Advanced reactors: Safety and environmental considerations

An international perspective on the next generation of nuclear plants

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Attaining — and sustaining — a high level of safety has been of uppermost importance throughout the development of nuclear energy's civilian applications. Safety goals have been pursued not only through prudent designs, backed up by extensive experimental work and analytical research and development, but also through quality controls and practices in component manufacturing, plant construction, operation, maintenance, and management.

Over the past 30 years, civilian nuclear power plants have accumulated more than 5600 reactor-years of experience producing electricity around the world. While two major accidents have occurred, only one involved significant off-site consequences. Overall, the world's nuclear power plants generally have established a very satisfactory level of safety.

Advanced nuclear plants are expected to equal or enhance the safety characteristics of the best presently operating plants. To a large degree, efforts are being driven by what has been termed a "safety culture", whose establishment has become a prerequisite for any country's deployment of nuclear power. The term basically refers to the ongoing quest for system-wide excellence, including the technical infrastructure and management associated with both the design, construction, and operation of nuclear plants.

By taking maximum advantage of research efforts and the accumulated operating experience of more than 400 nuclear plants worldwide, the work has become a major driving force for technological progress. One important consequence of this evolutionary approach is that it builds upon, and does not call into question, the operational safety of the majority of today's generation of nuclear plants.

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Consensus on safety principles emerges

At the international level, safety-related activities directed at supporting the development of the next generation of nuclear plants are drawing greater interest.

In September 1991, participants at the IAEA's international conference on nuclear safety recommended that the Agency take a number of actions. The conference specifically urged the IAEA to support the work of its Member States towards the development of an international consensus on safety targets for future generations of nuclear power plants, and towards the development of appropriate safety principles and characteristics. A step-by-step approach was suggested to lead to a comprehensive set of safety criteria for which the documents of the International Safety Advisory Group (INSAG) could provide important input.

Among other goals, the safety level of the next generation of nuclear power plants is to be improved such that the risk of a significant accidental release of radioactivity to the environment is even more negligible than it is today. The long-standing defense-in-depth principle continues to be the fundamental means of ensuring safety. Its implementation involves the use of successive levels of protection, including independent physical barriers to prevent the release of radioactivity to the environment, and redundancies and spatial separation to protect against sequential failures. The four barriers comprise in essence: the fuel matrix, fuel cladding, primary coolant boundary, and the containment structure.

Nuclear designers today are striving to improve the barriers themselves, and the level of protection each provides, so as to achieve an enhanced overall level of safety. But, in achieving this objective, it is not necessary that each barrier and associated protective level carries equal weight. Clearly, enhancement of the first barrier decreases the burden on the subsequent barriers; so does enhancement of the second barrier, and so on. Moreover, placing higher priority on the earlier barriers would provide greater assurance of preserving the plant investment, and keeping the radioactive material closer to where it is generated.

Even though all designs provide protection at each stage, the degree of emphasis varies among the different concepts. The evolutionary designs have been critically examined, and they have improved all four barriers. In the innovative designs, all four barriers also were examined. But in some cases major emphasis was given to the second barrier, i.e. to preventing fuel cladding failure. The owners' interest in protecting their investment and limiting the escape of fission products emphasizes prevention of accidents, which also tends to place more emphasis on the earlier barriers.

Development becomes international

A survey could easily identify more than 40 nuclear power plant concepts currently under various stages of development worldwide, an impressive testimony to the belief that nuclear power is going to have a future. *(See table.)* Due to this multitude, only some general trends are commented upon in this article.

Both by stage of maturity and base of experience, the spectrum is dominated by the evolutionary designs of large water-cooled reactors, followed by medium-sized plants of this same type that emphasize passive features for greater accident resistance. A third group, often called innovative designs, comprises more substantially modified water reactors of yet smaller size, and high-temperature gas-cooled as well as liquid metal cooled reactors.

One observable trend is the strengthening of international co-operation in the development of advanced reactors. For example:

- the USA with both Japan and Korea for the advanced light-water reactors (ALWRs);
- Canada with the Republic of Korea for pressurized heavy-water reactors (PHWRs);
- France and Germany in Europe for ALWRs;
- European countries for fast-breeder reactor development.

These examples are not comprehensive, since other countries, such as the Russian Federation, are also striving for more intensive international co-operation.

