Advanced nuclear power plants: Highlights of global development

Building on today's best safety and operational features, new nuclear plants are being designed and introduced in many countries

by
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Worldwide, considerable efforts are being made to develop advanced nuclear power plants. 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 the major reactor types combined is estimated to exceed US $1.5 billion per year.

Through activities within the framework of its nuclear power programme, the IAEA is serving as an international source of objective reference information about the different concepts being developed and the project status, as well as typical development trends throughout the world.

The full spectrum of advanced nuclear power plant designs or concepts covers different types of designs — evolutionary ones, as well as 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 such a plant represents the major part of the resources needed. Designs in both categories need engineering, and may also need research and development (R&D) and confirmatory testing prior to freezing 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. *(See box, page 20.)* 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, costs jump from the need to build a reactor as part of the development programme.

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Overview of water-cooled reactor development programmes

A main focus of development efforts in several industrialized countries is on the design of large light water-cooled reactor (LWR) units, with power outputs well above 1000 megawatts-electric (MWe). They typically aim to achieve certain improvements over existing designs. The alterations and modifications to a specific design are generally kept as small as possible. This is done to take maximum advantage of successful proven design features and components while taking into account feedback of experience from licensing, construction, commissioning and operation of the water-cooled reactor plants currently in operation.

In general, the design improvements span a wide range. Common goals for the new designs are increased reliability, more user-friendly features, better economics, and enhanced safety.

Advanced light-water reactors (ALWRs). Designs for large ALWRs are being developed in a number of countries. Advanced mid-sized plants are also being developed, in most cases with a great emphasis on the use of passive safety systems and inherent safety features.

United States. Important programmes in development of ALWRs were initiated in the mid-1980s in the United States. In 1984, the Electric Power Research Institute (EPRI), in cooperation with the US Department of Energy and with participation of US nuclear plant designers, initiated a programme to develop utility requirements for ALWRs to guide their design and development. Several foreign utilities have also participated in, and contributed funding, to the programme. Utility requirements were established for large boiling-water reactors (BWRs) and pressurized-water reactors (PWRs) having power ratings of 1200 to 1300 MWe, and for mid-sized BWRs and PWRs having power ratings of about 600 MWe.

In 1986, the US Department of Energy, in cooperation with EPRI and reactor design organizations, initiated a design certification programme for evolutionary plants based on a new licensing process, followed in 1990 by a design certification programme for mid-size plants with passive safety systems. The new licensing process allows nuclear plant designers to submit their designs to the US Nuclear Regulatory Commission (NRC) for design certification. Once a design is certified, the standardized units will be commercially offered, and a utility can order a plant confident that generic design and safety issues have been resolved. The licensing process will allow the power company to request a combined license to build and operate a new plant, and as long as the plant is built to pre-approved specifications, the company can start up the plant when construction is complete, assuming no new safety issues have emerged.

Four advanced reactor designs developed in the United States have been submitted to the NRC for certification under the US Department of Energy ALWR programme. Two large evolutionary plants — the System 80+ of ABB-Combustion Engineering and the ABWR of General Electric — received Final Design Approval in 1994 and Design Certification in May 1997. The 600-MWe AP-600 of Westinghouse is under NRC review and a Final Design Approval is expected by March 1998. Up to mid-1996, the 600-MWe simplified BWR developed by General Electric was also under review, but then the company stopped work on the 600-MWe version and shifted its emphasis to a unit with larger output. The first-of-a-kind engineering programme (FOAKE, the detailed design needed to verify cost and the construction schedule) authorized by the 1992 Energy Policy Act was completed for the ABWR in September 1996, and similar work on the AP-600 is under way with completion scheduled in 1998. The power company in Taiwan, China, recently selected General Electric's ABWR design for two new units slated for operation in 2004.

