COMPARISON OF ACCIDENT RISKS IN DIFFERENT ENERGY SYSTEMS

HOW ACCEPTABLE?

BY STEFAN HIRSCHBERG AND ANDRZEJ STRUPCZEWSKI

Although electricity is very much needed in our lives, it does not come "risk free." No technology of electricity production has achieved the goal of avoiding risks entirely.

Of all societal risks from energy systems, those from potential accidents account for only a small fraction. Even so, most of the public's attention is often directed at the risks from accidents. It is clear that the development of specific energy systems will be slowed or stopped entirely if their attendant risks become unacceptable to society.

What is, or is not, an acceptable risk is a multi-faceted question. Answers depend not only on the energy analyst's objective assessment of accident frequency and consequences, but also on public perceptions of risk. These perceptions may involve public aversion to large catastrophes, to certain illnesses like cancer, or hereditary diseases, and to environmental damage.

While public perceptions influence policy-makers, objective scientific assessments should remain the basis of informed decisions about energy options, and a considerable range of work is being done internationally. Through its safety programmes, the IAEA has given much attention to the problem of assessing accident risks in an objective and documented manner.

Over the years, the co-operation of experts has made it possible to formulate the necessary and desirable conditions to compare accident risks from different energy systems. Since the results of comparative risk assessment are usually presented to decision-makers in support of new developments for energy systems, the data used in analyses should not be incompatible with actual safety features of plants being considered. All stages of energy chains should be covered, even if some of them take place outside the national or regional boundaries; this can be the case for oil, coal, or uranium extraction and transportation.

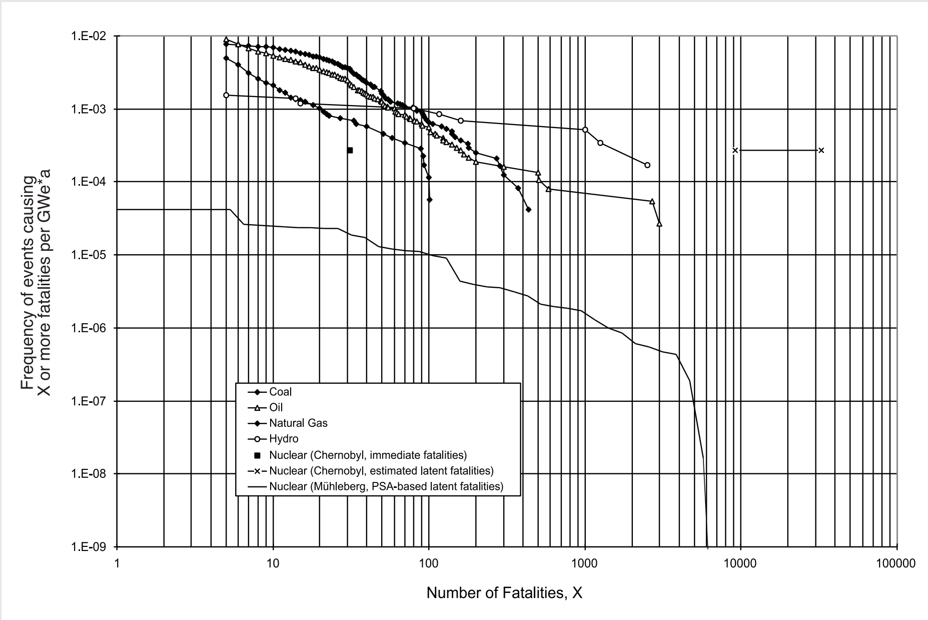
Furthermore, the indicators of accident severity should cover a spectrum of consequences, although fatalities have the largest influence both on costs of accidents and on public perceptions. Data used in evaluating accident hazards should be updated and technological achievements should be taken into account, yet without giving excessive credit for expected technological improvements that can take a long time to implement and market.

A study which fulfils these requirements was undertaken by the Paul Scherrer Institute (PSI) in Switzerland. This study lasted over five years, involved the largest database ever collected on accidents in all branches of the power industry and was finally published at the end of 1998. In contrast to many earlier attempts to evaluate accident risks, the PSI study – entitled "Severe Accidents in the Energy Sector"and issued in November 1998 — assessed a variety of factors.

