IAEA-SM-353/7

TECHNOLOGICAL READINESS OF EVOLUTIONARY WATER COOLED REACTORS

XA0053538

P.E. JUHN
International Atomic Energy Agency,
Vienna

Abstract

Nuclear energy has evolved to a mature industry that supplies over 16% of the world's electricity, and it represents an important option for meeting the global energy demands of the coming century in an environmentally acceptable manner. New, evolutionary water cooled reactor designs that build on successful performance of predecessors have been developed; these designs have generally been guided by wishes to reduce cost, to improve availability and reliability, and to meet increasingly stringent safety objectives. These three aspects are important factors in what has been called technological readiness for an expanded deployment of nuclear power; a major increase in utilization of nuclear power will only occur if it is economically competitive, and meets safety expectations. To this end, the industry will also have to maintain or improve the public perception of nuclear power as a benign, economical and reliable energy source.

1. INTRODUCTION

During the last 50 years, nuclear energy has evolved from the research and development environment to an industry that supplies over 16% of the world's electricity. There is now an opportunity for nuclear energy to significantly contribute to the global energy demands of the coming century in an environmentally acceptable manner. At the end of 1997, according to data reported in the Power Reactor Information System, PRIS, of the IAEA, there were 437 nuclear power plants in operation and 36 under construction. Over eight thousand five hundred reactor-years of operating experience had been accumulated. Of the operating plants, 346 were LWRs totalling 306 GWe and 30 were HWRs totalling 16.4 GWe. The considerable experience and lessons learned from these plants are being incorporated into new water cooled reactor designs.

In the early years of nuclear energy utilization, various design concepts were developed and implemented. Subsequently, a pattern of evolutionary improvements led to the successful designs of today. Now, most of the efforts in water cooled reactor development are on evolutionary designs. This arises from conservatism in licensing new developments; from the conservatism of utilities which recognise that financial risks can be better controlled if new developments build on proven technologies; and from the reluctance of governments to contribute to the financing of new prototypes.

Evolutionary developments have generally progressed to reduce costs, to meet increasing safety demands and to increase reliability and availability. The nuclear industry is now faced with increased competition from natural gas, the trend to deregulation of electricity markets, difficulties in financing new projects, and increasingly stringent safety objectives. This paper addresses the technology readiness of evolutionary developments in water-cooled reactors for meeting these challenges.

2. EVOLUTIONARY DESIGNS

Advanced nuclear power plant designs or concepts can be divided into two categories: evolutionary designs and innovative designs that require substantial development efforts. A natural dividing line between these two categories arises from the necessity of having to build and operate a prototype or demonstration plant to bring a concept with much innovation to commercial maturity, since building and operating such a plant represents a significant step increase, with respect to both cost and

Advanced design

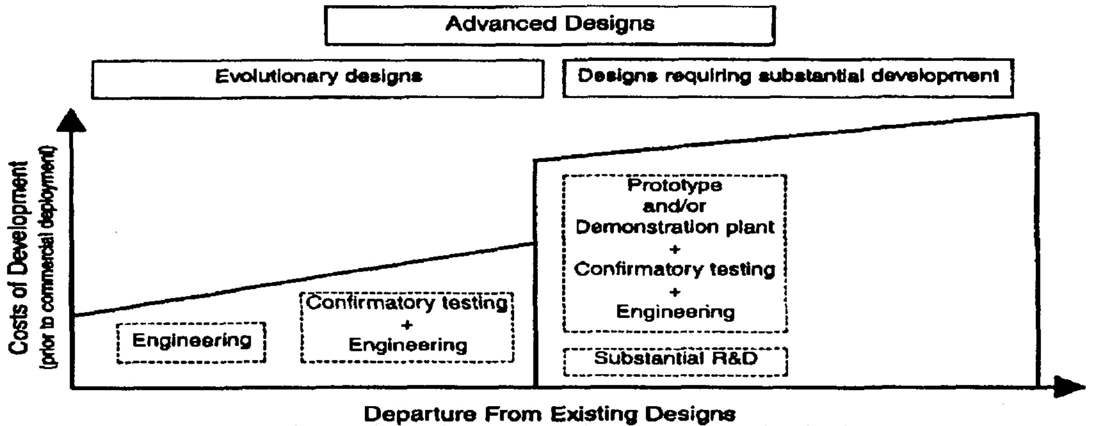
Different types of new nuclear plants are being developed today that are generally called advanced reactors. In general, an advanced plant design is a design of current interest for which improvement over its predecessors and/or existing designs is expected. Advanced designs consist of evolutionary designs and designs requiring substantial development efforts. The latter can range from moderate modifications of existing designs to entirely new design concepts. They differ from evolutionary designs in that a prototype or a demonstration plant is required, or that insufficient work has been done to establish whether such a plant is required.

