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Comparing Nuclear Accident Risks with Those from Other Energy Sources

NUCLEAR ENERGY AGENCY

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NUCLEAR ENERGY AGENCY

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FOREWORD

Following the accidents at Three Mile Island and Chernobyl, nuclear power development slowed dramatically worldwide. Since that time, the safety of nuclear power has been a topic of frequent discussion, but is often not put in the context of the safety record of the whole nuclear industry or compared to the risks from other energy sources.

This report looks at how the safety of nuclear power plants has improved over the years, as designs have progressed from Generation I to Generation III. It highlights the importance of the defence-in-depth concept and the increased focus on safety culture. Using probabilistic safety assessment, it compares core damage frequencies and large radioactive release frequencies to show how the designs of nuclear power plants have evolved to reduce the likelihood and consequence of severe accidents. It compares severe accident data (accidents with five or more fatalities) from a wide range of energy sources to illustrate that nuclear energy risks are often much lower than in other industries. The comparison examines both immediate fatalities and delayed (latent) fatalities, while recognising that the latter are more difficult to estimate and to verify. Finally, the report uses results from opinion surveys to consider public confidence in nuclear operations and how this is correlated with trust in legislation and regulatory systems.

From these assessments, conclusions are drawn on the need to continuously enhance safety and to improve public knowledge of how nuclear power plants are operated and regulated. Vital to public confidence is the need for transparency and openness in the decisions and activities related to nuclear power plants. The report has been written mainly for a general audience and energy policy departments.

Acknowledgements

This report was written by Stan Gordelier and revised by Ron Cameron, Head of the NEA Nuclear Development Division, under the supervision of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC).

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KEY ISSUES FOR POLICY MAKERS

This report is aimed at providing energy policy makers with data and information that will enable an understanding of how accident risks are managed in nuclear plants and as well as providing them with an analysis of the relative risks presented by nuclear and various other energy chains. It also provides policy makers with insights on the public perception of nuclear risks. It is not aimed at nuclear safety specialists who will know much of this material already, nor is it intended to be a comprehensive discussion of the key elements in nuclear design and operation.

A primary means of preventing and mitigating the consequences of accidents is by the application of the concept of defence in depth, in which consecutive and independent levels of protection are used to minimise or eliminate harmful effects that could be caused to people and the environment.

A strong safety culture by operating organisations is also essential to ensuring the integrity of the multiple barriers of defence. Data on indicators of operational performance and indirectly of safety culture show a steady improvement over the last two decades, in all regions of the world and for all types of reactors.

Reactor designs have also evolved to reduce the level of risk presented. Since accidents that result in a significant release of radioactivity are extremely rare, the estimates of risk are based on calculations using well known probabilistic techniques. These illustrate that the theoretically calculated frequency of a severe nuclear power plant accident followed by a large radio-activity release has reduced by a factor of 1 600 between the original designs of early Generation I reactors and the Generation III/III+ plants being built today. It is important to note that the "as originally designed" performance of the earlier plants has also been improved by upgrades over subsequent years.

Comparison of real accident statistics for severe accidents (defined as those resulting in 5 or more prompt fatalities) with the theoretically calculated

accident statistics of nuclear power plants show that, contrary to many people's perception, nuclear energy presents very much lower risks. For example:

- More than 2 500 people are killed every year in severe energy related accidents and this figure is increasing as energy demand increases.
- Between 1969 and 2000 there were 2 259 and 3 713 fatalities in the coal and oil energy chains respectively in OECD countries, and 18 017 and 16 505 fatalities in non-OECD countries. Hydropower was responsible for 29 924 deaths in one incident in China. In contrast, there has only been one severe accident in nuclear power plants over this period of time (Chernobyl) which resulted in 31 fatalities.

Assessment of the delayed (latent) fatalities associated with the exposure of radioactive material released by the Chernobyl accident indicates numbers up to 33 000 over the next 70 years assuming a linear non-threshold effect of radiation (i.e. even a small amount of radiation will result in an associated very small risk). On this basis, natural background radiation would result in 1 500 times as many deaths (about 50 million) over the same timescale, so these additional fatalities, if they occur, would be very difficult to observe.

Any comparison of latent deaths should also include a comparison with those resulting from the exposure to emissions from fossil fuel use. Data on these is difficult to find but we note that the OECD Environment Directorate estimates that 960 000 premature deaths resulted from levels of particulates in the air in the year 2000 alone, of which energy sources accounted for about 30%. Latent deaths from fossil fuel use thus outweigh the deaths resulting from all energy chain accidents, including those from Chernobyl.

In addition to the main responsibility of the operator, the excellent safety performance of nuclear power generation is, at least in part, related to the efforts of nuclear regulatory bodies over the years in setting demanding standards of design and operation. Opinion polls also show that trust in the regulators and regulations is correlated with confidence that nuclear power plants can be operated safely. It is important that governments continue to ensure that regulatory bodies have the resources and competences they need to maintain the necessary high standards.

EXECUTIVE SUMMARY

Many countries are reconsidering the role of nuclear energy in their energy mix, as a means to alleviate the concerns over climate change, security of energy supply and the price and price volatility of fossil fuels. However, nuclear energy remains a contentious technology in some political circles and in the minds of many members of the public.

One of the issues that causes concern is that of the safety of nuclear power plants. However a rational choice of energy sources should involve an even handed comparison of the risks presented by the various energy chains available. There is little real value in rejecting one source if that which replaces it presents even greater hazards. The purpose of this document is to provide energy policy makers with quality data and information that will enable an understanding of how accident risks are managed in nuclear plants and also provide a rational analysis of the relative risks presented by the various major energy chains used for the production of electricity.

The report starts by considering a major component of the design philosophy adopted in nuclear reactors, explaining the concept of defence in depth. Defence in depth is implemented through the combination of consecutive and independent levels of protection that would all have to fail before harmful effects could be caused to people or to the environment. If one level of protection or barrier were to fail, the subsequent level or barrier is still available to provide protection.

Next, the report discusses the important issue of the safety culture of operating organisations in maintaining a low level of risk. The quality of an operator's safety culture cannot be measured directly. The international community has developed a number of indicators which are tracked and compared to allow a judgement of the performance trends in nuclear power plants. The report presents data for the indicators of unplanned automatic trip rate, worker collective and worker individual radiation exposure. The data shows that there have been very positive trends in all of these indicators over the last two decades in all the regions of the world and in all types of reactors.

The risk associated with the operation of a nuclear plant is that radioactivity is released to the environment, resulting in exposure by and health effects to the population. Since significant releases of activity are extremely rare, reliance on statistics of events is not possible. The report uses the analytical technique of probabilistic safety assessment (PSA) by which potential accidents, their probabilities of occurrence and their consequences can be assessed. It is common to look at the outcomes in terms of the theoretical probabilities of core damage (an accident in which the fuel cladding is ruptured, for example by overheating and melting) and the more severe events in which significant radioactivity breaches the primary circuit and the secondary containment and is released to the environment. These two measures are termed the theoretical core damage frequency (CDF) and the theoretical large release frequency (LRF). While these are not actual statistics on accident rates, they serve to illustrate the trends.

The report looks at the "as originally designed" CDFs and LRFs over the evolution of reactor designs from Generation I to Generation II and on to Generation III/III+. It shows that, over this evolution, there has been a very significant reduction in both CDF and LRF. While this clearly indicates that modern designs are extremely safe, it is important to recognise that earlier designs have also been back-fitted with safety improvements, often evaluated using the techniques of PSA. If the world turns to nuclear energy in large measure to alleviate the energy issues it confronts, it can be expected that this evolution in CDF and LRF reduction will continue and it is desirable that it does so.

The report then looks at real accident data from full energy chains, using an impressive collection of data assembled by the Paul Scherrer Institute (PSI) in Switzerland. Using this severe accident data (events that have resulted in 5 or more prompt fatalities that have actually occurred from 1969 onwards) it compares the outcomes with the theoretical accident outcomes from PSA analysis (since there are no real nuclear accident data from OECD countries and only one data point from non-OECD countries). This shows that, contrary to the expectation of many people, nuclear power generation presents a very low risk in comparison to the use of fossil fuels.

The latent fatalities (i.e. deaths resulting from the exposures of radioactivity over long periods after the event) from the Chernobyl accident are also considered. These are of the same size as the prompt deaths from the world's biggest non-OECD hydro accident. They are also considerably smaller than the latent deaths resulting from fossil fuel use, although data on these is difficult to find.

Finally, public confidence in the legislative and regulatory process is discussed. In addition to the rigorous work performed by the industry, the low level of risk presented by nuclear power is also a tribute to the efforts of regulatory bodies over the years and the standards that they have demanded in design and operation. The role of the regulators in enabling public trust is also explored using data from public opinion polls. Public acceptance that nuclear reactors can be operated safely seems to come as a package with trust in the regulators and there is a strong correlation between trust in regulators and trust in operators. Those countries already with nuclear power in their energy mix show much higher levels of confidence and trust than those without.

1. INTRODUCTION

This report is aimed at providing energy policy makers with data and information that will enable an understanding of how accident risks are managed in nuclear plants as well as providing a rational analysis of the relative safety of various energy chains. It is not aimed at nuclear safety specialists although they may find some of the material of interest. Specialists in the area of nuclear safety are directed to the extensive work of the NEA Committee on Nuclear Regulatory Activities (CNRA) and the Committee on the Safety of Nuclear Installations (CSNI). The work of these two committees can be accessed via the NEA website.

