Test Site, at Idaho Falls in the USA, killed three members of the operating staff. The accident was caused when a reactor control rod was withdrawn by hand during maintenance. This operation would be physically impossible in today's nuclear power plants. Although the SL-1 had no containment, only 0.01% of the fission products escaped into the atmosphere and there was no hazard to the general public.

The only other death reported from reactor accidents occurred from inadvertent criticality in a research reactor at Vinca in Yugoslavia in 1958. Five laboratory workers were injured and one subsequently died from his injuries.

The most widespread environmental consequences of a reactor accident occurred in England in 1957 when an air-cooled, graphite-moderated reactor at Windscale caught fire, releasing 20,000 curies of iodine-131 and other fission products to the atmosphere. No member of the public was hurt but, as a precautionary measure, the use of milk from cows in the district was restricted for a short period. The sole purpose of the Windscale reactor was plutonium production for the British weapons program. It produced no electricity and bore no resemblance to current designs of commercial power reactors.

Another serious accident in terms of plant damage involved the failure of some twenty fuel elements in the Canadian NRX research reactor in 1952. About 10,000 curies of long-lived fission products were released inside the reactor building, but there were no known injuries. The accident was caused by a complex sequence of events including common mode failures of control and protection systems. The reactor core was damaged beyond repair, but the reactor later went back into service with a new and improved core.

Two accidents occurred more recently in the Enrico Fermi experimental fast breeder reactor in the USA (1966) and the Lucens pressure tube reactor in Switzerland (1969). In both cases localised failure of fuel elements occurred due to overheating and the reactors shut down automatically. There were no significant releases of fission products outside the containments, and no injuries.

2. *Has there ever been an accident in a nuclear power station?*

There have been conventional industrial accidents, but there has never been a harmful release of radioactivity. The worst accident on record which caused limited melting of fuel in a nuclear power station was in the French 500 megawatt (electrical) St. Laurent 1 reactor in 1969. A fault during refuelling, which was carried out with the reactor at power, caused partial blockage of coolant flow in one channel. All safety systems functioned correctly and there was no fission product release even inside the reactor building. The reactor was of a natural uranium fuelled, gas-cooled type which is no longer built.

3. *But there must have been many near misses. There are many reports of failures of plant in nuclear reactors, so haven't we just been lucky so far?*

We all know from our experience with man-made machines that they sometimes fail. We know with certainty that failures will occur in a large machine with many component parts. This is allowed for in the design of nuclear reactors and is not left to chance.

A review of all the failures which have occurred in commercial plants shows that none of them came even close to releasing fission products to the environment. Furthermore, many of these so-called 'failures' were detected and corrected before the component could fail in service. This is testimony to the effectiveness of inspection and fault finding techniques.

The failures which did occur in service give a clear indication of the ability of modern nuclear plant to survive a wide variety of component failures with no serious consequences. They refute the argument of some people that nuclear plants must be perfect and that any small failure may have a disastrous consequence. In fact it is difficult to think of any other complicated machine that is so tolerant of failures within its systems. This is because reactors are designed that way. It is not luck!

4. *With all these component failures aren't nuclear power stations very unreliable as sources of electricity?*

They are not greatly different from any other type of power station.

There is certainly scope for improvement in some nuclear plants, but the average availability of most nuclear power stations and modern conventional power stations has been quite comparable.

5. *What guarantees do we have that the good safety record of nuclear power will continue? Can we rely upon manufacturers and operators of nuclear plant to maintain safety standards, particularly if it costs money to do so?*

The manufacturers and operators of nuclear plants must comply with legally enforced regulations. Any activities in any industry which is potentially harmful to either employees or the general public must be conducted in a responsible and safe manner. Included in this category are civil aviation, the chemical industry, the use of boilers, lifts, scaffolding and applications of radioisotopes. The necessary control over such activities is provided by the enforcement of legal requirements which are designed to ensure that due consideration is given to the potential hazards.

6. *Who is responsible for issuing and enforcing safety regulations?*

The appropriate National, Federal or State Government.