The study took into account accident risks in the full life-cycle of each energy system. It further provided data separately for developed and less developed countries; considered allocation of accident risks as appropriate in view of the distribution of risks to various countries along the life-cycle; and based the evaluation on realistic technological data for each energy system. Results of the PSI study are referenced in this article, since in our view they represent the most

Mr. Hirschberg is with the Paul Scherrer Institute in Switzerland, and Mr. Strupczewski is a staff member in the IAEA Division of Nuclear Installation Safety.

FREQUENCY OF EVENTS CAUSING FATALITIES FOR DIFFERENT ENERGY CHAINS



The curves for coal, oil, natural gas, and hydropower chains are based on historical accidents worldwide from 1969-96 and show immediate fatalities. For the nuclear chain, the immediate fatalities are represented by one point (Chernobyl) and delayed fatalities by a range of values for that accident. Results for the Muehleberg nuclear plant in Switzerland originate from the plant-specific PSA and reflect latent fatalities.

comprehensive in-depth effort in the comparative analysis of accident risks associated with energy systems.

Considerable data on accident risks in the nuclear industry have been obtained. They have come through programmes of Individual Plant Examinations pursued in the nuclear industry in the United States, and from probabilistic safety assessments (PSA) conducted in many countries and supported by the Organization for Economic Cooperation and Development (OECD) and the IAEA.

These data — together with data on everyday "normal" risks of accidents in various energy systems published in the European Commission's "ExternE" project in 1995 — enable comparisons of the societal risks of various accidents in the field of electricity production.

NUCLEAR SAFETY REQUIREMENTS

The first safety requirements were formulated in the initial stage of nuclear power plant construction. The aim was to minimize the risks of nuclear-based power generation. A number of important principles of nuclear safety were formulated and refined over the past four decades.

The IAEA supports efforts to introduce all nuclear safety principles to new and existing nuclear power plants, including those in which the original design would not correspond to contemporary safety requirements. The modifications of reactor safety features being introduced in many countries are guided by safety targets set by the International Nuclear Safety Advisory Group (INSAG), an advisory body to the IAEA Director General.*

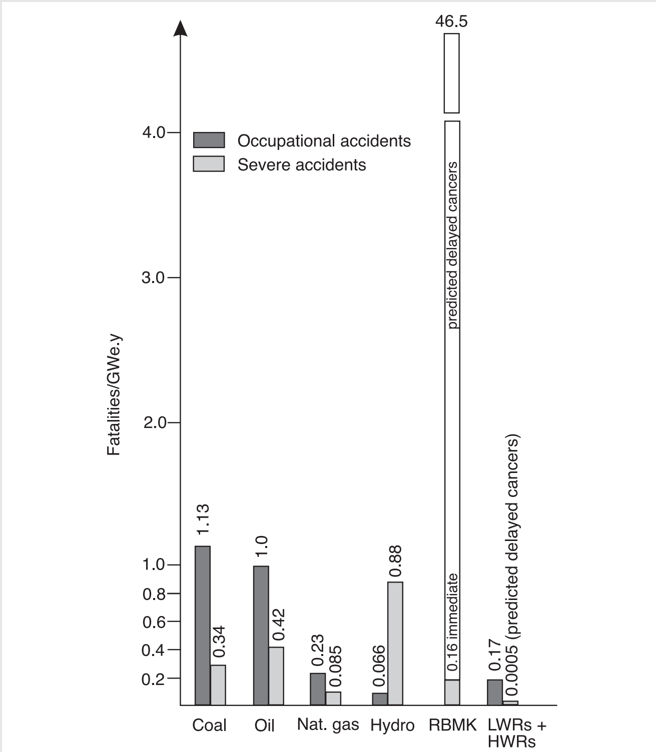
A number of countries have developed approaches and defined risk criteria for hypothetical nuclear power plant accidents involving damage to the reactor core.

In the United States, an approach was formulated in the 1983 Policy Statement of the Nuclear Regulatory Commission. According to it, the individual fatality risks of early deaths due to nuclear power for the critical group of people in the vicinity of a nuclear power plant (one mile) should be limited to 0.1% of the sum of prompt fatality risks from other accidents, and the individual cancer risk in the population near a nuclear power plant (10 miles) should be limited to 0.1% of the sum of cancer risks due to all other causes.