France and Germany. In Europe, Framatome and Siemens have established a joint company, Nuclear Power International, which is developing a new advanced reactor, the European pressurized-water reactor (EPR), a 1500-MWe plant with enhanced safety features. The basic design will be completed in mid-1997, and the design will be reviewed jointly by the French and German safety authorities. This procedure will provide strong motivation for the practical harmonization of the safety requirements of two major countries, which could later be enlarged on a broader basis. Siemens is also, together with German utilities, engaged in the development of an advanced BWR design, the SWR-1000, which will incorporate a number of passive safety features, for initiation of safety functions, for residual heat removal, and for containment heat removal.

Sweden and Finland. In Sweden, ABB Atom, with involvement of the utility Teollisuuden Voima Oy (TVO) of Finland, is developing the BWR-90 as an upgraded version of the BWRs operating in both countries.

Republic of Korea. In the Republic of Korea, an effort started in 1992 to develop an advanced design known as the Korean Next Generation Reactor (KNGR), a 4000-MWth PWR design. The basic design is currently being developed by the Korea Electric Power Corporation (KEPCO) with support of the Korean nuclear industry. The goal is to complete a detailed standard design by the year 2000.

Russian Federation. In the Russian Federation, design work is under way on the evolutionary V-392, an upgraded version of the VVER-1000, and another design version is being developed in cooperation with the Finnish company Imatran Voima Oy (IVO). Also being developed is a mid-sized plant, the VVER-640 (V-407), an evolutionary design which incorporates passive safety systems, and the VPBER-600, which is a more innovative, integral design. Construction of the first unit of the VVER-640 is planned to start at Sosnovy Bor in 1997. Construction of two

1000-MWe VVERs is being discussed with the People's Republic of China.

Japan. In Japan, the Ministry of Trade and Industry is conducting an "LWR Technology Sophistication" programme focusing on development of future LWRs and including requirements and design objectives. A large, evolutionary 1350-MWe advanced PWR is being developed by Japanese utilities together with nuclear vendors, with construction of a twin unit being planned at the Tsuruga site. In addition, an advanced BWR Improvement and Evolution study was started in 1991. It involves development of a reference 1500-MWe BWR that reflects the accumulated experience in operation and maintenance of BWRs. Also in progress are development programmes for a Japanese simplified BWR (JSBWR) and PWR (JSPWR), projects which involve vendors and utilities. The Japan Atomic Energy Research Institute (JAERI) has been investigating conceptual designs of advanced water-cooled reactors with emphasis on passive safety systems. These are the JAERI Passive Safety Reactor (JPSR) and the System-Integrated PWR (SPWR).

China. In China, the Nuclear Power Institute (Chengdu) is developing the AC-600 advanced PWR, which incorporates passive safety systems for heat removal.

In all of these countries, the advanced LWRs under development incorporate significant design simplifications, increased design margins, and various technical and operational procedure improvements. These include better fuel performance and higher burnup, a better man-machine interface using computers and improved information displays, greater plant standardization, improved constructability and maintainability, and better operator qualification and simulator training.

Heavy-water cooled reactors (HWRs). In addition to light water-cooled reactors, the technology for HWRs has also proven to be economic, safe, and reliable. Approximately 7% of all current operating plants are HWRs. A mature infrastructure and regulatory base has been established in several countries, notably in Canada, the pioneer in the development of the HWR concept. Two types of commercial HWRs have been developed, the pressure tube and the pressure vessel versions, and both have been fully proven. HWRs with power ratings from a few hundred MWe up to approximately 900 MWe are available. The heavy-water moderation yields a good neutron economy and has made it possible to utilize natural uranium as fuel which leads to lower fuel costs compared with LWRs. The amount of fissile material is quite limited, however, and the pressure tube designs are therefore using on-load refuelling to achieve adequate reactivity for the plant operation. The effectiveness of this on-load refuelling has been successfully demonstrated; the annual and lifetime load factors of most of the pressure tube HWRs have been among the best of all commercial reactor types. Safety performance has also proven to be very good.