Nuclear safety is a global issue; a serious event in one country may have a significant impact in neighbouring countries. In the 1970s, the utilisation of nuclear energy was expanding rapidly. The accident at the Chernobyl nuclear power plant in 1986, which directly affected the local community and neighbouring countries, globally affected the expansion of new nuclear power plants. It is clear that another severe accident will have similar consequences should it ever occur. While most nuclear power plant designs included a reactor containment building, since the Generation III/III+ plants, all reactors are designed so that the consequences of any severe core damage are contained within the reactor containment building – the probability of a large radioactivity release is much reduced. However, the economic consequences of such an event would still be very significant and would have a major negative impact on future investment decisions.

Despite nuclear energy's potential to help combat the serious issues of energy security and climate change, a poll for the European Commission showed that over half of Europeans think the risks of nuclear power outweigh its advantages. Intense media and public sensitivity to nuclear energy means that an event which, in reality, has small safety significance comes to have a disproportionate impact on the international industry. Safety standards must be above reproach even if, as this study shows, public concern on the relative safety of nuclear compared to other sources of electricity generation is not supported by the statistics.

Nuclear safety seeks to ensure the protection of people and the environment against radiation risks by achieving the highest practicable safety levels in nuclear power plants. Nuclear safety is not negotiable; safety is, and will remain, the nuclear industry's top priority. As will be seen from the content of this report, nuclear energy in OECD countries has an impressive record of safety performance compared to other energy chains. At least in good part, this is a tribute to the efforts of regulatory bodies over the years and the standards that they have set in design and operation.

A fundamental safety principle is that the prime responsibility for safety must rest with the person or organisation responsible for operation of the facilities and activities that give rise to radiation risks. Another is that an effective legal and governmental framework for safety, including an independent regulatory body, must be established and sustained. Nuclear power generation is a highly regulated activity: the regulators have a pivotal role in ensuring continued nuclear safety.

The safety of a nuclear power plant is usually addressed in terms both of normal operation and also of accident frequency and consequence. Safety during normal operation includes the impact of any environmental discharges. The impact during normal operation is small. It does not normally attract significant public or media attention and is not the subject of this present report. Here the focus is on accidents that have the potential to release quantities of radioactivity to the environment.

A good safety culture is a major factor in preventing accidents. Therefore, after reviewing the design philosophy for nuclear power plants, this study starts by reviewing internationally accepted performance indicators that provide information on the improvements in operations and indirectly on safety culture. Next, the report reviews changes in the estimated probabilities of severe core damage and subsequent large releases of radioactivity over the 50-year history of commercial nuclear power, as designers build additional safety features into new reactor types. It should be noted that these improvements to new designs have also led to back fitting to earlier reactors to enhance their "as originally designed" safety performance. The study then considers historical evidence of the frequency and consequence of severe accidents in the global energy industries (accidents where more than five people were killed), and compares this with risk assessments for the nuclear industry. Finally the report considers the key role of the regulator in developing and maintaining nuclear safety, together with issues of public trust.

2. NUCLEAR POWER PLANT SAFETY PHILOSOPHY

The safety standards required for nuclear plants have been and continue to be a national responsibility. Fundamental safety principles were internationally agreed in 2006 and issued by the International Atomic Energy Agency (IAEA), jointly sponsored by eight other international organisations, including the NEA (IAEA, 2006). This document states "The fundamental safety objective is to protect people and the environment from harmful effects of ionising radiation". The document explains that this fundamental safety objective of protecting people – individually and collectively – and the environment has to be incorporated in the systems that ensure safe operation of facilities or the conduct of activities that give rise to radiation risks.

2.1 IAEA Fundamental Nuclear Safety Principles

Ten safety principles were agreed as the basis on which safety requirements are to be developed and safety measures implemented to ensure that facilities are operated to the highest standards of safety that can reasonably be achieved. These internationally agreed principles powerfully encapsulate global nuclear power plant safety philosophy; they are set out in the Table 1.

This publication is primarily aimed at matters associated with severe accidents, to which Fundamental Safety Principle 8 is relevant. The primary means of preventing and mitigating the consequences of accidents is the application of the concept of defence in depth.

Table 1: IAEA Fundamental Safety Principles

Principle 1: *Responsibility for safety*	The prime responsibility for safety must rest with the person or organization responsible for facilities and activities that give rise to radiation risks.
Principle 2: *Role of government*	An effective legal and governmental framework for safety, including an independent regulatory body, must be established and sustained.
Principle 3: *Leadership and management for safety*	Effective leadership and management for safety must be established and sustained in organizations concerned with, and facilities and activities that give rise to, radiation risks.
Principle 4: *Justification of facilities and activities*	Facilities and activities that give rise to radiation risks must yield an overall benefit.
Principle 5: *Optimization of protection*	Protection must be optimized to provide the highest level of safety that can reasonably be achieved.
Principle 6: *Limitation of risks to individuals*	Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm.
Principle 7: *Protection of present and future generations*	People and the environment, present and future, must be protected against radiation risks
Principle 8: *Prevention of accidents*	All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.
Principle 9: *Emergency preparedness and response*	Arrangements must be made for emergency preparedness and response for nuclear or radiation incidents.
Principle 10: *Protective actions to reduce existing or unregulated radiation risks*	Protective actions to reduce existing or unregulated radiation risks must be justified and optimized.

Source: IAEA (2006).

2.2 Defence in depth

The objectives of defence in depth are (IAEA, 1996):

- to compensate for potential human and component failures;
- to maintain the effectiveness of the barriers by averting damage to the plant and to the barriers themselves;
- to protect the public and the environment from harm in the event that these barriers are not fully effective.

Defence in depth is implemented through the combination of consecutive and independent levels of protection that would all have to fail before harmful

effects could be caused to people or to the environment. If one level of protection or barrier were to fail, the subsequent level or barrier would be available. Defence in depth ensures that no single technical, human or organisational failure could lead to harmful effects, and that the combinations of failures that could give rise to significant harmful effects are of very low probability. The independent effectiveness of the different levels of defence is a necessary element of defence in depth. This is achieved through redundancy and diversity where, for example, there are always several different ways of measuring an essential parameter such as fuel temperature. If one sensor or set of cables were to fail, others are available; if power supplies to a critical system fail, there are always diverse ways of providing alternative supplies. Operating systems ensure that plants are not allowed to operate unless a minimum number of diverse systems are available. Figure 1 provides a visualisation of the concept.

The primary defences for prevention of accidents are adequate site selection and high quality in design, construction and operation of the nuclear plant, thereby ensuring that failures – deviations from normal operation – are infrequent. Operating systems are designed to deal with events that might occur as a result of equipment and human failures.

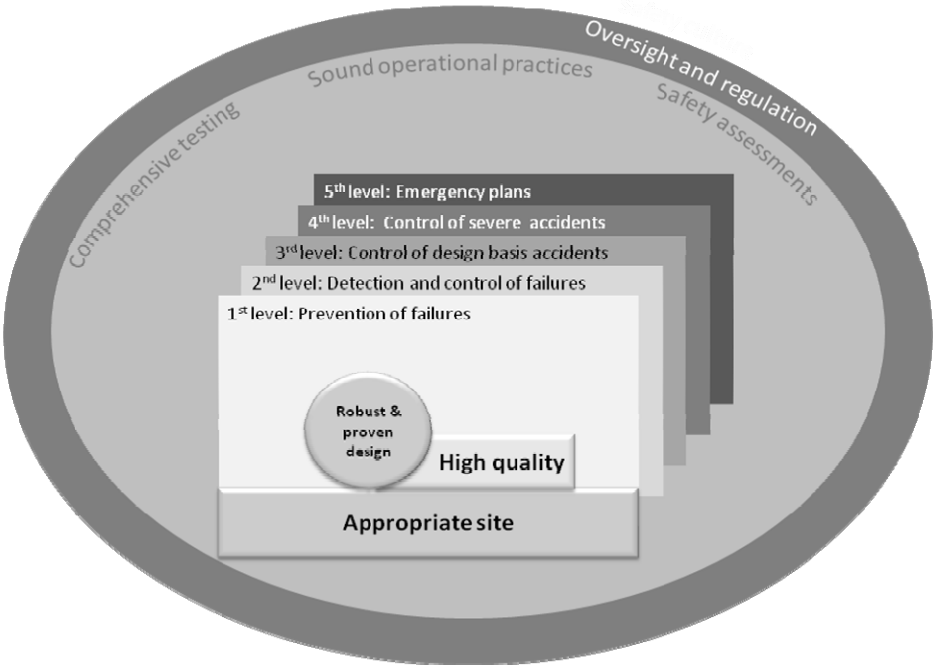
The next line of defence is provision of control and protection systems, and other surveillance features, designed to detect failures and manage any abnormal operations before their consequences become significant.

Reactor safety is based on the concept of Design Basis Accidents; engineered safety features and accident response procedures are built into the plant and its infrastructure to handle such events and provide a third line of defence. The effectiveness and reliability of safety systems to cope with these accidents is demonstrated during the safety assessment process. The design of the safety systems focuses on the prevention of core damage and ensuring the retention capability of the containment to prevent uncontrolled releases of radioactive materials to the environment.