Evolutionary design

An evolutionary design is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining proven design features to minimise technological risks. The development of an evolutionary design requires at most engineering and confirmatory testing.

Innovative design

An innovative design is an advanced design which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. Substantial R&D, feasibility tests, and a prototype or demonstration plant are probably required.



(A prototype is normally a scaled down unit, whereas a demonstration plant is a more substantial plant that can be as large as full size.)

Fig. 1. Efforts and development costs for advanced designs versus departure from existing designs (Terms are excerpted from Ref. 1).

time, in the resources needed for the development. Designs in both categories need engineering, and may also need research and development (R&D) and confirmatory testing prior to finalizing the design of either the first plant of a given line in the evolutionary category, or of the prototype and/or demonstration plant for the second category. The amount of such R&D and confirmatory testing depends on the degree of both the innovation to be introduced and the related work already done, or the experience that can be built upon. This is particularly true for designs in the second category where it is entirely possible that all a concept needs is a demonstration plant, if development and confirmatory testing is essentially completed. At the other extreme, R&D, feasibility tests, confirmatory testing, and a prototype and/or demonstration plant are needed in addition to engineering. Different tasks have to be accomplished and their corresponding costs in qualitative terms are a function of the degree of departure from existing designs. In particular, a step increase in cost arises from the need to build a reactor as part of the development programme (see Figure 1).

3. TECHNOLOGY READINESS

Technology readiness relates to many of the factors that influence the success of new designs. Currently-operating plants must continue to operate safely and reliably, and new designs must be able to economically meet increasingly stringent safety objectives. Economic competitiveness is a key to the introduction of any new product. Technologies must be available for reducing the investment cost, fuel cycle costs and operating costs. Readiness is not only based on what has been designed, fabricated and tested, but on the continuing presence and vigour of the institutional framework and technological base, including R&D and design organizations, manufacturing and construction resources, strong yet balanced and responsive regulatory organizations, and the infrastructure that trains and maintains the necessary human resources. During this Symposium, these factors will be addressed in detail, and the design organizations will describe their most significant technological developments, the status of their validation, how these developments meet regulatory and utility requirements, and projected costs. This Symposium is a major activity within the IAEA's nuclear power programme which promotes information exchange and co-operative research in reactor development, and provides a source of balanced, objective information for all Member States on the current status and recent advances in reactor design and technology [2, 3, 4, 5, 6, 7, 8].

4. DEVELOPMENT OF NEW DESIGNS

The technology of evolutionary water cooled reactors is building on the growing experience base and results of R&D programmes. World-wide, considerable efforts are being made to develop advanced nuclear power plants to meet the future demand for energy. Various organizations are involved, including governments, industries, utilities, universities, national laboratories, and research institutes. Expenditures for development of new designs, technology improvements, and the related research for all major reactor types combined is estimated to exceed US $ 2 billion per year.

For water cooled reactors, utility requirements documents have been formulated to guide the design and development activities by incorporating experience from current plants with the aim of reducing costs and licensing uncertainties by establishing a technical foundation for the advanced designs. Large evolutionary designs are being developed with power outputs up to the 1500 MWe range which incorporate mainly proven, active engineered systems to accomplish safety functions, and mid-size evolutionary designs are being developed which place more emphasis on utilization of passive safety systems. The experience base on which these developments are building is large: over 6100 reactor years for LWRs and over 600 reactor years for HWRs. Common goals for these new designs are high availability, user-friendly features, competitive economics and compliance with internationally recognized safety targets.