Despite the large number of concepts under consideration and the large number of design institutions, the ultimate goals are few and straightforward: maintain and improve both the economics and the safety of nuclear power. In general, there seems to be agreement that the basic safety principles for nuclear power plants issued by INSAG, which are based on operating experience, should be extended, as INSAG has proposed, to include the following specific aspects for future nuclear power plants:

- operating and maintenance procedures;
- simplified, more user-friendly design;
- design for systematic confinement of fission products in the event of severe accident conditions;
- reduction of the probability for major accidents, and their potential consequences, through design features;
- protection through design features against sabotage and conventionally armed attacks;
- consideration of passive safety features.

Examples of advanced nuclear power plants being developed worldwide

Designation	Type	Power (MWe)	Vendor/Designer	Country
N4	PWR	1400	Framatome	France
CONVOY B	PWR	1350	Siemens	Germany
EPR	PWR	1400-1500	NPI (Framatome/Siemens)	France/Germany
SYSTEM 80+	PWR	1300	ABB/Combustion Eng.	Sweden
ABWR	BWR	1300	GE/Hitachi/Toshiba	USA/Japan
BWR 90	BWR	1100	Asea Brown Boveri (ABB)	Sweden
EFR	FBR	1500	European Fast Reactor Associates	Belgium/France/Germany/ Italy/UK
CANDU	PHWR	600-900	AECL	Canada
CANDU-3	PHWR	480	AECL	Canada
AP-600	PWR	600	Westinghouse	USA
WWER 500/600	PWR	635	Hydropress/others	Russian Federation
SBWR	BWR	600	General Electric (GE)	USA
PIUS	PWR	600	ABB	Sweden
VPBER-600	PWR	600	OKBM	Russian Federation
MHTGR	HTGR	4 x 170	General Atomics	USA
		4 x 80	Siemens/ABB	Germany/Sweden
PRISM	LMR	3 x 150	General Electric	USA

Some of the more important items from this admittedly impartial listing of general considerations are addressed in the following sections.

Operating experience is the basis

Feedback of operational experience from existing nuclear power plants is playing an important role in the design of the next generation of nuclear power plants. All advanced reactor designs have factored in prior experience to the largest extent possible. Some of the more innovative designs, by definition, incorporate features or other facets for which a large amount of prior experience may not be available.

Any plant feature within a design that is not previously demonstrated should only incorporate components or systems that are introduced after thorough research and prototype testing at the component, system, or plant level, as appropriate. Proof of performance, including that regarding the safety of some of the very innovative designs, may require a full-scale demonstration plant.

Human factors. Advanced plants are being designed to be easy to operate so that the behaviour of the plant can be readily understood by the operator and, as a result, the possibility of human error can be reduced.

The designs provide for automatic responses to abnormal situations to the maximum extent, with a sufficient period of time (grace period) during which no operator action is required. This allows the operators time to assess both the event and the plant state and, thus, after careful consideration, to initiate appropriate actions if warranted.

The man-machine interface is also being improved by taking advantage of advances in modern electronic, digital, and computer technology, for example microprocessors, video displays, multiplexing, fibre optics, etc. Organized and hierarchical alarm displays and controls, "expert systems", and improved diagnostic systems are available technologies that are being used to best advantage in advanced nuclear designs.

New designs stress simplification

A number of current plant designs are regarded as unnecessarily complex to operate, inspect, maintain, and repair. Unnecessary complexity is a root cause of a wide range of problems and therefore design simplification is being pursued with high priority, particularly where operational safety is affected.

Simplification is being addressed in every aspect of advanced plant design and operation. The basic spirit of simplification is to include only systems in the design that perform essential functions, and to reduce complexity by adding design margins, or by having the essential function perform passively, thus reducing the need for complex controls.

Simplicity in plant operation will help make the operator's tasks easier, and therefore help reduce human error. Finally, simplicity in manufacturing and construction is generally considered a priority.

Passive safety features, by definition, do not rely on human actions and, to some extent, also do not rely on external mechanical and/or electrical power, signals, or forces. Instead, they rely on naturally available sources of motive power, such as natural circulation, and on actuation mechanisms, such as check valves.

Several levels of "passivity" exist, including systems which are actively initiated but operate passively. The use of passive safety features in a nuclear power plant is a desirable method of achieving simplification and increasing the reliability of the performance of essential safety functions, i.e. reactor control and shutdown, core and containment cooling, and retention of fission products.

Passive systems also tend to reduce redundancy requirements, operational complexity, and need for operator actions. They have the potential of achieving higher reliability and presenting fewer performance uncertainties than active systems. An important aspect of passive systems is their sole dependence on stored, readily accessible sources of energy and, hence, their capability for operating in a station blackout condition. Use of passive features already is incorporated to a limited extent in present plants. Their increased utilization is being considered for safety systems in many advanced plants.