The fourth line of defence, in the case of severe accidents beyond those anticipated in the design basis, is primarily provided by the reactor containment. The Three Mile Island accident, in which the fuel melted, did not release significant amounts of radioactivity because the containment building remained intact. By contrast, the Chernobyl nuclear power plant did not have a strong containment building, that is characteristic of most nuclear power plant designs and large amounts of radioactivity were released to the environment following the core melting.

The fifth and final layer of defence, to mitigate the radiological consequences of significant releases of radioactive materials from the reactor containment is the off-site emergency plan. In the event of an accident, this involves the collection and assessment of information about the levels of exposures expected to occur following the accident, and the implementation of short- and long-term protective actions.

Figure 1: The concept of defence in depth



Source: IAEA (1996).

In the design of reactors, successive physical barriers for the confinement of radioactive material are put in place. For LWRs, the barriers confining the radioactivity are typically:

- the sintered fuel matrix;
- the fuel cladding;
- the boundary of the reactor primary coolant system;
- the containment system.

Surrounding these layers of defence must be an effective management system with a strong commitment to safety and a strong safety culture, efficient

oversight and regulation and ongoing sound operational practises, comprehensive testing and safety assessments. A strong safety culture is essential to ensure the integrity of the multiple barriers of the entire defence in depth safety system. The safety values, norms and attitudes of an entire operating organisation are just as important as the design and construction of the nuclear power plant.

References

IAEA (2006), *Fundamental Safety Principles Safety Fundamentals*, Safety Standards Series No SF-1, IAEA, Vienna, Austria.

IAEA (1996), *Defence in Depth in Nuclear Safety*, INSAG-10, IAEA, Vienna, Austria.

3. TRENDS IN PERFORMANCE INDICATORS

Protection of the public, workers and the environment from radiation has been the prime objective of operators and regulatory authorities since the start of the civilian nuclear power industry. Improvements in the overall performance of nuclear facilities can be judged from indicators such as the unplanned automatic trip rate and worker radiation exposure. All utilities around the world measure these and other indicators, which are routinely reported to regulators and to industry peer groups such as the World Association of Nuclear Operators (WANO). These indicators have shown continued improvements. As examples, this Section considers trends in trip rates and in exposure to workers.

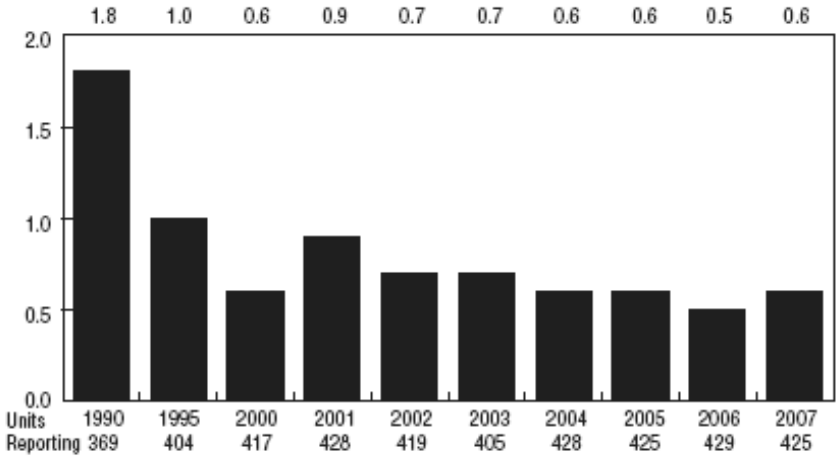
3.1 Unplanned automatic trip rate

The unplanned automatic trip rate is one of a number of broad indicators of safety culture. An automatic trip is where a reactor is shut down by its safety systems rather than by its operators; automatic trip rates are recorded per 7 000 hours (approximately one operating year).

Reductions in unplanned automatic trip rate provide an overall indication of success in improving plant safety. Fewer trips mean less undesirable and unplanned thermal and hydraulic transients; this parameter is also an indicator of how well a plant is maintained and operated. Plants with low trip rates tend to have operations, engineering, maintenance and training programmes that are more effective; this demonstrates management attention to a wide range of matters that all impinge on safety.

Figure 2 provides data on unplanned automatic trips collated by the industry peer group WANO (WANO, 2008), showing that the indicator has been improving year on year. For 2007, this figure includes data from 425 of the world's 439 operating reactors. The average global unplanned trip rate of 0.6 per 7 000 hours of reactor operation was three times lower in 2007 than in 1990.

Figure 2: Average number of global unplanned automatic reactor trips per 7 000 hours of operation



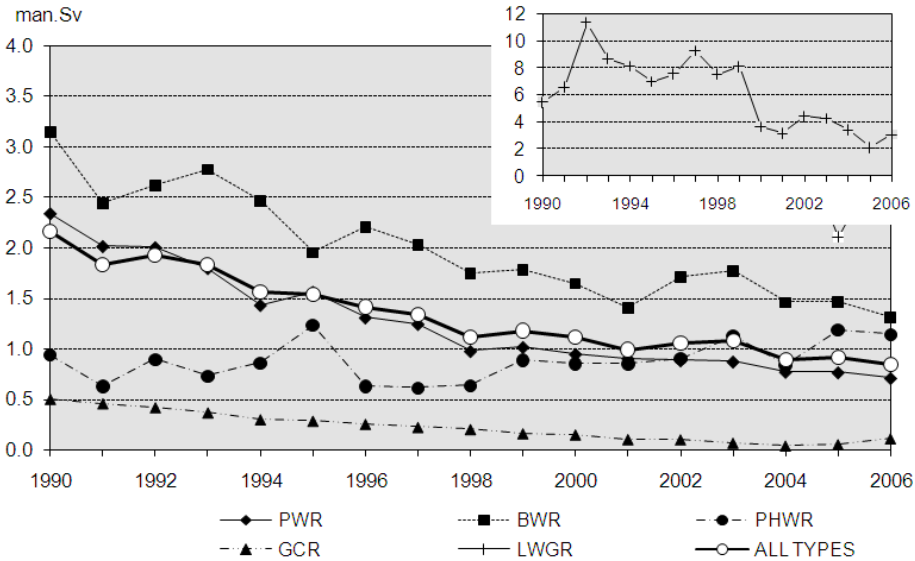
Source: WANO (2008).

3.2 Worker exposure

Radiological protection in the nuclear industry has tended to follow the recommendations of the International Commission on Radiological Protection (ICRP). These have been broadly adopted by all national regulatory authorities and international bodies and are based on state-of-the-art radiological protection science, as summarised by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). ICRP recommendations are used to assess radiation exposure to both workers and the general public.

The Information System on Occupational Exposure (ISOE) also collates data on worker exposure to radiation. Figure 3 shows how this indicator has reduced over the past 17 years. The data in this figure are annual collective exposure – the total exposure received by all members of a particular reactor's workforce in a given year. Radiation exposure is measured in units of Sieverts (Sv). Collective exposures are expressed in man-Sv per year. The data in Figure 3 display medians calculated for all reactor units of the same type (the median value is less susceptible to influence from outliers and is therefore more representative of overall performance). Data for light water graphite moderated reactor (LWGMR or RBMK) units are shown separately as an inset to Figure 3.

Figure 3: Average collective dose per reactor for operating reactors included in ISOE by reactor type (1992-2006)



Source: NEA and IAEA (2007).

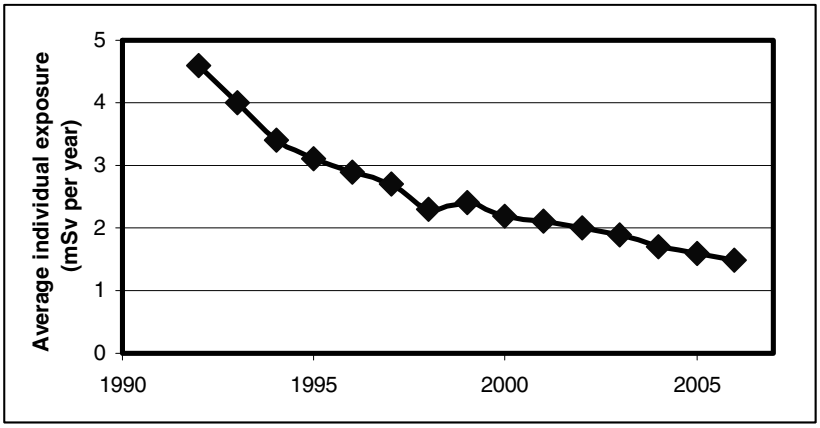
Figure 3 shows that the world average collective worker exposure per unit has been cut by a factor 2.6 between 1990 and 2007. For 2007, this figure includes data from 424 of the world's 439 operating reactors. In particular, exposures from the most widely used reactor type – the PWR – have generally shown steady reductions over this period. The inset to Figure 3 shows very significant reductions in LWGMR worker exposures over the ten years between 1995 and 2005.

Many factors have lead to these reductions; in particular, better implementation of exposure optimisation through rigorous application of the ALARA[1] (as low as reasonably achievable) principle has played a major part.

