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PROSPECTS FOR THE DEVELOPMENT OF ADVANCED REACTORS *

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ABSTRACT

Energy supply is an important prerequisite for further socio-economic development, especially in developing countries where the per capita energy use is only a very small fraction of that in industrialized countries. Nuclear energy is an essentially unlimited energy resource with the potential to provide this energy in the form of electricity, district heat and process heat under environmentally acceptable conditions. However, this potential will be realized only if nuclear power plants can meet the challenges of increasingly demanding safety requirements, economic competitiveness and public acceptance.

Worldwide a tremendous amount of experience has been accumulated during development, licensing, construction and operation of nuclear power reactors. The experience forms a sound basis for further improvements. Nuclear programmes in many countries are addressing the development of advanced reactors which are intended to have better economics, higher reliability and improved safety in order to overcome the current concerns of nuclear power. Advanced reactors now being developed could help to meet the demand for new plants in developed and developing countries, not only for electricity generation, but also for district heating, desalination and for process heat.

The IAEA, as the only global international governmental organization dealing with nuclear power, promotes international information exchange and international co-operation between all countries with their own advanced nuclear power programmes and offers assistance to countries with an interest in exploratory or research programmes.

1. INTRODUCTION

Many countries are already heavily reliant on nuclear energy for electric power production; as of December 1991*, there were 420 nuclear power plants in operation worldwide with a total net capacity of 327 GW(e). In several countries, nuclear generated electricity has already reached a high percentage of the total generated electricity, e.g. in 1991 in France 72.7%, in Belgium 59.3%, in Sweden 51.6%. In the USA, the country with the highest amount of installed nuclear power generating capacity in the world (99.8 GW(e)), 21.7% of the electricity is generated by nuclear power.

Nuclear energy can play an important future role in supplying the world population with energy. However, this form of energy will be successful only under certain conditions: it must meet very strict safety requirements, it must be economically competitive, and it must be acceptable to the public. The nuclear industry is faced with a demanding challenge in attempting to meet these conditions. Much development work on advanced reactors is going on in several countries, with participation of both governmental and private industries.

2. ROLE OF NUCLEAR POWER: PAST, PRESENT AND FUTURE

Nuclear energy is an essentially unlimited energy resource. However, the projections made in the early days of nuclear power concerning its rate of introduction have turned out to be overly optimistic. The actual rate of introduction of nuclear power plants remains below even the more pessimistic earlier forecasts despite growing concerns regarding use of fossil energy resources. Many factors have contributed to this lower than initially expected rate of introduction. Some of the more significant factors were the reduction of the economic advantage relative to alternatives, difficulties in licensing, public concerns about nuclear plant safety and nuclear waste disposal, and the general reduction in energy demand growth rate which developed in part from the increased adoption of an energy conservation/efficiency ethic in most industrialized countries following the oil supply crises of the 1970s.

Nevertheless, nuclear energy today accounts for 17% of the world's total electricity generation. Future electricity generation capacity is difficult to predict and involves social, political and economic factors. Both economic growth and population growth effect demand for new electricity generating capacity. However, previously entrenched axioms that industrialized and developing countries can create ever-expanding economies driven by consumptive economics and still preserve our fragile ecology are being called into question.

* Source: IAEA PRIS data base

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We are gaining experience in the task of protecting the environment by limiting science and technology to appropriate applications, and we must learn how to keep world population within an ecological balance. With the increasing focus on environmentally acceptable economic development and close examination of appropriate applications of science and technology, it is reasonable to expect a reduced rate of increase of demand for electric generation capacity in industrialized countries, and ultimately a leveling of demand.

A reference scenario for future electricity demand, drawing on work of the Commission of the European Communities and the World Energy Council presented at the Senior Expert Symposium in Helsinki on Electricity and the Environment,[1] predicts nearly a doubling of the world electricity generation capacity from 1990 to the year 2010. Regarding the total world nuclear generating capacity, the IAEA estimates an increase from the current capacity of 327 GW(e) to a capacity of 456 GW(e) (low estimate) to 577 GW(e) (high estimate) by the year 2010.