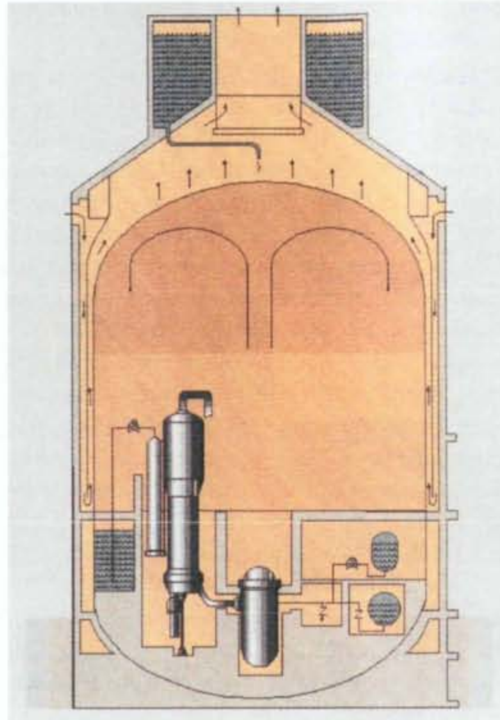
Canada. The continuing design and development programme for HWRs in Canada are primarily aimed at reduction of plant costs and at an evolutionary enhancement of plant performance and safety. Two new 715-MWe CANDU-6 units with improvements over earlier versions of this model are under construction in Qinshan, China. Up-front basic engineering continues on the 935-MWe CANDU-9 reactor, a single unit adaptation of reactor units operating in Darlington, Canada. The two year licensability review by the Canadian Nuclear Safety Commission was completed in January 1997, and found that the CANDU-9 meets the country's licensing requirements. Further studies are being carried out for advanced versions of these reactor models to incorporate further evolutionary improvements and to increase the output of the larger reactor up to 1300 MWe.

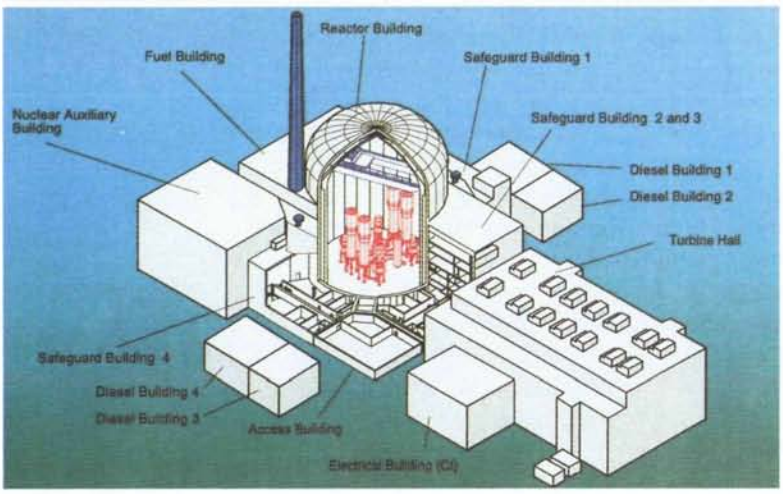
India. Also under development is an advanced 500-MWe HWR in India, and construction of such units is planned. This HWR design takes advantage of experience feedback from the 220-MWe HWR plants of indigenous design operating in India.

Recent important events. Important events in 1996 in the field of water-cooled reactors included the startup of new plants in several countries: the 1130-MWe Genkai-4 PWR, and the first two 1315-MWe Advanced Boiling Water Reactors (ABWRs) at Kashiwazaki Kariwa, in Japan; the first 1455-MWe N4 PWR at Chooz in France; the 650-MWe Cernavoda-1 HWR in Romania; and the 1165-MWe Watts Bar-1 PWR in the United States.