The overall trend in exposure reduction can be verified by looking at occupational exposures for the average individual worker. Using as an example the French nuclear power industry, Figure 4 shows that average annual worker exposures fell by nearly a factor of three over the fourteen years between 1992 and 2006.

1. This principle is known as ALARP in some countries: as low as reasonably practicable.

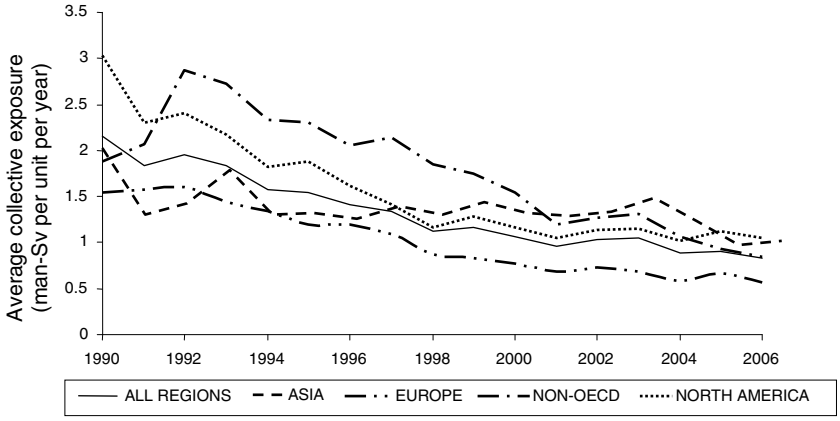
Figure 4: Reductions in average annual individual worker exposure in the French nuclear power generation industry



Source: EDF (2007).

Historically, average collective exposures in non-OECD countries were higher than in other OECD regions, as shown in Figure 5. Now, regionally averaged exposures are converging due, amongst other matters, to peer review through organisations like WANO and to the continued global exchange of operational experience between utilities, particularly with respect to good practice in maintenance and outage work.

Figure 5: Evolution of average annual collective exposure per reactor by world region



Source: NEA and IAEA (2007).

Figures 3 to 5 show a continued trend towards lower exposure per reactor and it is to be expected that this trend will continue through any new build programmes using Generation III/III+ reactor designs. It is expected that both individual and collective exposure per plant will continue to reduce as new reactors with improved safety features come online and as improvements in plant safety management continue to be implemented by the operators. Global reductions in worker exposure and in unplanned automatic trip rate suggest a steadily improving safety culture in the nuclear power industry. This improvement can be seen across all regions of the world and for all reactor types.

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4. TRENDS IN PREDICTED SEVERE ACCIDENT RISK

Further evidence of the trend towards improved levels of safety performance can be seen in the reduction over time of the assessed "as originally designed" core damage frequencies of the world's reactors. The risks from nuclear power plants are analysed using quantitative techniques.

4.1 Probabilistic safety assessment

Probabilistic safety assessment (PSA) is a systematic and comprehensive technique used to evaluate risks associated with complex systems such as nuclear power plants. It is also used in other industries that use complex technologies like the chemical industry, commercial airline operation and aeroplane construction. PSA was first applied in the nuclear industry in 1975, when a study entitled WASH 1400 – Reactor Safety Study (also known as the Rasmussen Report after Professor Norman Rasmussen who chaired the committee of experts to produce this report for the USNRC in 1975) evaluated the probability of a number of accident sequences that might lead to fuel melting in the reactor (core damage).

PSA is used during both the design and the operating stages of a nuclear plant to identify and analyse conceivable faults and sequences of events that might result in severe core damage. PSA looks at three questions:

1. What are the initiating faults and sequences of events that could lead to core damage?
2. What are the consequences of core damage and potential radioactivity release?
3. How likely are these events to occur?

A PSA numerically assesses the probability and consequence of foreseeable faults, and determines risk for each. Analysis of potential system faults includes assessment of human reliability and common mode failure (which looks at effects that could cause simultaneous failures across several systems). PSA considers both internal and external events. Internal events

include component failure and human error; external events include natural hazards like seismic events and man-made events like aircraft crash.

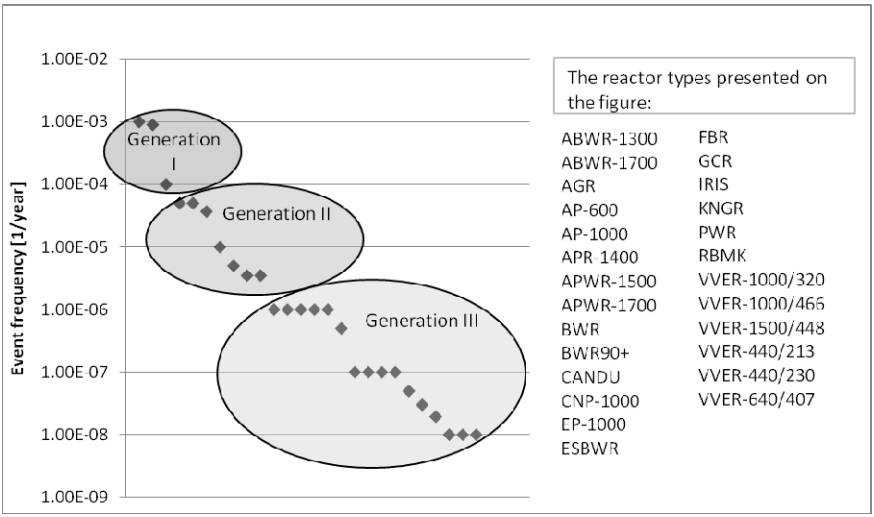
The results of a PSA can be expressed in a number of ways, including as a core damage frequency (CDF) and as a calculated theoretical large release frequency (LRF). The CDF combines the probabilities of natural or man-made events that could threaten the plant with the probability that, given the way the particular reactor is designed and operated, such events could cause the fuel in the reactor to be damaged. The LRF is an estimate of the frequency of those accidents that would lead to a significant, unmitigated release of radioactivity to the environment. LRF gives a picture of the potential risk to the environment and to the public from a nuclear reactor accident. The CDF and LRF are specific to particular plants.

PSAs can identify strengths as well as weaknesses in nuclear plant safety. Over several decades, PSAs have assisted in setting priorities and focusing efforts on the most important aspects for improving safety as reactor designs have advanced. They have also identified useful improvements to be back fitted to earlier reactor designs.

4.2 Core damage and large release frequency reductions

Figure 6 shows how the LRFs have reduced over the past decades. This Figure includes data for 26 of the reactor designs used around the world, from the early Generation I to the latest Generation III/III+ plant. It is important to note that these data relate to the reactors as originally designed. Upgrades to these earlier plants over the years have resulted in significant improvements to their safety performance, for example for Dukovany NPP (see Figure 7). The Generation III/III+ plants, designed to account for the lessons learned from the Three Mile Island and Chernobyl accidents and subsequent regulatory requirements, have significantly lower LRF values than do their predecessors (as originally designed). Market competition has also played a role, as utilities have demanded higher levels of safety along with higher efficiency and reliability, so they could compete economically within the safety envelope set by the regulatory requirements within which they operate.

Figure 6: Reduction in design estimates of the large release frequency between reactor generations over the past five decades



Source: IAEA (2004).

Figure 7: Core damage frequency for Dukovany NPP with VVER/440 V-213

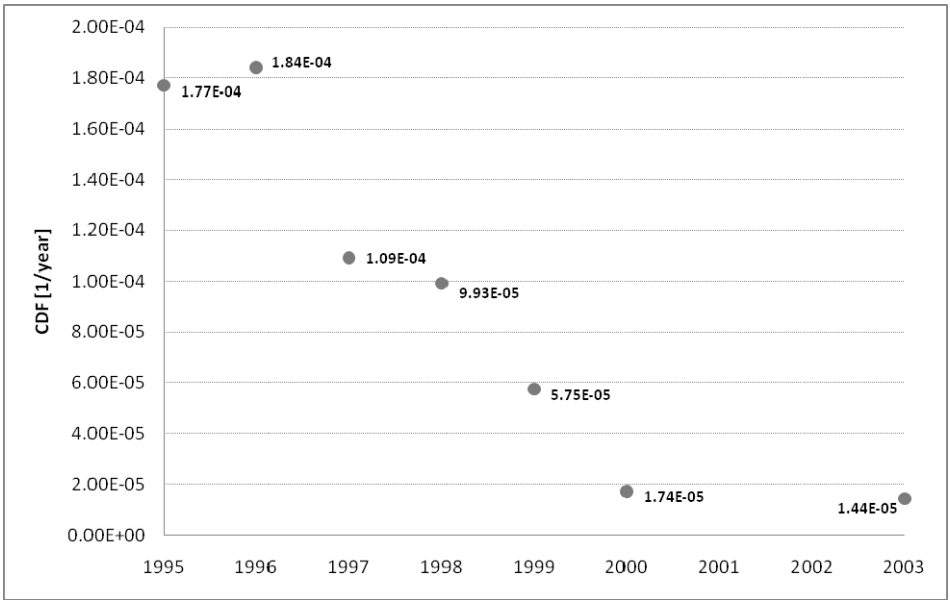
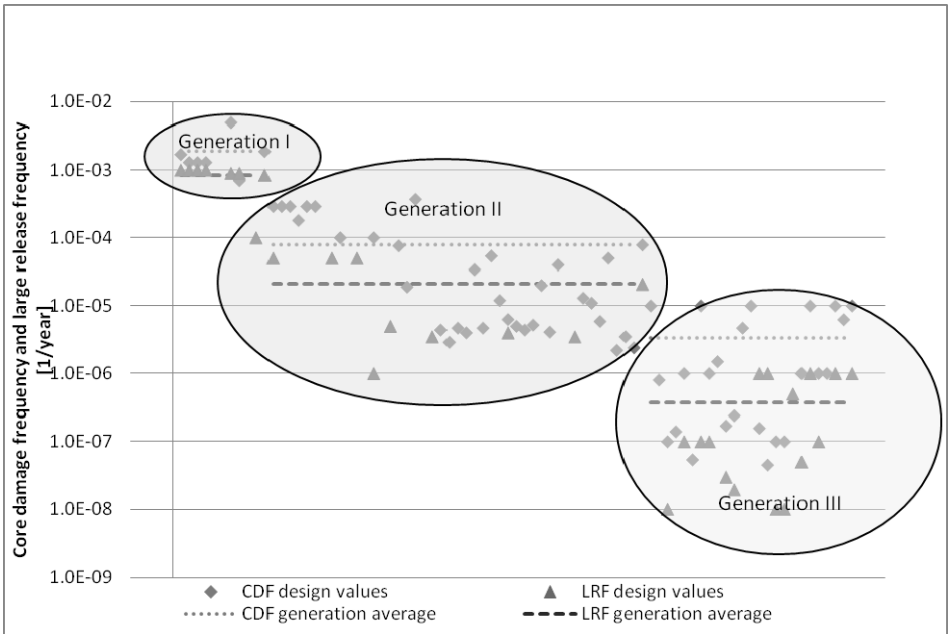