If the challenges of increasingly demanding safety requirements, economical competitiveness and public acceptance can be met, nuclear energy can play a more important role in the future than it plays today in supplying the world population with energy. The desire to conserve fossil fuels, which at the same time are valuable raw materials, the commitment to decrease CO_2 emissions below certain levels, and the limited prospects of large scale use of renewable sources tend to emphasize the potential contribution of nuclear power. It is significant to note that the recent Helsinki Symposium concluded that one of the key elements in the strategy to cope with the increasing risk of global warming and climate change due to CO_2 emissions from fossil plants is the deployment of advanced nuclear power plants, although the social acceptability of nuclear energy remains in question.

Currently only a few nuclear plants are being used for non-electric applications (with a total capacity of only 5 GW(th) to supply hot water and steam). However, at present, about 30% of the world's primary energy consumption is used for electricity generation, about 15% is used for transportation and the remaining 55% is converted into hot water, steam and heat. This shows that the potential for applications of nuclear energy in the non-electric energy sector may be quite large. Non-electric applications include desalination, hot water for district heating, heat energy for petroleum refining, for the petrochemical industry and for the conversion of hard coal or lignite, for example, to produce methanol for transportation fuel.

Clearly the incentives for nuclear power are strong. If the objectives of advanced nuclear power development programmes are met, nuclear power will provide a long term, safe and economical energy supply.

3. ADVANCED REACTOR DEVELOPMENT

Nuclear plant designers are developing new approaches to address the challenges of increasingly demanding safety requirements, economic competitiveness, and public acceptance. The use of the word "advanced" in this paper means any nuclear plant which is not yet constructed and operating and is therefore being developed, designed, or possibly even in the early stages of construction. The large base of experience in plant licensing, construction and operation accumulated up to now is being incorporated into advanced reactor development activities.

Advanced reactors are being developed for all principle reactor types, i.e. the light and heavy water-cooled reactors, the liquid-metal-cooled reactors and the gas-cooled reactors.[2,3,4,5] Some of these developments are primarily of an evolutionary nature, i.e. based on improvements in the technology, in components and systems, and in construction and operation as a result of experience gained with presently operating plants. Other developments are also evolutionary but typically incorporate innovative features such as passive systems to assure safety. Designs incorporating such innovative features may require construction of a prototype or demonstration reactor before commercialization.

3.1 Objectives for the Development of Advanced Reactors

The objectives of the designers of advanced nuclear power plants can be generally categorized into the areas of achieving a high degree of safety and reliability and achieving an economic advantage relative to alternatives.[6]

The overall goal relative to the objective of achieving a high degree of safety is to have a negligible radiological impact on the public, on personnel operating the plant and on the environment during normal operation or as a result of an accident. The negligible radiological impact as a result of an accident has generally been interpreted to mean reducing radioactivity releases to levels less than the levels which would require evacuation of the public. The following aspects are considered among the most important:

- Assuring stability of the reactor core under all modes of normal operation and assuring that the reactor core will always tend toward stability under all upset conditions. Sufficient safety margins and an optimum set of reactivity feedbacks are key aspects.

- Assuring the removal of residual heat from the reactor under shutdown conditions. Facilitating such assurance by having sufficient residual heat removal capability available at all times, without reliance on operator action and without reliance on any equipment and systems whose operational status for the function is not continuously verifiable is a key aspect. The ability to limit maximum temperatures in the reactor core below prescribed limits without the need for rapid operator action i.e., having a reasonably long grace period, is considered very important.

- Taking advantage of inherent safety characteristics and utilizing passive safety systems. An inherent safety characteristic, by definition[7], provides absolute assurance of the elimination of a potential internal hazard to the safety of the nuclear plant. A passive safety system[7] provides a safety-related function without reliance on operator action or on external mechanical and/or electrical power, signals or forces.

- Improving man-machine interfaces. Extensive consideration is being given to human factors so as to enable easier operation of the plant. The goal is to minimize both the opportunity and the potential for human error by providing a high degree of automation for all situations.