7. *How do Governments achieve safety through regulations?*

In the case of nuclear installations a body of specialist experts is formed with the capability of establishing the regulatory requirements and subsequently of implementing a policing action to ensure that they are enforced. This is achieved through a system of permits and licences which are conditional upon meeting the regulations.

8. *Is an accident possible in a nuclear power station?*

Yes it is. However for there to be a harmful release of fission products several simultaneous failures would be necessary. This is obviously very unlikely. For example, there would have to be some failure of the reactor plant such as a leak of coolant, and simultaneously a failure of some protection system or engineered safety feature such as the emergency core cooling system. This could lead to melting of the fuel and release of fission products. However, there would also have to be a failure of the containment systems to allow these fission products to be released into the atmosphere.

9. *But hasn't it been shown that the emergency core cooling system would fail to work in any loss of coolant accident?*

Not at all. In the great majority of conceivable failures for which the emergency core cooling system has been designed to give protection, it would be quite adequate. There are some relatively unlikely modes of reactor failure in which it is difficult to provide a fully quantitative estimate of the performance of the emergency core cooling system, but this doesn't mean it would not work.

10. *Is it possible for a nuclear power station to blow up like an atomic bomb?*

No, this is physically impossible because the fuel contains such a small percentage of the fissile isotope uranium-235. This is agreed even by the critics of nuclear power who have studied the problem.

11. *What is the reactor hazard then?*

A hazard to the public could arise from exposure to radioactive fission products released as a result of a reactor accident. These fission products are contained within the fuel elements during normal operation. Acute or short-term effects (The Acute Radiation Syndrome) are associated with a large whole-body dose of ionising radiation delivered over a short period of time. A few such casualties would be possible in a very severe reactor accident, but most predicted casualties would be delayed cancer and genetic effects. If fission products escape into the atmosphere, they can cause cancer and genetic damage by external irradiation of the body, or they may enter the body by inhalation or ingestion and cause these effects from internal irradiation. Internal irradiation is usually more dangerous and the principal hazard is from volatile fission products, such as iodine-131 which concentrates in the thyroid gland.

12. *What about the hazard from an accidental release of strontium-90?*

Strontium-90 is chemically reactive and forms a refractory oxide, so that only a very small fraction of this material could be released even at the melting point of the fuel elements. Experiments have in fact shown that it is very difficult to extract a high proportion of fission products from irradiated fuel by heating. Releases to the atmosphere would probably be much lower than are generally assumed in safety analysis calculations and it is unlikely that any significant amount of strontium would escape.

13. *If a reactor accident occurs is there any protection against fission products?*

Yes. A precondition, required by the licence, for the operation of a nuclear power station is the existence of an emergency organisation. In the event of any accidental release of fission products, designated staff would immediately take appropriate countermeasures to protect the public.

This might involve simply telling people to stay indoors for a short period, but in extreme circumstances temporary evacuation of some areas might be deemed advisable. It would also be normal to control any foodstuff which might be contaminated with radioactivity. Medical authorities in Australia have recommended levels of radiation dose at which these actions should be taken. If people are exposed to radioactivity despite these precautions, health physics and medical attention would be available.

14. *How would the dose levels be known at the time?*

Safety staff are equipped with sensitive instruments capable of measuring radioactivity over a wide range, which covers all the appropriate activity levels.

15. *The release of fission products from a large reactor would surely cause enormous damage and loss of life much greater than any other accident that could conceivably occur.*

No, this is not true. Certain risks such as earthquakes, dam failures and aeroplane crashes into crowded areas have the potential for producing considerably more damage and deaths from a single event than the largest possible nuclear accident. However, these large accidents are very unlikely.

16. *There is no aircraft crash on record which involved more than a few hundred deaths.*

Quite true, and the worst reactor accident on record killed three people who were all members of the operating staff (see Answer to Q.1). Worse reactor accidents and worse aircraft accidents are possible though very unlikely. The sizes of passenger carrying aircraft are continually increasing and we have all seen jumbo jets taking off and landing over crowded surburban areas. What if two loaded airliners collided? Furthermore, there is quite often a large sports stadium near an airport. The most hazardous time for aircraft is during take off and landing. From statistics on aircraft accidents obtained throughout the world it is possible to calculate the probability that a fully laden jumbo jet could crash into a crowded stadium during a popular sporting occasion. This hypothetical accident could involve many thousands of deaths and many millions of dollars worth of damage. Lesser accidents (e.g. crashes into high density residential or business areas) would be more probable and some have occurred. The risk is extremely small and society has accepted it. The risk of a serious reactor accident is even lower.