Figure 8 shows the evolution of CDF and LRF for reactors around the world for which data are publicly available. The groupings are by generation only. The horizontal axis does not imply exact time separations, other than Generation I comes before II, and II before III.

Figure 8: Evolution of core damage frequency and large release frequency for existing (Generation I and II) and for future reactor types (Generation III/III+)



Source: IAEA (2004).

PSA is a powerful method of assessing safety improvements for a particular plant. However, it is difficult to make comparisons between different reactor units because of differences in plant configurations, initiating events included in the study and the accuracy and completeness of reliability data used in the calculation. Therefore, the CDF and LRF values shown here provide an indication of general safety trends in reactor design developments; they should not be used to make comparisons between reactor types of the same generation.

The data presented here are readily available via the internet and they show that the predicted frequency for a large release of radioactivity from a severe nuclear power plant accident has reduced by a factor of 1 600 between the early Generation I reactors and the Generation III/III+ plants being built today.

In addition to improved safety for operating reactors, shown by the reduction in CDF, there is an increasing trend for LRF values to fall faster than CDF values as shown in Figure 8. In the early 1960s, an accident that resulted in core damage could well have led to a large radioactivity release. However, engineering improvements to the fuel, the primary circuit and the containment have evolved to cope with the consequences of an accident, such that the probability of a release to the environment is about ten times less than that of core damage. Starting from the early 1990s, the risk of core damage for existing Generation II reactors was efficiently reduced through safety upgrades. Based on the experience gained and the lessons learned through design assessments for Generations I and II, safety improvements for Generation III/III+ reactors designs are already "built-in" rather than "added-on".

The evolution of CDF and LRF is an example of nuclear operators' ability to assess and implement safety improvements in the operation of nuclear power plants. The decrease in CDF and LRF for new reactor designs could be seen as representing the global response from the industry to ensure that nuclear power generation must continuously strive to be as safe as possible.

Reference

IAEA (2004), *Status of advanced light water reactor designs 2004*, IAEA-TECDOC-1391, International Atomic Energy Agency, Vienna, Austria.

5. COMPARATIVE ANALYSIS OF SEVERE ACCIDENT RISKS IN THE ENERGY SECTOR

There is a growing need for accurate data on the number of, and associated damage from, natural catastrophes and man-made accidents to satisfy an increasing demand for information from decision makers and stakeholder groups.

Although data on accidents and their damage impacts have improved significantly in the last three decades, data from different sources are difficult to compare, as there are no standard definitions, methodologies or verification procedures. Accidents in the energy sector form the second largest group of man-made accidents after transportation; however, their level of data coverage and completeness was not adequate until the Swiss Paul Scherrer Institute (PSI) started a risk assessment project on energy-related accidents in the early 1990s. All data used in this Section were provided to the NEA by the Paul Scherrer Institute.

When assessing energy-related accidents and risks, it is essential to consider full energy chains because, for the fossil chains, accidents at power plants are minor compared to the other chain stages – analyses based on power plants only would radically underestimate the real situation. In general, an energy chain comprises exploration, extraction, transport, storage, power and/or heat generation, transmission, local distribution, waste treatment and disposal, although not all these stages are applicable to every energy chain. Severe accidents evoke most concern and have the greatest impact on public perception and energy politics. Therefore, they are the main focus of investigations, even when the total sum of the many small accidents with minor consequences is more substantial. There are many ways of defining a "severe" accident. PSI has adopted the definition that severe accidents are those that result in five or more prompt fatalities. This cut off also enables the collection of a more reliable data set since smaller accidents attract less attention and may go largely unreported.

PSI has analysed severe accidents in the energy sector for the years 1969-2000 (see references 1 to 5) and is currently extending its database to include accidents that occurred up to the end of 2005. The information in this Section only refers to the period 1969-2000. The database comprises real historical accident data from a large variety of sources encompassing fossil, hydro and

nuclear energy chains, all of which entail significant health, environmental or socio-political risks.

Results are provided separately for OECD and non-OECD countries because of differences in levels of technological development and safety performance, including regulatory frameworks and safety culture. In the case of China, coal chain data were only analysed for the years 1994-1999 when data from the China Coal Industry Yearbook were available.

For comparative analyses, two methods were used. First, indicators that provide a direct comparison of severe accident consequences, expressed as fatalities per unit of energy produced, between different energy chains and country groups were produced. These are presented in Table 2. In a second step, the comparison of results was expanded by combining frequency and consequence analyses to generate risk estimates. These are shown in Figure 9. In the case of nuclear energy, application of Probabilistic Safety Assessment (PSA) was used to supplement the data because there has been only one severe accident, at Chernobyl. Likelihoods and consequences of hypothetical nuclear accidents were therefore analysed using PSA techniques. Hence these results need to be understood in their context as theoretical estimates.

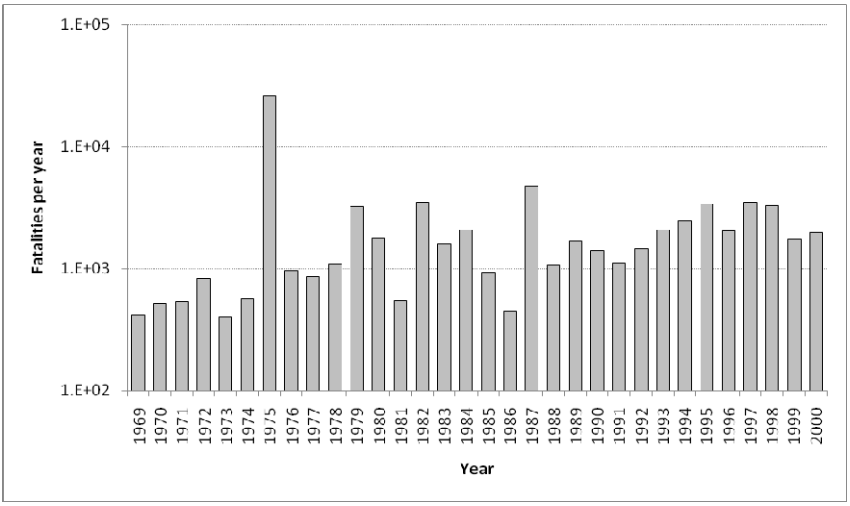
5.1 Comparative analysis of major energy chains

PSI's database currently contains data on 1 870 energy-related accidents that resulted in five or more fatalities. Figure 9 shows the very large number of fatalities that occurred each year between 1969 and 2000 from energy-related, man-made severe accidents (≥ 5 fatalities). These amount in total to 81 258 immediate fatalities summed over all energy chains. The worst energy-related accident was the Banqiao/Shimantan dam failure in China in 1975 when some 30 000 people were killed. Among the fossil chains, coal accounted for most fatalities, followed by oil, liquefied petroleum gas (LPG) and natural gas. Table 2 summarises the severe (≥ 5 fatalities) accidents that occurred in the fossil, hydro and nuclear energy chains in the period 1969-2000. The statistical basis for individual energy chains differs radically. For example, there are 1 221 severe accidents with at least five fatalities in the coal chain and only one in the nuclear chain (Chernobyl).

OECD countries exhibit significantly lower fatality rates per unit of energy generated than non-OECD countries for all energy chains. Among the fossil chains, LPG has the highest fatality rate, followed by oil and coal; natural gas performs best. OECD nuclear and hydropower plants have the lowest fatality rates, whereas in non-OECD countries historical evidence suggests that dam

failures pose a much higher risk. Table 2 also shows that the Chinese coal chain should be treated separately as its accident fatality rates are about ten times higher than in other non-OECD countries and about forty times higher than in OECD countries.