In considering the objective of achieving a high degree of reliability, advanced nuclear plants are being designed so that both scheduled and unscheduled downtimes will be very low. The plants are being designed to facilitate inspection, maintenance, repair and replacement of equipment. Equipment that, by design and operational evidence, requires minimal maintenance is being employed. The capability for in-service inspection and the use of automated equipment is being incorporated. The plant layouts are being designed to facilitate repair and replacement by providing for rapid and adequate access for the removal and installation of components and equipment. Also to achieve high reliability, simplicity and standardization are being pursued in all aspects of the plant design.

Using proven technology is another important aspect of achieving a high degree of reliability. All advanced reactor designs have incorporated prior experience to a large extent. Some of the more innovative designs, by definition, incorporate components or systems for which a large experience base is lacking. These components and systems should undergo thorough testing before they are used in a power plant.

In considering the objective of achieving an economic advantage relative to alternatives, advanced nuclear plants are being designed for as long a life as feasible. Provisions are made in the plant design for component inspection, component replacement and possible upgrading in order to assure the long life capability.

To give assurance that expensive delays during licensing and construction will not occur, the highest feasible state of completion of detailed plant engineering design and of proof-testing of equipment and systems prior to the start of plant construction work is being sought. Efforts are also being made to develop techniques and procedures which can shorten the construction schedule. Reducing on-site construction labour by using factory-fabrication of components and the pretesting, prior to installation, of components is being considered, as is modularization, i.e., factory-fabrication and pretesting of complete systems or subsystems, piping, control and instrumentation systems.

Decommissioning of nuclear plants has only recently been recognized as potentially a significant cost factor. Consideration of preliminary decommissioning plans is becoming part of the design effort so as to optimize, where possible, the capability of decommission the plant and minimize the associated costs.

3.2 Economics and Public Acceptance of Advanced Reactors

Regarding economic competitiveness, nuclear energy faces strong challenges from fossil energy well into the future. Although nuclear plants have much lower fuel costs, they require a higher initial capital investment than fossil fuelled electric generating stations. Comparative assessments, presented at the Helsinki Symposium, of total electricity generation costs of advanced fossil and advanced nuclear electricity generating technologies through the year 2010 show competitiveness of advanced nuclear systems.

Regarding public acceptance, a key finding of the International Conference on the Safety of Nuclear Power convened by the IAEA in Vienna in September 1991[8] was that design features incorporated into advanced reactors should permit the technical demonstration of adequate public protection with significantly reduced emergency planning requirements: for example, relief from the requirement for rapid evacuation. Certainly this would have a positive influence on public acceptance of nuclear power, and it is recognized that improving public acceptance of nuclear power is very necessary if the potential offered by the next generation of nuclear power plants is to be realized.

4. BROADER APPLICATIONS OF NUCLEAR ENERGY

As noted in Section 2, the potential for applications of nuclear energy in the non-electric sector is quite large. For non-electric applications, the specific temperature requirements vary greatly. Hot water for district heating and heat for seawater desalination require temperatures in the 80 to 200°C range. Temperatures in the 250 to 550°C range are required for petroleum refining processes. The use of heat for enhancing heavy oil recovery can be applied by the method of hot water or steam injection. The temperature and pressure conditions required for heavy oil recovery are highly dependant on the geological conditions of the oil field, the requirements ranging up to 550°C and above. Temperatures required for oil shale and oil sand processing range from 300 to 600°C. Processes used in the petrochemical industry require higher temperatures, in the range of 600 to 880°C. Still higher temperatures (up to 950°C) are needed for refining hard coal or lignite (for example, to produce methanol for transportation fuel). Temperatures of 900 to 1000°C are necessary for the production of hydrogen by water splitting.

Water-cooled reactors can provide heat up to about 300°C. Liquid-metal-cooled fast reactors produce heat up to about 540°C. Gas-cooled reactors provide even higher temperatures, about 650°C for advanced gas-cooled, graphite-moderated reactors (AGRs), and up to 950 to 1000°C for high-temperature gas-cooled reactors (HTGRs).