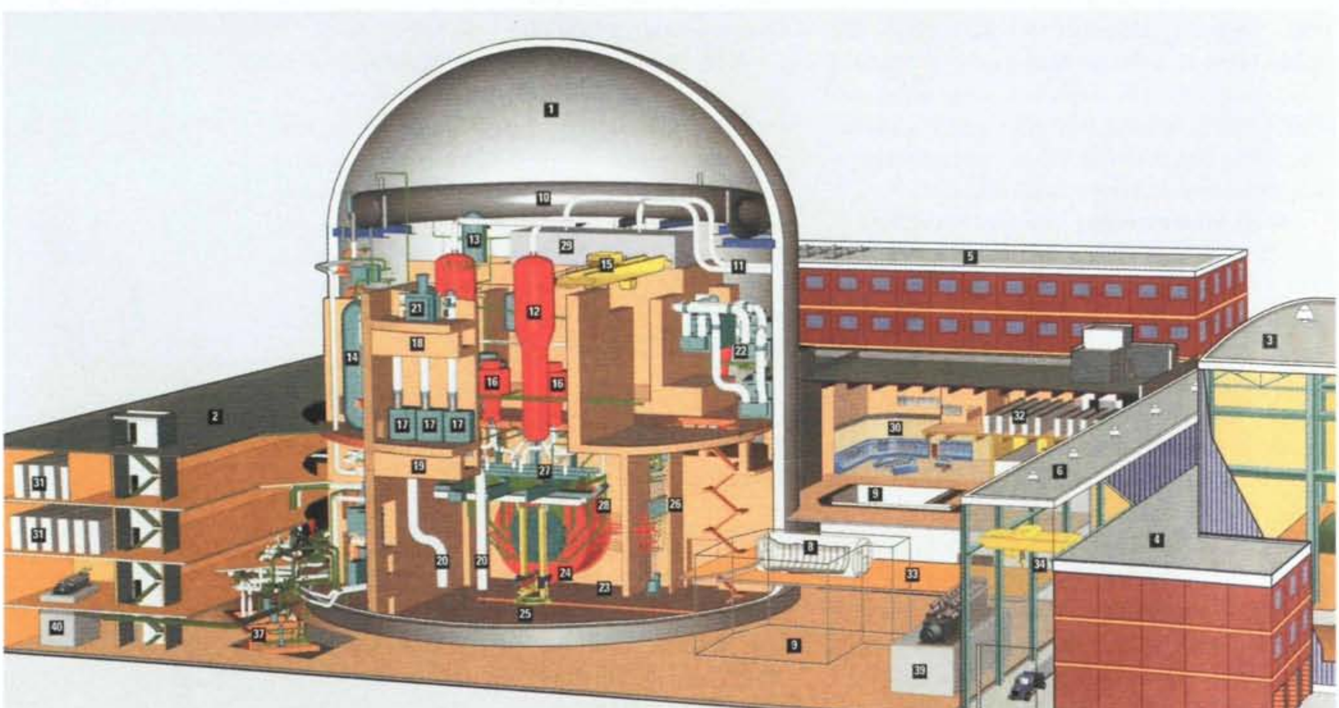
Overview of gas-cooled reactor development programmes

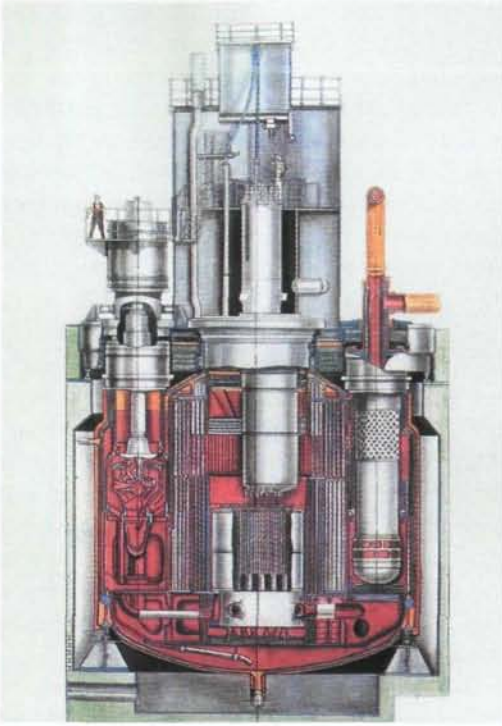
Significant activities are occurring in the development of high-temperature gas-cooled reactors (HTGRs), particularly with regard to the utilization of the gas-cooled reactor to achieve high efficiency in the generation of electricity and in process heat applications. Technological advances in component design