Figure 9: Number of fatalities per year for severe (≥ 5 fatalities) man-made, energy-related accidents



Source: Data provided to NEA by PSI.

Table 2: Summary of severe (≥ 5 fatalities) accidents that occurred in fossil, hydro and nuclear energy chains in the period 1969-2000

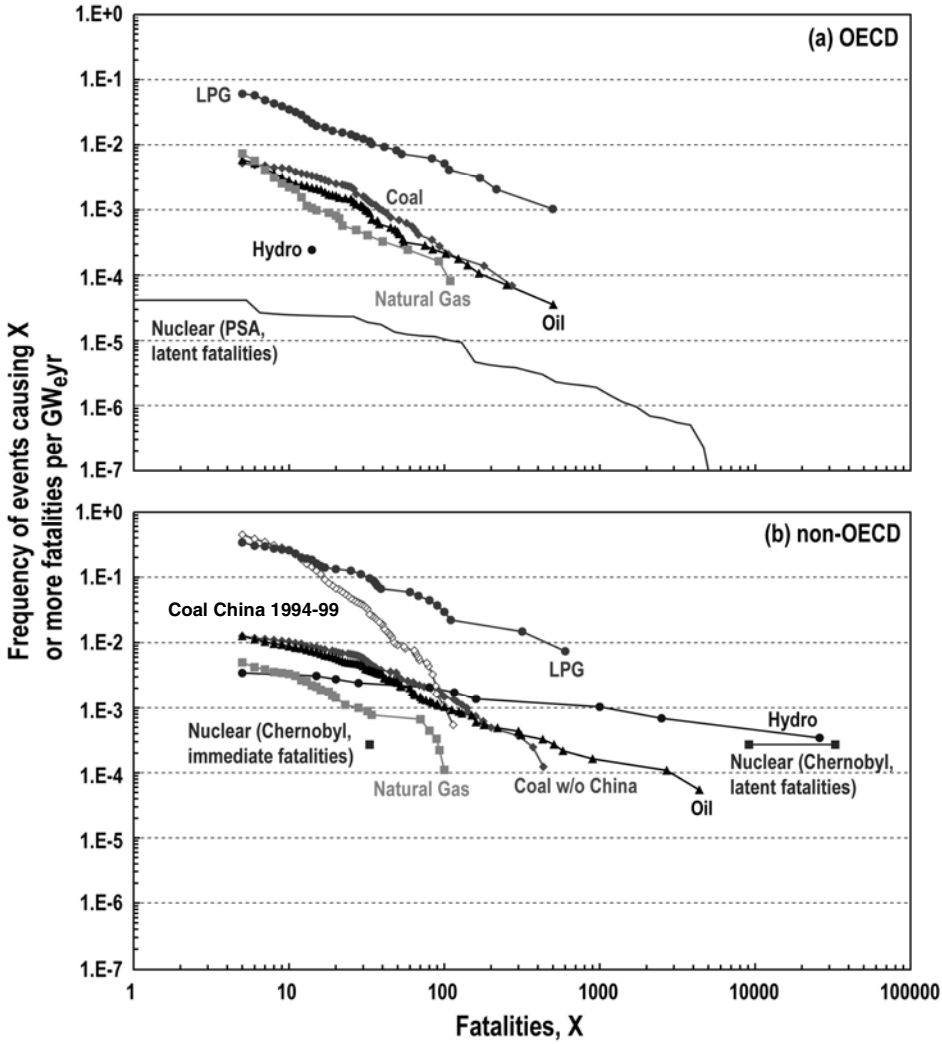
	OECD			Non-OECD		
Energy chain	**Accidents**	**Fatalities**	**Fatalities/ GWey**	**Accidents**	**Fatalities**	**Fatalities/ GWey**
Coal	75	2 259	0.157	1 044	18 017	0.597
Coal (data for China 1994-1999)				819	11 334	6.169
Coal (without China)				102	4831	0.597
Oil	165	3 713	0.132	232	16 505	0.897
Natural Gas	90	1 043	0.085	45	1 000	0.111
LPG	59	1 905	1.957	46	2 016	14.896
Hydro	1	14	0.003	10	29 924	10.285
Nuclear	0	0	–	1	31*	0.048
Total	**390**	**8 934**		**1 480**	**72 324**	

Note: * These are immediate fatalities only.

Source: Data provided to NEA by PSI.

5.2 Frequency-consequence curves

Figure 10: Comparison between frequency-consequence curves for full energy chains, based on historical experience of severe accidents (≥ 5 fatalities)



Note: (a) OECD and (b) non-OECD countries for the period 1969-2000, except for China 1994-99 (see text). Latent fatality estimates were derived from probabilistic safety analysis for the Mühleberg Swiss nuclear power plant and dose-risk assessments for Chernobyl.

Sources: [2 to 6] and data provided to NEA by PSI.

Frequency-consequence (F-N) curves are a common approach in complex engineering industries to express collective or societal risks in quantitative risk assessment. They show the probability of accidents with varying degrees of consequence, such as fatalities. F-N curves provide an estimate of the risk of accidents that affect a large number of people by showing the cumulative frequency (F) of events having N or more fatalities, usually presented in a graph with two logarithmic axes in order to condense a large data range onto one diagram.

Figure 10 shows F-N curves for severe energy-related accidents (≥ 5 fatalities) in OECD and non-OECD countries. For OECD countries (Figure 10a), fossil energy chains show higher historical frequencies of actual severe accidents than hydro, with LPG exhibiting the worst performance and natural gas the best. There is only one data point for hydro because there was only one severe hydro accident in the period being analysed (Teton, United States in 1976 with 14 fatalities).

Nuclear energy in OECD countries is very safe in comparison with fossil chains; there were no accidents resulting in 5 or more prompt deaths. Hence, as discussed in the introduction to this section, any comparison can only be made with the theoretical accident frequencies derived from PSA analyses. That shown in Figure 10a is for the latent fatalities for a Swiss nuclear power plant. Although not directly comparable with the actual fatality data, it is shown for comparison. Latent fatalities from these other accidents are not included, so in that sense, the nuclear data is conservative.

For non-OECD countries (Figure 10b), the ranking of F-N curves by energy chain is similar to the OECD, except for the Chinese coal chain that shows a significantly worse performance than other non-OECD countries. Accident frequencies at corresponding numbers of fatalities were higher for non-OECD compared to OECD countries, and for LPG and coal (China, 1994-99), chain frequencies for accidents that killed five people or more were as high as 0.4 per GWey.

For the single non-OECD nuclear severe (≥ 5 fatalities) accident at Chernobyl, immediate fatalities were less significant than latent fatalities (i.e. fatalities arising many years later due to the subsequent health effects of exposure of released radioactive material). Studies by EC/IAEA/WHO and UNSCEAR formed the basis for estimates of total latent fatalities associated with Chernobyl, supported by numerous sources including those from Russia. Estimated latent fatalities, shown in Figure 10b, range from 9 000 (based on dose cut-off) to 33 000 (entire northern hemisphere with no dose cut-off) over the next 70 years. This is equivalent to between 13.9 and 51.2 deaths per GWey,

for non-OECD countries. However extrapolating these nuclear energy risks to current OECD countries is not appropriate, because OECD plants use other, safer technologies that are operated under a stricter regulatory regime than was in force in the Ukraine at the time of the Chernobyl accident. It is notable that the estimated latent death rates for the Chernobyl accident are of the same size as the prompt deaths resulting from the largest non-OECD hydro dam failure.

With respect to latent deaths from exposure to radioactivity, while the risk to individuals receiving a very small dose is equivalently small, a huge number of people in space and time can be affected by an accident of the scale of Chernobyl. When the large collective dose (resulting from summing millions of very small doses) is combined with a linear dose response relationship with no threshold (i.e. the probability of a fatal cancer in the long term is assumed to be directly related to the dose received, even down to infinitesimally small doses) for the individual exposure, the estimated health effects may result in a very large figure.

To put this in perspective, the global effective dose of 600 000 person-Sieverts from the Chernobyl accident is equivalent to only 5% of some 13 000 000 person-Sieverts estimated to be **annually** delivered to the world population from natural sources. For the 70 years over which the above fatality figures were calculated for the accident, the collective dose from natural background would be 910 000 000 person-Sieverts (assuming a constant population), some 1 500 times larger, therefore theoretically causing 1 500 times as many fatalities (some 50 million) due to exposure to natural background radiation. However there is no way to definitely confirm these figures for Chernobyl, since death rates from all cancers are very much higher.

Some further perspective can also be gained by considering the latent health effects of fossil fuel burning, the main alternative for baseload electricity production. The *OECD Environmental Outlook* [6] reports that outdoor air pollution due to fine particles (≤ 10 microns) is estimated to have caused approximately 960 000 premature deaths in 2000 alone and 9 600 000 years of life lost worldwide. Of this pollution, about 30% arises from energy sources. Hence, even on a latent deaths basis, the results of the Chernobyl accident are small in comparison with those that result from other energy sources, predominately fossil fuel burning. Overall, accident related deaths from energy use are much smaller than those that result from the health effects of fossil fuel emissions, but they attract much more media and public attention.