Deterministic and probabilistic safety assessments complement each other

It is generally acknowledged that probabilistic safety assessments (PSAs) are very important for identifying vulnerabilities in a particular design configuration. They also provide valuable insights into the likelihood of accident scenarios. Despite acknowledged limitations, PSA targets have been proposed in several instances by different groups. For instance, INSAG has proposed the following minimum targets for future plants:

- Severe core damage frequency limited to 10^{-5} per reactor year;

- Large off-site release frequency limited to 10^{-6} per reactor year.

These targets are design goals. It has not yet been shown that they can be met by each design, not withstanding the fact that some designers strive for even lower figures. In general, though, the range given above is considered feasible.

Prudency within the defense-in-depth concept, however, mandates that non-probabilistic methods, such as deterministic analysis and good engineering judgement, must also be used, particularly if PSA indicates a very low level of accident probability. This dual approach gives the highest degree of assurance that core power level is controlled, sufficient cooling is maintained, and radioactivity is safely contained, the essence of nuclear safety.

Advanced nuclear plants hold benefits for the environment

Many nuclear opponents agree that nuclear power would have substantial environmental benefits over other established means of providing electricity in sufficient quantities at attractive costs if, primarily, the severe accident issues were solved to their satisfaction. The designs for the next generation of nuclear plants give highest importance to this topic.

Current plants meet conservative design requirements within a defined set of accidents called the licensing design basis. Future plants will meet this same licensing design basis, and in addition, even lower probability events will be considered explicitly and systematically.

Many approaches are being considered within an emerging common framework of general safety principles. Although they may differ in detail, there is a strong common effort to reduce the off-site consequences of any accident to an insignificant level, irrespective of the seriousness of the accident. This principle has always been part of the basic safety philosophy.

Within the design basis framework, credible serious accidents were thoroughly analysed and the plant was designed with sufficient barriers to prevent and mitigate the consequences of such accidents. In recognition of the fact that there could perhaps be less credible sequences of events, very large design margins and off-site countermeasures were required.

As a result, emergency plans for nuclear plants, as opposed to emergency plans for other industrial activities, were obligated to include complex provisions for rapid sheltering and/or evacuation. Such provisions and associated rapid notification requirements placed onerous responsibilities on the plant owner and on various public agencies who were to act rapidly. Some recent studies and evaluations of nuclear accident scenarios indicate that rapid evacuation may not be necessary for public safety, and that a more orderly approach is indicated.

Hence, designers and users of future nuclear power plants have focused on more realistic accident analyses, and protection strategies, and on prevention and mitigation features with the goal of delaying the need for sheltering and/or evacuation for a reasonable period and, if possible, establishing a strong technical basis for not requiring such measures at all. Similarly, because of the Chernobyl event, there has been a recent focus on ensuring no contamination of surrounding land and water bodies that could significantly affect public health, or at least limiting this contamination in space and time. In particular, it has been emphasized that contamination should not require the long-term relocation of a large number of people.

Enhancement of all barriers within the defense-in-depth principle, including appropriate accident management in combination with the incorporation of modern research results and more realistic accident analysis, has now provided the technical basis for minimizing and delaying releases of radioactivity. This would allow the simplification of emergency planning for advanced reactors, and in the process foster greater public acceptance.

Further aspects for reducing environmental impacts of advanced nuclear plants include the reduction of occupational doses, minimization of waste generation, and improvements in the fuel cycle.

Technical excellence fosters acceptance

Advanced nuclear power systems will capitalize both on the accumulated experience of current systems, and the results of worldwide research and development. Safety enhancements and improved economics are achievable together, particularly when a high degree of standardization is implemented.

The advanced designs enhance the barriers within the defense-in-depth philosophy to a degree that any off-site consequences for severe accidents, in the event they do happen, can be handled with substantially simplified emergency planning procedures.

The success of these various designs depends not only on their technical excellence. It also depends on the understanding and acceptance of nuclear power by the public and decision makers, i.e. a generally favourable nuclear climate.❐

The Next Generation: References for more technical reading

The following references feature a number of technical reports recently issued by the IAEA.

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Safety-related Terms for Advanced Nuclear Plants, IAEA-TECDOC 626, Vienna (1991).

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More than 40 designs for the next generation of nuclear electricity plants are being developed around the world. (Credit: Mitsubishi)