There is considerable incentive to utilize the capability of nuclear plants to provide co-generation of electricity, steam and heat for residential and industrial purposes.[9] Experience in co-generation with water-cooled reactors has been gained in the Russian Federation, China, Canada, the Czech and Slovak Federal Republic, Switzerland, Germany, Hungary and Bulgaria. One of the largest uses of nuclear process steam is at the Bruce Nuclear Power Development Facility in Ontario, Canada, where the CANDU PHWRs are capable of producing 6000 MW(e) of electricity as well as process steam and heat for use by Ontario Hydro and an adjacent industrial energy park.

An important milestone in the development of high-temperature nuclear process heat was reached in March 1991 with the start of construction of the High Temperature Test Reactor (HTTR) at the Oarai Research Establishment of the Japanese Atomic Energy Research Institute. The HTTR will be the first nuclear reactor in the world to be connected to a high-temperature process heat utilization system.

5. IAEA ACTIVITIES IN ADVANCED REACTOR DEVELOPMENT

The early development of nuclear power was conducted to a large extent on a national basis. However, for advanced reactors, international co-operation is playing a greater role, and the Agency promotes international co-operation in their development. Especially for designs incorporating innovative features, international co-operation can play an important role allowing a pooling of resources and expertise in areas of common interest to help to meet the high costs of development.

To support the IAEA's functions of encouraging development of atomic energy for peaceful uses throughout the world, the IAEA's programme in nuclear power technology development promotes technical information exchange and co-operation between Member States with major reactor development programmes, offers assistance to Member States with an interest in exploratory or research programmes, and publishes reports available to all Member States interested in the current status of reactor development. Activities are focused on key issues (for example, safety concerns, high capital costs, complex and expensive operating procedures) which currently hinder further introduction of nuclear power.

The IAEA activities in development of water-cooled, liquid-metal-cooled and gas-cooled reactors are co-ordinated by three International Working Groups (IWGs) which are committees of leaders of national programmes in these technologies. Each IWG meets periodically to serve as a global forum for information exchange and progress reports on the national programmes, to identify areas of common interest for collaboration and to advise the Agency on its technical programmes and activities. This regular review is conducted in an open forum in which operating experience and development programmes are frankly discussed.

The activities planned within the framework of these IWGs include technical information exchange meetings and co-operative Co-ordinated Research Programmes. Small Specialists Meetings are convened to review progress on selected technology areas in which there is a mutual interest. For more general participation, larger Technical Committee Meetings, Symposia or Workshops are held. The IWGs sometimes advise the Agency to establish co-operative programmes in areas of common interest in order to pool efforts on an international basis. These co-operative efforts are carried out through Co-ordinated Research Programmes (CRPs). CRPs are typically 3 to 5 years in duration and often involve experimental activities. Such CRPs allow a pooling of efforts on an international basis to develop technology at a lower cost than would be required with separate national efforts, and to benefit from the experience and expertise of researchers from the participating institutes.

6. CONCLUSIONS

Advanced nuclear power systems are currently under development with the potential to make a significant contribution to meeting the energy needs of the world in an environmentally acceptable manner. These systems can provide both the electric power demand and heat energy for district heating and industrial processes. These systems are being developed to meet the challenges of increasingly demanding safety requirements, economical competitiveness and public acceptance.

Because of the high cost of development of advanced reactors, especially the innovative concepts, Member States which have ongoing programmes in advanced reactor development may find it attractive to co-operate internationally in technology development. The IAEA's programme in nuclear power technology development encourages international co-operation through technical information exchange and co-operative research. To assure that the Agency's efforts are desirable and useful to Member States, the Agency's efforts in development of water-cooled, liquid metal-cooled and gas-cooled reactors are guided by three International Working Groups which are committees of leaders of the national programmes in each technology area. Co-operation conducted within the frame of these International Working Groups allows a pooling of efforts in areas of common interest and benefits from the experience and expertise of researchers from the participating countries.

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