17. *But wouldn't a reactor accident cause permanent radioactive pollution of the whole biosphere, like fall-out from atomic bombs?*

Radioactive materials released into the atmosphere or surface waters would disperse within a short time and most of the more dangerous radionuclides decay quite rapidly. For example, iodine-131 has a half life of eight days. Even in the worst reactor accident, only a small fraction of the exposed population around the site would receive doses in excess of a single diagnostic X-ray, and the dose commitment to the rest of mankind would be immeasurably small. Radioactivity which entered the soil would be a less acute and more readily controlled hazard than air-borne material. However, it would be a longer-term problem possibly leading to higher costs for decontamination, monitoring etc.

18. *If a serious reactor accident has never occurred how can we know what the consequences would be?*

It has already been mentioned that there have been several small-scale reactor accidents and a great deal was learnt from the study of these. However, by far the greatest store of knowledge comes from the billions of dollars worth of investigations that have been carried out throughout the world in the past 30 years by means of theoretical analysis and experiment. A great deal is in fact now known about the behaviour of nuclear plants under fault conditions, the behaviour of fission products released from molten fuel, and the effect of radiation on living organisms.

The dispersion of wind-borne pollutant material in the atmosphere and the uptake of elements and their compounds by living organisms are subjects of much wider interest, but again the nuclear industry pays more attention to them than most other industries. Where there is uncertainty in all this information, pessimistic assumptions are made so that estimates will err on the conservative side. Further research is continuously in progress to remove these uncertainties.

19. *And what about the probabilities of nuclear plant failure?*

There has been a great deal of experience in the operation of nuclear plants, and data are available from the failures of components within these plants. Furthermore the nuclear industry makes use of conventional technology so that data on the failure of components in other industries are relevant to the estimation of accident probabilities in the nuclear industry. These data have been collected for many years and are available from a number of data banks in various parts of the world, particularly the UK and the USA. Information of experience of failures serves two purposes: it helps to identify ways of avoiding such failures in future and it provides the basis for estimating the probability that similar components will fail.

20. *What about the reactor pressure vessel? Wouldn't the failure of such a massive component lead to widespread damage and cause failure of all the reactor protection systems and engineered safety features?*

It depends upon the type of reactor we are talking about. In a reactor with a steel pressure vessel this could conceivably be true, particularly if failure occurred in a brittle manner producing missiles. However these pressure vessels are fabricated from materials which are chosen to be ductile for the full life of the plant, and are inspected both before and during service by a number of means including ultrasonic and radiographic techniques to determine whether any faults exist in the material or the welds which could lead to failure. Again, the widespread experience of conventional pressure vessel technology is relevant and there has never been a catastrophic failure in service of a vessel constructed and tested this way. This type of failure is in fact one of the least probable reasons for a major reactor accident. It is estimated to occur less than once in a million reactor-years' operation.

21. *What different sorts of reactors are there?*

Apart from reactors with steel pressure vessels, using water or gas as coolant, there have been two main types of reactors licensed in various parts of the world for operation as commercial power stations. These are gas-cooled reactors with prestressed concrete pressure vessels, and pressure tube reactors which use heavy water as their moderator. Each type of reactor has somewhat different safety features but the general comments made here apply to every licensed reactor type, particularly the very low probability of occurrence of a serious accident.

22. *What about the safety of the fast reactor?*

The fast reactor is still under development and has not yet been licensed for commercial use. Assuming that fast reactors are licensed in the future, they will be required to conform with the same standards of safety as present nuclear power stations.

