The next generation of nuclear power plants and beyond: Raising the level of ambition

A common goal is driving the development of advanced reactors

by
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Practically all countries with civilian nuclear power programmes are developing improved versions of currently existing nuclear power plants for implementation before the turn of the century. They are called evolutionary plants, as they have incorporated improvements in a step-by-step fashion, drawing on the accumulated experience of existing nuclear plants, which together have recorded more than 6000 reactor-years of operation. The targeted improvements concern many aspects, from design, construction and operation, to safety and economics.

In particular, enhancing safety even beyond the impressive level that has already been achieved for the vast majority of existing plants is a common goal. An impartial comparison with alternative means of economical large-scale electricity production — as was presented at the Senior Expert Symposium in Helsinki in 1991 — shows nuclear to be significantly superior in terms of minimizing the impact on human life and on the environment. Although this fact is not new, it needs reiteration and appropriate publicity to assure the unsure public, very often confused by sensationalistic media, to reassure politicians and, somewhat surprisingly so, also to reassure some of the people with doubts inside the nuclear community.

In the context of this article, the term safety stands for the result of accomplishing by technical means the following two essential tasks: Firstly, to design, build, operate, and maintain the reactor plant in such a way that neither equipment failures, nor operator errors, nor external events such as earthquakes, can lead to overheating of the nuclear fuel and, as a consequence, to a subsequent release of dangerous amounts of radioactivity to the reactor cooling system. Secondly, to provide and maintain a strong and leak-tight containment shell around the reactor cooling system in order to retain the bulk of radioactivity which might be released in an accident sequence that is not terminated within the reactor plant itself, as it should be in compliance with the first task.

What is significant is that nearly all currently operating reactors are to a high degree in accordance with internationally accepted safety principles. To achieve this status, many older plants had to be modernized with additional equipment in the plant proper, with ergonomically improved control panels, and with improved operating procedures, the latter in conjunction with intensified operator training.

A respective large impetus came from the very thorough examination of the serious accident at the Three Mile Island (TMI) plant in 1979. Other lessons have been drawn from the ever increasing operating experience in the world. This experience is openly being exchanged at an international level between operators, designers, research and development institutions, and regulatory organizations. The lessons learned represent a significant input to the designs of the next generation of evolutionary nuclear power plants. It can be expected that this input will enhance their safety even further. This is because the modernization measures mentioned before can be tailored right into the design. This is far more effective than backfitting existing plants.

For assessing or "measuring" safety improvements, designers employ sophisticated methods which are also being used in other industries, such as the aerospace industry. One method is known as probabilistic safety assessment (PSA). It basically describes, or models, the entire power plant in terms of interacting components, systems, functions and operator ac-

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tions. It identifies the probability that an initiating failure or error is not being stopped by one of the layers of defense from further propagating into a severe fuel damage. This is done for a large number of initiating events and results in a single cumulative figure for the probability of a severe core damage per reactor and year. This characteristic figure has significantly decreased from typically about one in-a-thousand before the TMI-accident to well below one-in-ten thousand today. The goal for the next generation of nuclear plants is another decrease by at least a factor of ten. Most designers strive for a figure of one-in-a-million.

Apart from evaluating these figures for comparing the effectiveness of different design options for meeting the defense-in-depth principle, such probabilistic analyses help, and force, the designer to identify the weak points in the design. They clearly indicate where improvements are needed, and allow the selection of the best engineered countermeasures. Achieved safety levels are very high and further improvements can be expected. There is thus no reason not to continue for a long time to come with the evolutionary plants that are currently under construction or in various stages of planning.

Yet, in spite of nuclear power's highly satisfactory record, there is an intensive debate among the experts on to how to do better. Not because the achieved safety is inadequate, but rather in the quest of excellence. In particular, by doing better still, some hope to make significant progress in regaining public acceptance.

Two broad directions can be identified. The first one stresses the desirability, or even necessity, of continuing the evolutionary path, primarily since the ever increasing experience with existing plants provides a solid foundation for the future. Enhancing safety even further, where considered necessary, could be done best within that framework. The other line of thinking argues instead for a novel approach with more innovative reactor concepts, particularly if the use of nuclear power is to be substantially increased. Both views will be briefly discussed.

The evolutionary approach

Within the context of enhancing the safety for the next generation of advanced water-cooled reactors, improved protection is being sought against the consequences of a severe accident, such as melting of the fuel. Investigating severe accident phenomena is a major worldwide research and development task. It aims to more precisely identify all potential challenges to the desired containment performance and to eliminate by design measures any weak points that may be found. The ultimate objective of these activities is to be able to demonstrate that, from a technical point of view, no emergency measures, such as evacuation, would be needed to protect the general public even after a severe accident inside the nuclear power plant. The impact of the accident is to be limited to the site itself so that the life of the population on the outside is not disrupted.