The statistically calculated "expected" values for severe accident fatality rates associated with the nuclear chain in OECD countries are very low, but the maximum credible consequences may be large due to the dominance of latent

fatalities, calculated with no dose cut-off. Latent fatality rates for modern nuclear plants where there have been no accidents can only be assessed using Probabilistic Safety Assessment (PSA), described in Section 4.1. PSI used PSA studies available for the Mühleberg Swiss nuclear power plant. These data (see Figure 10a) show there is about a 1 in 1 million-year probability of an accident causing more than 2 000 latent fatalities. While this number is very large, the Paul Scherrer data shows the largest real energy accidents in the world have caused prompt fatalities of comparable size or larger. In addition to the Chinese dam failure, an oil accident in the Philippines caused 4 386 prompt fatalities, an oil accident in Afghanistan caused 2 700 prompt fatalities, other non-OECD hydro accidents are large and an oil accident in South Korea shortly after it joined the OECD caused some 500 prompt fatalities.

Accidents on this scale are fortunately very rare. Since there is no equivalent to the PSA analysis for fossil fuels, it is not possible to form a reasonable view on the size of maximum credible accidents from fossil chains.

5.3 Summary of severe accident risks in the energy sector

More than 2 500 people are killed every year in energy-related severe accidents, and this number appears to be rising as energy use continues to increase. Between 1969 and 2000, there were 1 870 such accidents that killed five or more people. The largest number of immediate fatalities in the fossil energy chains was in coal and oil, with 2 259 and 3 713 immediate fatalities respectively in OECD countries and 18 017 and 16 505 immediate fatalities in non-OECD countries. Hydropower was responsible for the deaths of 29 924 people in one incident in China.

There were 31 immediate fatalities following the Chernobyl accident, with latent deaths estimated to be between 9 000 and 33 000 over the next 70 years based on current radiation dose risk coefficients. Extrapolating these nuclear energy latent fatality estimates to current OECD countries, where demonstrably safer technologies are operated under a stricter regulatory regime, is not appropriate.

Latent fatality rates for modern nuclear plants can only be assessed using PSA. PSA studies available for the Mühleberg Swiss nuclear power plant show there is about a 1 in 1 million-year probability of an accident causing more than 2 000 latent fatalities. For OECD countries, frequency-consequence curves show that the risk of a nuclear accident with more than 100 latent fatalities is a factor of ten or more lower than the risk of an accident with 100 immediate fatalities from coal, oil, natural gas or hydro energy chains, and almost a factor of one thousand lower than the risk from LPG.

References

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6. PUBLIC CONFIDENCE IN NUCLEAR OPERATIONS

While the nuclear industry is, by any comparison, a very safe industry, public confidence evolves only slowly. It is influenced by local, national and global issues and is not particularly volatile. Nevertheless, nuclear power remains a contentious issue, with a range of concerns raised by people when considering its use.

In *Public Attitudes to Nuclear Energy* (NEA, 2010), the NEA reviewed a variety of public opinion data to try to understand public attitudes towards nuclear and noted that there was a correlation between knowledge and support and between countries with existing nuclear power plants and support for their use.

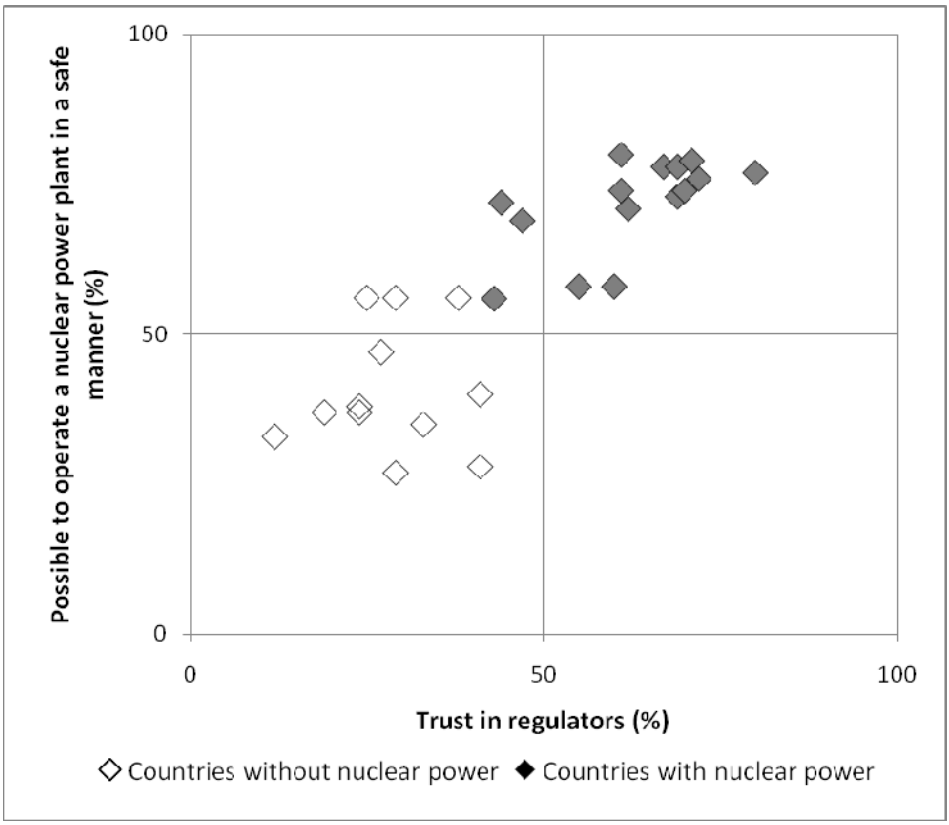
Legislation and regulatory effectiveness are key factors in affecting the public's view of nuclear power acceptability. Responsibility for nuclear regulation resides within each country and in national regulatory bodies. Regulators put in place sets of safety requirements that operators must follow in order to be licensed to operate the facility, to assure the security of nuclear materials, to protect the environment and to manage radioactive waste and spent nuclear fuel. Regulators conduct oversight activities at facilities to gain assurance that activities are being conducted in a safe manner and, if they are not, operators are required to take corrective actions to bring their facility into compliance with requirements.

Governments are responsible for ensuring a competent regulatory body with adequate financial and human resources. Effective independence of regulatory bodies is an essential element in nuclear safety, to ensure that there is no undue pressure or interference from operators or governments.

The issue of public confidence in nuclear legislation was considered in a Eurobarometer public opinion poll (Eurobarometer, 2007) that covered the EU25 plus two countries, Romania and Bulgaria, that were about to join the European Union when the data were collected. The poll included questions relating to confidence in nuclear safety regulations, nuclear regulators and operators.

This poll showed a strong correlation between trust in regulators and trust that nuclear plants can be operated in a safe manner as shown in Figure 11. It is very clear that trust in the regulators is crucial to gaining support for nuclear energy programmes. Furthermore, countries with nuclear programmes, where citizens have (or feel they have) more first-hand experience of nuclear matters, have more trust in the regulatory system and greater support for nuclear energy than those without.

Figure 11: Correlation between trust in regulators and belief that nuclear power plants can be operated safely



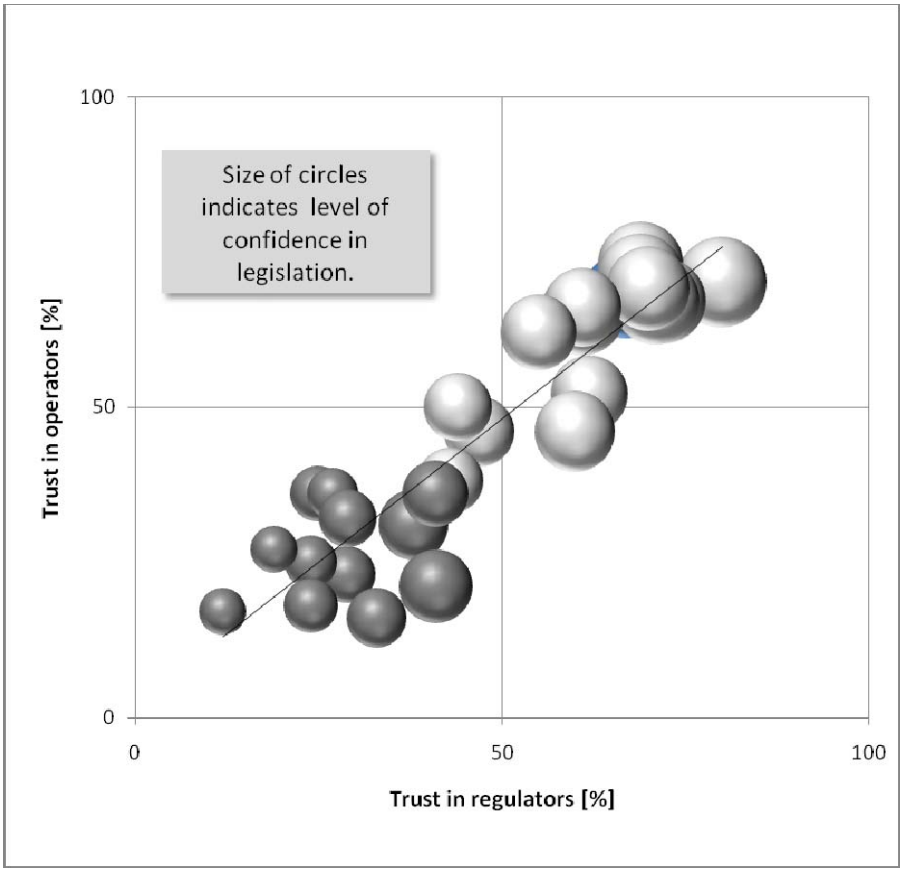
Source: Eurobarometer (2007).