The approaches to defining risk criteria vary among countries. For example, in the United Kingdom, the definition is based on the dose to the individual who after the accident remains at the site boundary. For such a person,

*In 1988, INSAG set as the safety target the reduction of core damage frequency (CDF) to values below 10^{-4} per reactor year. It also stated that the implementation of all safety principles at future plants should lead to a CDF of less than 10^{-5} per reactor year, and the probability of large off-site releases should be smaller by a factor of at least ten. These recommendations have been appended to IAEA Safety Fundamentals and are reflected in regulations of IAEA Member States.

COMPARISON OF ACCIDENT RISKS ASSOCIATED WITH VARIOUS ENERGY CHAINS



Sources: European Commission ExternE Project; PSI Study, Switzerland; IAEA.

Notes: Graph reflects historical experience. Occupational data is for the European Union. Data for severe accidents are world averages.

the risk of one in 100,000 per annum was proposed as just tolerable, and a risk of one in a million per annum as broadly acceptable.

Evident today from the regulations of various countries is a visible trend to decrease the frequency of accidents involving core damage and large admissible releases. For new nuclear power plants, the acceptable frequency of large radiological releases is much less than for existing nuclear power plants, usually below one in a million.

For example, according to Finnish regulations that entered into force in 1997, a PSA analysis prepared for the licensing of a nuclear power plant must show the frequency of a large release to be below one in two million per reactor year.

NON-NUCLEAR ENERGY SOURCES

Accident risks in electricity production systems not utilizing nuclear energy appear at various stages. These stages include, for example, coal mining, oil or coal transport, gas storage, or dam operation. In most countries the approach to accident prevention is deterministic, assuming that if the regulations are fulfilled the plant is “safe”.

Only a few countries have quantified risks and set numerical safety goals. In the European Union, the regulation of major industrial hazards at fixed installations is the subject of the Seveso Directives of 1982 and 1996. The 1996 Directive covers many of the elements which long have been treated as standard elements of nuclear safety, such as notification of safety authorities about existence of facilities creating potential hazards, preparation of safety reports and emergency plans, modifications of facilities, land use planning or information to be supplied following a major accident.

In most OECD countries, the regulations still have deterministic rather than probabilistic character. The application to build a new facility must be accompanied by a safety report, which identifies hazards, lists measures to reduce probability and consequences of an accident, and provides information needed by public authorities to prepare emergency plans.

In Germany the application for a license must be accompanied by a safety analysis, which should prove that the safety measures are adequate to prevent a sequence of events which might lead to a hazardous incident. The consequence assessment is only required to consider what is credible, without taking account of the worst scenario if the organizational and technical measures are judged sufficient to prevent such scenarios from arising. The concept of acceptable risk is not formally recognized, although expert bodies evaluating safety analyses have their own guidelines, including the possible scale of damage and its probability of occurrence.

In the United Kingdom and the Netherlands, safety objectives are expressed in quantitative terms and risk assessments are requested to demonstrate compliance. In the United Kingdom, the safety analyses are evaluated by the Health and Safety Executive (HSE) using the concept of tolerable risk (TOR). The maximum TOR to any member of the general public for an existing large-scale industrial installation is 10^{-5} per year. For land use planning near major hazardous installations, the risk of 10^{-6} per year is the lower limit below which the risks are considered negligible, and the risk above 10^{-5} per year is considered intolerable. The area of risks between those two values is where judgement should be exercised and the risks decreased to a level as low as reasonably practicable (ALARP).

According to the British approach, the lower limit of a broadly acceptable region is set by the point at which the risk becomes truly negligible in comparison with other risks that an individual runs. As technology advances, new measures become reasonable and the judgement required in the ALARP principle moves the tolerable risks downwards to keep in line with the knowledge and technology of the day. What is considered acceptable for currently operating plants might become unacceptable for new plants.

In the Netherlands, the operator of each industrial hazard site must prepare safety reports concerning on-site and off-site hazards. The maximum permissible individual off-site risk for an existing situation is 10^{-5} per year, and for new situations 10^{-6} per year. The societal risk is defined as acceptable if the frequency of accidents involving 10, 100, and 1000 deaths does not exceed 10^{-5}, 10^{-7} and 10^{-9} per year, respectively. However, exceptions to this rule are possible and in fact practiced when the situation demands it, for example for areas around Rotterdam harbour or Schiphol airport, where accepted risks are higher than the guideline values.