23. *Risks and probability numbers are very difficult for the layman to understand. What do they actually mean in practice?*

The numbers show that the risk from a nuclear power station is extremely small. It may be easiest to appreciate this if the risk to the average member of the general public is compared with other risks he is already used to. If most of society's future needs for electricity were met by nuclear power, the risk of death from radioactive material released from these power stations would be about 5,000 times less for an average citizen living within 20 miles of a station than his risk of death in a motor car accident, and about 10 times less than the risk of being struck by lightning. His chance of being killed by electrocution in his home would be about 100 times greater than his chance of being killed by an accident in the nuclear power station which generated the electricity.

24. *But these are familiar risks which can be avoided with care. The risk from radiation is something we cannot see and the result may be cancer we do not even know we have caught until years later.*

This distinction is not valid. Even the most careful driver cannot entirely eliminate his chance of being killed in an accident. It is very difficult to reduce the risk of being involved in a motor car accident by more than a factor of about ten below the average for the community except by staying off the roads completely. (Have you ever thought how you would manage if you didn't use a motor vehicle?) Public transport is a little less risky but not 100% safe. If a person is injured in a motor car accident he will probably by X-rayed immediately and receive perhaps 100 millirems of radiation dose. Even this small dose produces a very small risk of cancer which is this case is considered to be justified by the need for medical diagnosis. Many of the casualties which are predicted to result from nuclear power station accidents are from individual doses less than 100 millirems. In view of the very large number of casualties who are X-rayed, motor car accidents lead in fact to a greater radiation hazard to the community than nuclear power station accidents.

25. *But radiation risks have been compared with risks from natural hazards such as lightning and earthquakes. We are exposed to these risks whether we like it or not.*

To some extent this is true. However the risk of being struck by lightning can be largely eliminated by staying indoors during a thunderstorm. Also a person has a large measure of choice in deciding where he lives. Areas which are particularly subject to a high risk of natural catastrophes such as earthquakes are usually well identified, and people who live there can at least decide to construct buildings, bridges etc. to standards that will withstand earthquakes. This is mainly a question of financial priorities. The risk to the community can therefore be controlled over a wide range as a matter of choice. To a very large extent therefore the risk from these natural hazards is caused by man himself.

Alternatively, consider pollution from conventional industries, which many of us might complain we are exposed to whether we like it or not. Some conventional pollutants are known to have poisonous effects including the induction of cancer, although much less is known about these than about the effects of radiation. The risk from nuclear power is much lower than the risk to health from industrial pollution even when strict environmental protection controls are applied to the latter.

26. *Could an earthquake cause a serious reactor accident?*

Nuclear power stations are designed to withstand earthquakes where there is a significant risk that these may occur. It is of course conceivable than an earthquake could occur which is greater than the reactor has been designed to withstand, but this is highly improbable. The extent of property damage and injury caused directly by such an earthquake would be much greater than the effects of the radioactivity which might be released.

27. *If the risks from nuclear power are so small why do personal insurance policies exclude damage from radioactivity?*

Because personal insurance cover for this risk is not needed. All countries which have significant nuclear power programs have enacted legislation which places absolute liability on the operators of these plants. The operator becomes liable for nuclear damage solely upon proof that such damage has been caused by an incident occurring in his establishment. The operator cannot escape his liability even if entirely blameless. The channelling of liability absolutely to the operator removes the public's difficulties in proving negligence and avoiding the need for costly and protracted litigation. Claims may usually be lodged within 10 years or so of the incident.

28. *How much insurance cover must the owner of a nuclear power station take out?*

The amount varies between different countries and is dependent upon the cover available from the insurers. In order to meet the demand for financial cover, the insurers have grouped themselves into nuclear insurance pools.

In the United Kingdom a cover of five million pounds sterling must be provided from private insurance. In the United States the law requires each operator to provide cover at the maximum amount available from private sources - currently some 120 million dollars (US).

29. *Is it possible that the extent of damage from a single nuclear power station accident could cost more than the amount covered by private insurance?*

Yes, this is possible but extremely unlikely. Such a situation is not unusual in insurance. When very rare major calamities occur, this becomes a national disaster and compensation is paid by governments. In the recent Darwin disaster for example the total cost was far greater than the insurance cover. Legislation in most advanced nuclear countries provides for government indemnity in excess of 100 million dollars (US).