Casting this objective into an internationally accepted recommendation is one of the major activities of the IAEA. The principles laid down by the International Nuclear Safety Advisory Group (INSAG), an advisory body to the IAEA's Director General, would be very well suited for this purpose. In essence, the technical safety objective stated in the report known as INSAG-3* would have to be expanded to deal also with severe accidents beyond the so-called design basis accidents. Certain modifications would in addition be needed for the principles concerning the containment, with significant work still outstanding for defining the technical implications and consequences.

The innovative approaches

Many proponents for innovative design approaches for future reactors subscribe to another view. They argue that, while the safety of present and future evolutionary reactors is acceptable, its implementation, and maintenance over time, requires technical systems that are functionally too complex and put an undesirably high burden on the operator. They call for significantly simpler plants whose ultimate safety depends much less — and in the extreme not at all — on the proper functioning of engineered safety systems and on proper operator responses, as compared with the evolutionary plants. Some proponents also believe that with such innovative reactor concepts public acceptance of nuclear power could be significantly improved.

It is further argued that the need for innovative approaches becomes much more pressing if nuclear power is to be substantially increased in the future, expanding into many regions of the world which today have little, or no experience with that technology. Is it affordable, the question is being asked, to establish, assure, and maintain the exacting technological and human resources that are necessary for designing, licensing, building, operating, and maintaining

Basic Safety Principles for Nuclear Power Plants, (INSAG-3), IAEA Safety Series No. 75, Vienna (1988).

the evolutionary descendants of current reactors in a way that the desired safety is uniformly maintained all over the world for a long time to come? Or, to put it differently, can this task be made easier with innovative reactor concepts? This is one line of reasoning for innovative approaches. Another one asserts that it may be possible to *a priori* "design out" the possibility, albeit very unlikely, of a severe core damage in the first place, ultimately resulting in a much improved public acceptance of nuclear power.

Simplification, and making the reactor plant more resistant to equipment failures and operator errors, is also an explicit objective for the evolutionary plants. Consequently, the controversy between evolution and innovation is less about the goal of safety, but rather about the means of reaching it, and is thus highly technical in nature.

A large number of innovative concepts have been under discussion for many years. Some are based on light-water reactor technology, others are derived from the development of gas- or liquid metal-cooled reactors. As to maturity, they range from pre-conceptual to already very detailed and backed by considerable specific research and development. The prevailing opinion, however, is that each concept would need an appropriate industrial-size prototype before it could be considered an option for expanding nuclear power. Some of the concepts may even need *a priori* feasibility tests.

To the extent that they are being proposed on grounds of improved safety, all concepts attempt to fulfill two major safety objectives. One is to reduce, or even eliminate, the necessity for correct operator actions when controlling major accidents. The other is to eliminate the need of forced coolant flow for removing the residual heat that all reactor fuel elements still release after the nuclear chain reaction has been terminated. Forced flow, in this context, means no reliance on rotating machinery, such as pumps, or the energy needed for driving them. Some of the concepts try to accomplish this "passive residual heat removal", as it is often called, also for conditions when the reactor coolant system has been afflicted by an accidental leak.

Although differing in individual solutions, all innovative concepts try to engineer protection against accidents into the design to the maximum extent possible. No initiating event, e.g. loss of electrical power due to a severe thunder storm, should escalate into endangering the integrity of the fuel elements. Of the three imperatives enunciated by INSAG — namely controlling the reactor power, cooling the fuel, and confining the radioactivity within the appropriate barriers — the innovative concepts stress the first two.

They thus place maximum emphasis on the preventive level in line with defense-in-depth principles, and with INSAG's principle that "principal emphasis is placed on the primary means of achieving safety, which is the prevention of accidents, particularly any which could cause severe core damage".

The innovative concepts can thus hardly be criticized on grounds that they would move away from established principles, an important strategical aspect. Quite the contrary. The price in terms of capital costs does seem to be high, though, and relief must be sought and granted somewhere else in the design by relaxing certain engineering requirements.

Innovative concepts strive for less "safety culture" than is presently the case for established reactors since in emergencies the response of the operator, or the function of certain systems in some cases, is not decisive for adequate protection. It is somewhat surprising that error, inaction, or even maliciousness of the operator are considered as far more dangerous to safety than equipment failures. Two conclusions may be drawn from this. The first one would be a tribute to defense-in-depth. Redundancy, diversity, and physical separation, in conjunction with the operator's dedication to safety ("safety culture"), are obviously proven and acknowledged in their effectiveness and value. The second conclusion is as follows: If system simplification and man-machine interface improvements are implemented with an even higher degree of automation — an explicit objective for the evolutionary plants — then the concerns about operators could be considered greatly reduced. In other words, much of what is a major driving force for the innovative concepts will also be accomplished with the evolutionary designs.