EVALUATING ACCIDENT HAZARDS

Comparative analysis of severe accidents can be based on historical evidence, PSA, or on combinations of both.

The extensive work done at PSI in Switzerland resulted in the creation of an Energy-related Severe Accident Database (ENSAD). It includes not only data on fatalities, but also on injured, evacuees, polluting releases, contaminated areas and economic losses due to severe accidents in energy-related systems. According to the definition adopted in ENSAD, a severe accident is an event which involves one or more of the following effects: at least five fatalities, at least 10 injured, at least 200 evacuees, 10,000 tons of hydrocarbons released, more than 25 km^2 of enforced cleanup of land or water, and more than US $5 million of economic losses.

The review of accident risks in various regions of the world and consideration of technological developments resulted in differentiating the accident indicators into functions of these factors. The results are especially striking in the case of hydropower plants. The indicators for different types of dams show that the lowest failure rates in the West in the period 1930-96 were found for gravity dams (1.3×10^{-5}/dam-year) and the highest for rockfill dams (3.0×10^{-4}/dam-year). The date of 1930 as the border date has been chosen for several reasons. At that time, after failures of several dams in the USA and United Kingdom, the laws for the supervision of dam safety were enacted in several countries and in parallel the technology was changed, with structurally stronger concrete replacing masonry as the basic building material. This resulted in a much lower rate of dam failures for dams built after 1930.

Besides the design, the differences in quality assurance, monitoring, safety culture and effectiveness of safety authorities in various countries influence the results. For example, the fatality index for dams worldwide for the period 1969-96 shows a rather high risk of about 0.9 fatalities per gigawatt-electric year (GWe.y). However, after differentiating between OECD and non-OECD countries it has been found that the number of fatalities per GWe.y in non-OECD countries for that period was 2.2 fatalities, while for OECD countries only 0.004 fatalities. This shows that it would be misleading to apply world average data for "dams" in general to evaluate the safety of a new gravity dam to be built, for example, in Norway. Instead, an application of quantitative risk assessment would be desirable to reflect the actual conditions.

In the case of nuclear power, the differences in design have a decisive impact on the safety level of the plants. The historical data show that the accidents in nuclear plants utilizing light-water reactors (LWRs) and heavy-water reactors (HWRs) have not resulted in any early fatalities.

The only accident at such reactors with off-site releases, the 1979 Three Mile Island (TMI) accident in Harrisburg, USA, involved extremely small doses to the surrounding population. The collective dose was evaluated by various sources at values ranging from 0.5 to 50 man-Sv. The most probable cumulative population dose was evaluated by the President's Commission on the TMI Accident as 5 man-Sv. Thus the most probable number of fatalities at TMI is zero, though the upper bound estimate is two.

The 1986 accident at the RBMK reactor at Chernobyl occurred in a different type of reactor design. It cannot be treated as representative for considerations of accident risks in nuclear plants designed, built and operated in accordance with internationally accepted nuclear safety principles. Yet it is the accident that has most shaped public perceptions.

The RBMK design evolved from military applications of graphite moderated reactors for plutonium production. The plant was completely different from LWRs operating in other countries, and it included several features which made the accident possible and in fact predetermined its tragic course. The most important among these features was the tendency to increase spontaneously the reactor power when the temperature in the core increased.

This "positive feedback" was important only under certain conditions, and at the time of the accident just those conditions had been reached. The power of the reactor rose until it exceeded one million megawatts and the fuel evaporated.

Such a scenario is not possible in LWRs because in those reactors an increase of temperature inherently leads to the decrease of reactor reactivity and power. Other features of the RBMK design that contributed to the accident were also unique to this type of reactor.

Also missing at Chernobyl were basic principles of nuclear safety.

Safety issues did not receive the full attention they deserved, but were subordinated to actual political and production targets; safety authorities played a secondary role; operators had not been trained for accidents and were not aware of the hazards involved in the procedure undertaken during the accident; lessons were not learned as they should have been from international experience in reactor safety; and there was no international co-operation in safety matters of RBMK reactors. In fact, the RBMKs were treated as unique and not licensable outside the country of origin.

In 1989, British authorities in charge of health and safety of the population concluded that the basic differences in safety characteristics between the RBMK design and the pressurized-water reactor design are so fundamental that experiences with the former could not be used for judging safety aspects of the latter.