5. MEETING INCREASINGLY STRINGENT SAFETY OBJECTIVES

As the number of nuclear plants world-wide increases, safety targets are becoming more stringent. Operational safety records are good and steadily improving as shown by the low number of either unanticipated trips or spurious actuation of engineered safety systems. Thus, the basic safety level is considered acceptable, and the focus of the increasingly stringent safety objectives for new designs is on very low probability accident scenarios involving severe core damage. INSAG-3 [9] notes that "The target for existing nuclear power plants is a likelihood of occurrence of severe core damage that is below about 10^{-4} events per plant operating year. Implementation of all safety principles at future plants should lead to the achievement of an improved goal of not more than about 10^{-5} such events per plant operating year. Severe accident management and mitigation measures should reduce by a factor of at least ten the probability of large off-site releases requiring short term off-site response." The more stringent safety target for future plants was confirmed by INSAG-5 [10] which notes that [evolutionary] light and heavy water nuclear plants should meet the long term target of a level of safety ten times higher than that of existing plants. INSAG-10 [11] notes that prevention of accidents remains the highest priority among the safety provisions for future plants and that probabilities for severe core damage below 10^{-5} per plant year ought to be achievable. However, values that are much smaller than this would, it is generally assumed, be difficult to validate by methods and with operating experience currently available. Improved mitigation is therefore an essential complementary means to ensure public safety.

Evolutionary water-cooled nuclear power plants incorporate various technical features to meet the safety targets. In many cases, these features have been tested to demonstrate technological readiness. Examples of such features are:

- increased margins and grace periods, (e.g., larger water inventories, large pressurizer, large steam generators, lower power densities, negative reactivity coefficients) to limit system challenges;
- redundant and diverse safety systems to perform simplified tasks, improved physical separation between systems, and utilization of components of proven high reliability;
- reliable depressurization systems to preclude high pressure core melt sequences;
- passive cooling and condensing systems;
- provision for corium confinement and cooling;
- containments large enough to withstand the pressure and temperature from design basis accidents without fast acting pressure reduction systems, sometimes surrounded by a second containment which provides protection against external missiles and allows for detection and filtration of activity leaking from the first containment;
- systems to control hydrogen concentrations during accidents.

Importantly, design measures both for increased prevention as well as for accident mitigation tend to increase capital cost, although preventive measures may provide higher plant availability and therefore have a positive cost component. The added costs for measures only aimed at mitigating accidents must be overcome by other savings.

6. TECHNOLOGY FOR ENHANCED COMPETITIVENESS

Despite the prevailing low fossil-fuel prices, the generating cost of nuclear electricity continues to be competitive with fossil fuel for base-load electricity generation in many countries. Although the large capital investment required for nuclear power plants is a disadvantage, especially in developing countries, the nuclear fuel cycle cost is relatively low. Moreover, the prices of fossil fuels are likely to increase over the long term because the resource is limited and also if pressures are applied - by political or financial instruments, to discourage use; and there is still scope in the nuclear industry for standardisation, modular construction, shorter construction periods, higher burnup and simplification, resulting in better performance and lower generation cost.

In the next few years, however, nuclear utilities will experience an operating environment in which nuclear power plants will face increased competition, in a deregulated energy market, with other suppliers of electricity. Data on operating costs will be analysed to determine whether the continued operation of nuclear power plants provides power to consumers at the least cost. This competitive environment has significant implications for plant operations, including efficient use of all resources; more effective management of plant activities, such as outages and maintenance; and sharing of resources, facilities and services among utilities.

Achieving high plant availability and reliability are essential factors for achieving good economics, and they require attention to both the nuclear island and the balance of plant. Nuclear power plants world-wide are showing a steady increase in the average energy availability factor, which has increased from approximately 70 percent in 1989 to 77.4 percent[1] in 1997, with some utilities achieving significantly higher values. This is being achieved through integrated programmes including personnel training, quality assurance, improved maintenance planning, as well as technological advances in plant

---

[1] Based on IAEA Power Reactor Information System (PRIS) data. In PRIS, the energy availability factor is defined as 100 $[1\text{-}EL/E_m]$ with E_m being the net electrical energy which would have been produced at maximum capacity under continuous operation during the reference period, and EL is the electrical energy which could have been produced during the reference period by the unavailable capacity. (The numbers reported here are for plants with capacity greater than 100 MW(e) and with more than one year of commercial operation).

components and systems, and in inspection and maintenance techniques. International co-operation is playing a key role in this success. The various programmes of the World Association of Nuclear Operators (WANO) to exchange information and encourage communication of experience, and the activities of the IAEA including projects in nuclear power plant performance assessment and feedback, effective quality management, and information exchange meetings on technology advances, are important examples of international co-operation to improve the performance of current plants.