This matter is further addressed in Figure 12, which compares levels of trust in regulators and in operators and the degree of confidence in legislation for countries that have nuclear power and those that do not. It is clear that levels of trust in operators and in regulators are correlated, suggesting that confidence in regulation of nuclear power is a pre-requisite for confidence in nuclear power plant operators. In addition, trust in both operators and regulators rises as

confidence in legislation improves. Countries without nuclear power again show the lowest levels of trust in both operators and regulators.

These results clearly suggest that a strong independent regulator leads to greater public acceptance of nuclear energy or, at the very least, is a necessary element for such acceptance.

Figure 12: Relationship between public trust in operators, regulators and nuclear legislation



Source: Eurobarometer (2007).

As countries prepare for the next generation of nuclear facilities, the need to educate and inform the public about safety and security will be critical. There is a role for various organisations in this process, especially for governments in

explaining the reason for any decision to develop new or replacement nuclear capacity.

Effective nuclear regulation is a matter of key public interest and, as such, it should be transacted as openly and candidly as practicable to maintain the public's confidence. Ensuring appropriate openness explicitly recognises that the public must be informed about, and have a reasonable opportunity to participate meaningfully in the regulatory processes. Openness and transparency with all interested parties are important elements in maintaining confidence and trust in regulatory bodies and in the activities of the operating organisations.

Documents and correspondence related to licence renewals and licence applications, with the exception of certain security-related, proprietary, and other sensitive information, should be made available, and the public should have access to regulatory websites. Interaction with society is not only about public consultation or communication, but also implies public involvement.

The public is likely to show increased interest in the way hazards inherent to nuclear facility operations are handled by the responsible regulatory authorities. In the coming years, many regulators are likely to receive licence applications for the construction and operation of new nuclear power plants, and waste repositories. The process leading to the outcome of the regulatory assessment should be transparent. In addition, there may be an increase in the number of applications to extend the licences of operating reactors. These activities will all generate public interest.

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7. CONCLUSIONS

This study is primarily directed at energy policy makers. Specialists in nuclear safety may find some of the content of interest but are directed otherwise to the extensive work of the NEA specialist committees on nuclear safety, the Committee on Nuclear Regulatory Activities and the Committee on the Safety of Nuclear Installations. The work of these committees can be accessed via the NEA website. The conclusions from this more general study are:

Nuclear safety

- means ensuring the protection of people and the environment against radiation risks by achieving the highest practicable safety levels in nuclear power plants;
- is not negotiable; safety is, and will remain, the nuclear industry's top priority;
- needs to be globally applied, since a serious event in one country may have a significant impact in neighbouring countries and will affect nuclear development worldwide.

Nuclear power plant safety philosophy

- A primary means of preventing and mitigating the consequences of accidents is the concept of defence in depth in which consecutive and independent levels of protection would all have to fail before harmful effects could be caused to people or to the environment.
- A strong safety culture is essential to ensuring the integrity of the multiple barriers of the defence in depth safety system; the safety values and attitudes of the entire operating organisation are as important as the design and construction of the nuclear power plant.

Trends in performance

- Unplanned automatic trip rates, which are one broad indicator of overall operating performance and indirectly of safety culture, have reduced by a factor three since 1990.
- Worker annual collective exposure per reactor has reduced by a factor 2.6 over the same period; this improvement can be seen across all regions of the world and for all reactor types. This can be seen as suggesting a steadily improving safety culture.
- It is to be expected that this trend will continue through any new build programme. It is likely that both individual and collective exposure per plant will further reduce as new reactors with improved safety features come online, and as current operators continue their improvements in their safety management systems.

Trends in predicted severe accident risk

- The predicted frequency of a severe nuclear power plant accident followed by a large radioactivity release has reduced by a factor of 1 600 between the original designs of early Generation I reactors and the Generation III/III+ plants being built today (but note that the safety performance of these earlier plant designs has also been improved by plant upgrades over subsequent years).
- In the early 1960s, an accident that resulted in severe core damage may well have led to a large radioactivity release; however, engineering improvements mean that the probability of a release to the environment from a Generation III/III+ reactor is about ten times less than that of core damage.

Comparative analysis of severe accident risks in the energy sector

- More than 2 500 people are killed every year in energy-related severe accidents (accidents that kill five or more people).
- Even though nuclear power is perceived as a high risk, comparison with other energy sources shows far fewer fatalities.
- Between 1969 and 2000, there were 2 259 and 3 713 immediate fatalities in the coal and oil energy chains respectively in OECD countries, and 18 017 and 16 505 immediate fatalities in non-OECD

countries. By comparison the one severe accident at Chernobyl killed 31 people immediately.

- The latent fatalities following the Chernobyl accident, are estimated to be between 9 000 and 33 000 over the next 70 years. By way of comparison, OECD estimates of the latent deaths from particulates in air pollution were at a level of 960 000 for the year 2000 alone, with about 30% of this pollution attributable to energy sources.

Public confidence in nuclear operations

- While nuclear power remains a contentious issue, public confidence in nuclear power evolves slowly but there is a correlation between awareness of the technology and trust.
- Public opinion polls show a strong correlation between trust in regulators and trust that nuclear plants can be operated in a safe manner; it is clear that trust in regulatory bodies is crucial to gaining support for nuclear energy programmes.
- Openness and transparency in government decisions about the use of nuclear power and in the licensing process are vital elements in improving public confidence.

Appendix I

ACRONYMS*

ALARA	As low as reasonably achievable
ALARP	As low as reasonably practicable
CDF	Core damage frequency
CNRA	Committee on Nuclear Regulatory Activities
CSNI	Committee on the Safety of Nuclear Installations
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ISOE	Information System on Occupational Exposure
LPG	Liquified petrolium gas
LRF	Large release frequency
LWGMR	Light water graphite moderated reactor
LWRs	Light water reactors
NDC	Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
PSA	Probabilistic safety assessment

PSI	Paul Scherrer Institute
PWR	Pressurised water reactor
RBMK	Light water graphite moderated reactor *Reaktor Bolshoy Moshhnisti Kanal'ny*
Sv	Sieverts
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WANO	World Association of Nuclear Operators

* Please refer to Appendix II for a description of the technical terms.

Appendix II

DESCRIPTION OF THE TECHNICAL TERMS

CDF – Core Damage Frequency indicates the likelihood of fuel damage because of an accident in a nuclear reactor. Core damage accidents are considered as serious because they may influence the control of the chain reaction and potentially lead to melting of some or all of the core with associated radioactivity releases into the containment building.

LRF – Large Release Frequency indicates the likelihood of considerable radioactivity releases in the event of a nuclear accident. The ratio between the Core Damage Frequency (CDF) and LRF measures the efficiency of the accident mitigation facilities (like core melt trap) in preventing the radioactivity being released from the building.

PSA – Probabilistic Safety Assessment is a systematic and comprehensive technique used to evaluate risks associated with complex systems such as nuclear power plants. PSA is used during both the design and the operating stages to identify and analyse conceivable faults and sequences of event that might result in severe core damage (CDF) and releases of radioactivity (LRF). A PSA numerically assesses the probability and consequence of all foreseeable faults, and determines risk for each. PSA considers both internal and external events, in both operational and shutdown conditions. Given than the output relies on input reliability data and the comprehensiveness of the faults considered, the results should not be considered as an exact prediction of the event probabilities.

Generation-I – Represents the first batch of nuclear power reactors. In many countries, they were experimental reactors derived from smaller naval propulsion cores and, in some cases, the primary aim of these reactors was for defence applications. However in a few countries, they represented the first civilian nuclear power plants. Almost all reactors of this generation have finished their operation today.

Generation-II – Is a group of second batch of nuclear power plants built in the world. These reactors were explicitly built for electricity generation. Based on the operational experience of the Generation-I reactors, the safety features of the second generation plants were considerably increased. The main improvements consisted in introducing a third barrier (the containment, designed to prevent or significantly reduce the possibility of the radioactivity release into the environment) and in decreasing the influence of the human factor on the plant operation. Most of the nuclear power plants in operation today belong to Generation-II.

Generation-III – Represents a set of standardized light water nuclear reactor designs with increased safety and economic efficiency. These reactors are expected to ensure the core integrity in case of a serious external event like an aircraft fall or earthquake. Additional passive safety facilities (like core melt trap) are introduced, with the aim to prevent radioactivity release even in the case of a hypothetical core meltdown. Also, the impact of potential human errors should be considerably decreased. The core damage frequency (CDF) of a typical Generation III reactor is ten to hundred times lower than the one of an average Generation II reactor. Finally, the Generation-III plants are aimed to be economically efficient, with high availability factor, increased operational lifetime and improved use of nuclear fuel (thermal efficiency, burnable absorbers, etc.).

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