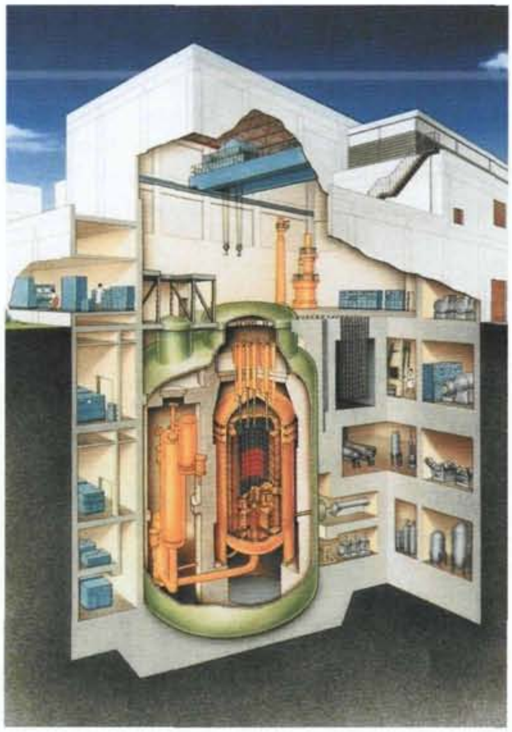




This page: **Among advanced reactors being developed worldwide are** ***(clockwise from top left)*** **the Advanced Boiling Water Reactor in Japan; the AP-600 in the United States; the Candu-9 heavy-water reactor in Canada; and the European Pressurized Water Reactor jointly by France and Germany.** ***Facing page:*** **A schematic of the BN-600 fast-breeder reactor in Russia; schematic of Japan's HTTR; and photo of work on China's HTR-10.**
(Credits: TEPCO; Westinghouse; AECL; NPI; Minatom; JAERI)







and processes — coupled with the international capability to fabricate, test, and procure the components — provides an excellent opportunity for achieving HTGR commercialization.

United Kingdom, Germany, and United States. Gas-cooled reactors have been in operation for many years. In the United Kingdom, nuclear electricity is mostly generated in CO_2-cooled Magnox and Advanced Gas-Cooled Reactors (AGRs). Other countries also have pursued development of high-temperature reactors (HTGRs) with helium as coolant, and graphite as moderator. The 13-MWe AVR reactor has been successfully operated for 21 years in Germany demonstrating application of HTGR technology for electric power production. Other helium-cooled, graphite-moderated reactors have included the 300-MWe Thorium High Temperature Reactor in Germany, and the 40-MWe Peach Bottom and 330-MWe Fort St. Vrain plants in the United States.

South Africa. In South Africa, the large national utility, Eskom, which has an installed generation capacity of about 38,000 MWe, is in the process of performing a technical and economic evaluation of a helium-cooled pebble bed modular reactor. It would be directly coupled to a gas turbine power conversion system for consideration in increasing the capacity of the utility's electrical system.

China and Japan. In China and Japan, test reactors are under construction which will have the capability of achieving core outlet temperatures of 950°C for the evaluation of nuclear process heat applications. Construction of China's High Temperature Reactor (HTR-10) at the Institute of Nuclear Energy Technology (INET) continues with initial criticality anticipated for 1999. This pebble bed reactor of 10

MWth will be utilized to test and demonstrate the technology and safety features of the HTGR. Development of the HTGR by INET is being undertaken to evaluate a wide range of applications. They include electricity generation, steam and district heat production, combined steam and gas turbine cycle operation, and the generation of process heat for methane reforming. The HTR-10 is the first HTGR to be licensed and constructed in China.

The principle focus of Japan's HTGR R&D programme is completion of the High Temperature Engineering Test Reactor (HTTR) at the Japan Atomic Energy Research Institute (JAERI) site in Oarai, Japan. This 30-MWth helium-cooled reactor will be utilized to establish and upgrade the technology for advanced HTGR development, and to demonstrate the effectiveness of selected high temperature heat utilization systems. Fuel loading of the HTTR is scheduled to begin in 1997 with initial criticality anticipated by the end of the year. The start-up physics testing programme for the HTTR will then continue throughout 1998.