Clarification and harmonization

One goal expressed by some proponents for innovative reactors is to come up with designs that can be called "deterministically safe". This is to mean that it would be desirable that adequate safety to the public could be demonstrated without emphasizing probabilistic arguments. As long as this is not understood as "nothing at all can happen under all circumstances", a position very difficult to defend, the antipodes of evolutionary and innovative approaches can probably be united. Both ultimately aim at demonstrating that accidents with severe consequences to the public can be excluded. The means for achieving this objective are deterministic in either case. The evolutionary designs do this by providing staggered layers of protection and mitigation within the defense-in-depth approach. The innovative ones seek specific features such as large temporary heat sinks and paths for dissipating decay heat in a passive manner, as it is sometimes called.

The term "deterministically safe" reactors can thus accommodate inherent, passive, active, and other features for achieving the ultimate objective of no severe consequences for the public. Much of the confusion that goes with terms such as passive, inherent or forgiving, wrongly applied when referring to the total plant, but entirely correct with reference to specific systems or functions would disappear. It would also be much easier for the public — which really only wants to know whether it can be affected by an accident or not, rather than having to decide on technical details for which it has little background.

Probability analyses would still be necessary to find out which conceivable accident sequences need deterministic protection, both for evolutionary and innovative plants. However, it must be clearly stated that "deterministically safe" ultimately only means that severe consequences have such a low probability that they should be accepted like any other major catastrophe.

Respective probabilities are sufficiently low for future evolutionary plants; innovative ones need not do better. Keeping the above qualification in mind, both types could be called deterministically safe. To the extent that the public is concerned, there is no dilemma left and an opposing view cannot be upheld.

The discussion is one that has to be done inside the nuclear community among specialists. Its thrust has to be directed away from which concept is the safest, irrespective of cost, to which concept leads to the lowest generating cost for a commonly accepted safety level.

Motives and constraints for the future

Motives. Innovative concepts cannot be primarily justified for safety reasons. Rather, they have to meet other needs. Probably the most significant ones concern their potential for helping to meet the world's growing energy consumption, and for helping to reduce the greenhouse problem at the same time.

Simplification is one major objective of the next generation of evolutionary plants for the industrialized countries. How much stronger would this objective weigh for the less developed countries that would have "to go nuclear" in the above context? It is almost inconceivable that industrialized nations could accommodate most of the estimated five- to ten-fold capacity increase over what is currently installed. The *a priori* requirements of adequate safety culture and adequate infrastructure are severe impediments against substantially increasing the use of nuclear power the world over. An evaluation of associated costs is greatly needed as it will influence the necessary choices. If, as suspected, the costs are high, then designing around the problem may very well be an endeavor that deserves careful consideration. However, if a solution for a "low safety culture concept" could be found, it will lead to two problems. First, how could it coexist in the long run with the traditional approaches? Could regulators live with a two-class reactor population? Second, will there be customers who would acknowledge needing such a special concept because they can't do any better? Will they not feel they are being discriminated against?

Achieving a desired safety level always rests on the proper combination of three key qualities: that of the plant proper, that of the available infrastructure, e.g. grid, and that of adequately trained operators. If the latter two are weak, then the machine has to make up for it. If a reactor could be found that does precisely this, what are the consequences if it were re-imported to the industrialized countries? Would it mean that in this case there would be a new standard that regulators would make mandatory?

Constraints. However, there are severe constraints that stand in the way of a rapid expansion of nuclear power, no matter whether they are based on evolution or innovation. Neglecting issues of favourable economics, ultimate waste disposal, treatment of currently unsatisfactory plants, and non-proliferation, the most important constraints comprise, almost as criteria, the following: The public must be made aware of, and must understand, the benefits of nuclear power and thereupon accept its desirability, or even its necessity. The public in industrialized countries must likewise understand that expanding nuclear into developing countries will need extraordinary financial efforts. Thirdly, promotion of innovative concepts must not be done in a way that questions what is being planned for the near future with the evolutionary concepts. If that is not understood, the possibility arises that the nuclear option will be lost altogether.

Overcoming these constraints is a formidable task. It would appear desirable to develop an appropriate master plan which defines in greater detail which sub-tasks have to be accomplished in what manner so as to foster a vigorous nuclear renaissance and expansion after the first decade of the next century. The IAEA would be the ideal institution for developing such a plan. ❐