Indicators of severe accidents presented here follow this approach. They treat the effects of Chernobyl as characteristic for RBMK reactors and take the indicators for all other types of reactors based on the TMI accident.

Overall, there are many severe accidents registered for non-nuclear energy systems, and the curves of expected frequency and severity of accidents can be constructed. However, the lack of data for nuclear accidents — they simply have not had any radiological results with the exception of the two cases of TMI and Chernobyl — makes it necessary, in practice, to use the data obtained from PSA studies.

These studies are primarily used for evaluation of the robustness of the nuclear power plant design and procedures and for indicating its weak points, so that the improvements can be oriented most effectively. They are also used in several countries to show compliance of nuclear plants with the safety regulations. PSA studies thus have become a useful tool in safety assessments.

A similar approach involving qualitative risk assessment has been used in the non-nuclear industry, e.g. for evaluation of the risks involved in liquid fuel storage at Canvey Island. Results showed clearly that the risks of non-nuclear installations are higher than the risks due to nuclear

INDICATORS OF DAMAGE FROM SEVERE ACCIDENTS

The number of early fatalities that historically occurred after severe accidents in non-nuclear energy systems has been estimated. For nuclear energy, both early fatalities (which resulted only from Chernobyl accident) and latent cancer fatalities have been estimated. In view of the lack of observations of negative health effects in large population groups subjected to radiation doses similar to those of the Chernobyl accident, the corresponding number of latent fatalities in territories of the former Soviet Union was estimated based on conservative assumptions. The number of fatalities expected to be observed should be much lower.

Damage indicator (per GWe·year)	Coal OECD	Oil OECD	Natural Gas OECD	LPG OECD	Hydro OECD/non-OECD	Nuclear LWRs/RBMK
Number of Immediate Fatalities	0.13	0.39	0.066	1.8	0.004/2.19	0.0/0.16
Number of Latent Fatalities	?	?	?	?	?	0.0005/46.5
Number of Injured	0.019	0.44	0.22	7.34	0.23/0.143	0/2.15
Number of Evacuees	0	7.41	4.83	481	10.1/70	33/726
Monetary Damage (million 1996 US $)	0.035	0.94	0.11	1.92	0.7/0.5	1.3/1760

Notes: The number of latent fatalities is usually not determined for non-nuclear accidents, although this number may be significant. In the case of nuclear plants, the data for RBMK and LWRs correspond to the expected maximum number of fatalities in historical accidents divided by the energy produced in those reactor types.

Source: Data for non nuclear energy systems in European OECD countries, and non-OECD countries in the period of 1969-96 taken from PSI, Switzerland; data for nuclear power for 1960-98 from the IAEA.

power plants with pressurized-water reactors.

COMPARISON OF ACCIDENT DATA

Results based on historical experience show considerable differences between the aggregated, normalized damage rates assessed for various energy systems. The highest immediate fatality rates associated with severe accidents in OECD countries apply to liquid petroleum gas, followed by oil, coal, natural gas, hydro, and nuclear power. The PSI study shows that the rates for all considered energy systems are significantly higher for non-OECD countries than for OECD countries.

In view of the strengths and limitations of historical and predictive methods, a joint approach is useful for comparing accident risks. In this approach, the data for non-nuclear systems — which exhibit a quite comprehensive statistical base on severe accidents — are based on historical experience and the data for nuclear power are shown based on PSA results, with historical data used as an additional reference point. For Western-type reactors, the public risks are typically in the range of 0.01 to 0.1 delayed fatalities per GWe.y. The representative estimates of the individual risks for the operating Western reactors are of the order of 10^{-9} per GWe.y and even lower for the emerging evolutionary designs of nuclear power plants.

Since fatalities are not only due to severe accidents, but also to small and more frequent everyday accidents, the data for occupational accidents available in the ExternE study (representative for OECD countries) are useful to review. They show that the highest occupational accident risks are associated with coal and oil, and that nuclear risks are several times smaller. The highest occupational accident risks are associated with coal and oil, with nuclear risks being significantly smaller.

Despite the good safety record of nuclear power plants built and operated according to internationally accepted nuclear safety principles, further work is needed. The seriousness of the Chernobyl accident is a reminder of the necessity of keeping safety standards high at all nuclear power plants. ❑