30. *But even if the risk is very small why should we take on any additional risk at all?*

This is a matter of community choice taken by balancing the risks and benefits of various alternative ways of life. No human activity can be undertaken without the acceptance of risk and sometimes we accept very high risks indeed in order to enjoy an activity or a life style of our particular choice. On the other hand, an individual can choose a simple life in the country away from all industrial pollution, never travelling in a motor car, never using electricity and never smoking, drinking or engaging in any sport or recreation. Unless he was prepared to expose others to the risks which he was himself avoiding, he would also have to live in a cave and forgo the products of industry, modern medical attention and drugs, and any money derived from an industrial society. This would probably be quite a high risk option compared with the lives that most of us now lead and he would suffer considerable privations. Witness the increase in the human life span over the last 100 and the last 1000 years. It is unlikely that many people would adopt this life style willingly and it is inconceivable in a democracy that it could be imposed.

Assuming therefore that most people would wish to continue approximately their present lifestyles, perhaps with restricted population growth, restricted economic development and more efficient use of resources, we should therefore ask ourselves which is the best and safest method of generating the energy which our society will require. Of the resources of energy presently available to us at a reasonable cost, nuclear power is significantly the lowest risk option for meeting future demands. Furthermore, the risk from utilising nuclear power is negligible compared with other risks that society already accepts.

GLOSSARY

The following definitions are provided for the reader not familiar with some nuclear and other terms used in this paper. The explanations are drawn from standard glossaries.*

biosphere	That part of the earth and the atmosphere surrounding it which is able to support life.
breeder	A reactor which produces more *fissile* material than it consumes. *Fertile* material included in the core is transformed into *fissile* material by *neutron capture*
containment	The prevention of release, even under the conditions of a reactor accident, of unacceptable quantities of radioactive material beyond a controlled zone; also the containing system itself.
coolant	A substance used to remove heat from a primary source such as a reactor core.
critical mass	The minimum mass of *fissile* material which can be made capable of sustaining a nuclear chain reaction; whence *criticality*, the condition of being critical; *criticality accident; critical assembly* (of materials for experimental purposes).
curie	A unit of activity defining the number of spontaneous nuclear disintegrations occurring per unit time; 1 curie = 3.7×10^{10} disintegrations per second; whence picocurie, microcurie and similar sub-multiples.
fast reactor	A reactor in which *fission* is induced predominantly by *fast neutrons*, that is, neutrons moving at high speeds; whence fast *breeder* reactor.
fissile	See *fissionable*.
fission	The splitting of a heavy nucleus into two approximately equal fragments. This is accompanied by the emission of neutrons and release of energy; whence *fission products*, the atoms formed in the fission process.
fissionable	Capable of undergoing *fission* by any process. In British usage it is equivalent to *fissile* but in US usage, *fissile* is restricted to interaction with slow neutrons.
genetic	Concerning origin; whence *genetics*, the study of heredity and variation.

heavy water	Deuterium oxide (D_2O); *deuterium* is an isotope of hydrogen with mass number 2.
ionising radiation	Radiation which knocks electrons from atoms during its passage, thereby leaving electrically charged particles (ions) in its path; whence *ionisation*.
irradiation	Exposure to ionising radiation.
megawatt	The normal practical unit of power station capacity (one million watts). Sometimes megawatts (electrical) and megawatts (thermal) outputs are signified, and are related by the thermal efficiency of the power stations.
moderator	A material used to moderate neutron energy.
monitor	A device used to measure the level of *ionising radiation* or quantity of radioactive material and possibly to give warning of departure from prescribed limits. Also a person who uses a *monitor*.
radiography	The examination of objects by passing X, *gamma* or *neutron radiation* through them and photographing the shadows cast.
radioisotope	An *isotope* which is radioactive.
radionuclide	A *radioactive nuclide*; a *nuclide* is a species of atom characterised by its mass number, atomic number and nuclear energy state.
rem	A unit of radiation dose equivalent, the product of absorbed dose, quality factor and other modifying factors necessary to obtain an evaluation of the effects of irradiation received by exposed persons, so that the different characteristics of the exposure are taken into account; whence *millirem* etc.
threshold dose	The smallest dose of a harmful agent that will produce a specified result.

* Sources :

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