Improved performance at current plants is supported by better application of existing technologies, for example, for processing information regarding the condition of components, and performing surveillance and diagnostics. Activities are being implemented at current plants to analyse information from operation of components and systems to understand the causes of unavailability, and to improve work processes during maintenance. New technologies are also being developed with the aim of improving performance of current plants. Examples include development of high burnup fuel which supports longer cycle length, computer-aided systems to provide early indication of sensor or component degradation, and simpler systems for control of hydrogen during accident conditions (systems that require considerably less testing and maintenance and thereby reduce outage duration).

Significant improvements are also being achieved in primary system components, which will contribute to high availability. As an example, the dominant cause of damage to PWR steam generator tubing has been due to corrosion of the tubing and support structures. Large efforts in several countries have been and are being carried out to control and improve the service environment to extend the service life of steam generator tubes. New materials (e.g. Inconel 690) have been shown to have superior corrosion resistance compared to Inconel 600 and are now used for new and replacement PWR steam generators.

Enhanced utilization of forgings in the pressure retaining parts of the primary system, to reduce the number and length of welds, is another example of efforts that aim at facilitating and improving plant operation. Weld length reductions reduce ISI (In-Service Inspection) requirements and work to be done in high-radiation areas, leading to less occupational radiation exposure.

User requirements documents for future plants specify plant availability factors of 87% and above. For new plants, the basis for achieving high performance is being laid down during the design phase. For example, design for short outages, design for on-line maintenance, and design for increased margins along with an overall goal of simplicity should contribute to the improved level of availability requested by user requirements documents. Also, advances such as better man-machine interface using computers and improved information displays, greater plant standardization, improved maintainability, and better operator qualification and simulator training, which have been applied at current plants will contribute to high performance of future plants.

Improved nuclear plant economics may also be gained by widened design margins, provided that the associated cost increase can be outweighed by a gain in operational availability. Substantial design margins provide benefit by:

- providing capability to accommodate disturbances and transients without causing challenges to the plant safety, and initiation of engineered safety systems;
- providing margin to enhance system and component reliability, and to minimise the potential of exceeding specified limits which would require de-rating or shutdown;
- providing additional assurance that the longer plant life requirement of 60 years can be met.

A significant thermal margin for the core design serves to ensure for the utility that the plant will be capable of being operated at 100% power when started up, in spite of unforeseen material and/or design problems for the fuel; in addition, such margins yield specific benefits with respect to enhanced transient performance and increased operational flexibility. In the longer term, the design margin also provides an option that may become attractive for the utility once experience has been gained with the new plant: uprating of the plant power level at a marginal cost that will be small compared with adding other new capacity.

7. CONCLUSION

In summary, evolutionary designs are being developed with the objectives of reduced costs, and higher availability while meeting increasingly stringent safety targets. The designs incorporate evolutionary improvements, and features which are well supported by operating experience and/or research, development and confirmatory testing. These new designs are ready to ensure that nuclear energy can continue to play an important and increasing role in global energy supply.

REFERENCES

[1] Terms for describing new, advanced nuclear power plants, IAEA-TECDOC-936, (IAEA, Vienna, 1997)

[2] Status of advanced light water reactor designs: 1996, IAEA-TECDOC-968, (IAEA, Vienna, 1997)

[3] Advances in heavy water reactor technology, IAEA-TECDOC-984 (IAEA, Vienna, 1997)

[4] Technologies for improving availability and reliability of current and future water cooled nuclear power plants, IAEA-TECDOC-1054, (IAEA, Vienna, 1998)

[5] Design measures for prevention and mitigation of severe accidents at advanced water cooled reactors, IAEA-TECDOC-1020 (IAEA, Vienna, 1998).

[6] Progress in design, research and development and testing of safety systems for advanced water cooled reactors, IAEA-TECDOC-872 (IAEA, Vienna, 1996)

[7] Technical feasibility and reliability of passive safety systems for nuclear power plants, IAEA, TECDOC-920 (IAEA, Vienna, 1996)

[8] Design and development status of advanced containment systems for next generation water reactors, IAEA-TECDOC-752 (IAEA, Vienna, 1994)

[9] **International Nuclear Safety Advisory Group**, Basic Safety Principles for Nuclear Power Plants, Safety Series No. 75-INSAG-3, (IAEA, Vienna 1988)

[10] **International Nuclear Safety Advisory Group**, The Safety of Nuclear Power, Safety Series No. 75-INSAG-5, (IAEA, Vienna 1992)

[11] **International Nuclear Safety Advisory Group**, Defence in Depth in Nuclear Safety, INSAG-10 (IAEA, Vienna, 1996).