Overview of liquid metal-cooled reactor development programmes

Liquid metal-cooled fast reactors (LMFRs) have been under development for many years in several countries. Twenty LMFRs — including five prototypes with electrical output of between 250 and 1200 MWe — have been constructed and operated, accumulating about 280 reactor-years of operating experience.

In most cases the overall experience has been very satisfactory. The restart and stable operation of the first large demonstration fast reactor Superphenix (1200 MWe) in France is an important achievement in LMFR technology. The demonstration fast reactor BN-600 in Russia with a power output of 600 MWe has operated successfully for 16 years with the average load factor being 77%. Considerable efforts have been made in recent years in France, the Russian Federation, Japan, the United States, and India to lower the capital costs of advanced LMFRs. The latest designs of the LMFR, such as the European fast reactor (EFR) project, are close to achieving economic competitiveness with other reactor types.

Significant technology development programmes for LMFRs are proceeding in several countries, notably France (in co-operation with smaller efforts in Germany, the United Kingdom, and other European countries), Japan, India, and the Russian Federation. Activities continue in some other countries at a lower level.

In the near and medium term, the flexibility of LMFRs may be utilized to manage plutonium and radioactive waste as well as to meet other future objectives. Depending on their core geometries and compositions, fast reactors at a given power rating and core size can either increase, maintain, or decrease the inventory of transuranics. Using this flexibility the loading of fast reactors can be variously configurated/composed to produce transuranic conversion ratios (CR) of less or more than one. If the conversion ration is greater than one, the reactor system would become a breeder and generate fissile materials in response to increased nuclear fuel (power) demand. If it is less than one, the fast reactor would become a burner and could decrease the stocks of fissile materials (as well as actinides).

China. In China, the basic research work on LMFRs was started in 1964. Since then and up to 1987, the major work has been on neutronics, thermal hydraulic, and sodium technology. During 1991-92, the conceptual design of the 15-MWe Chinese experimental fast reactor (CEFR) was completed and during 1992-93, the conceptual design was confirmed and optimization studies were carried out. Since 1993 onwards, major work has involved the preparation of a detailed design.

France. In France, the commercial introduction of LMFRs is being postponed. Meanwhile, the application of an additional important aspect of these reactors — to transmute long-lived nuclear waste and to burn plutonium — is being developed. The current programmes on operation of the 1200-MWe Superphenix (SPX) and the 350-MWth Phenix reflect these requirements. One objective of extending the lifetime of the Phenix reactor by another 10 years is to perform the necessary irradiation experiments.

India. In India the fast-breeder test reactor (FBTR) is in operation. Fuel development, material irradiation, and sodium technology are the principal technical programmes. The introduction of FBRs is linked to their economic acceptability. The basic design features are now selected for the 500-MWe Prototype Fast Breeder Reactor (PFBR). The emphasis in 1997-98 will be on detailed design, engineering development, sodium technology, and materials technology. Reduction in construction time is an important target.

Japan. In Japan, the prototype LMFR "Monju" with the capacity of 280-MWe reached initial criticality in April 1994 and was connected to the grid in August 1995. Reactor operation was interrupted in December 1995 due to a leak in the non-radioactive secondary cooling system. The design of a 660-MWe demonstration fast-breeder reactor (DFBR), which is expected to be constructed in the beginning of the next century, is in progress. In addition to this main stream of development work, studies are being performed regarding the development of technology capable of meeting the diverse needs of future society. These needs include the reduction of environmental impacts and the assurance of nuclear non-proliferation, demands that widen the technological options.

Republic of Korea. The Republic of Korea plans to develop the conceptual design of its first fast-breeder reactor, the 330-MWe Kalimer plant, by 2001. Construction is planned to enable achievement of criticality during 2011.

Russian Federation. Russia's experience in the operation of experimental and prototype fast reactors (the BR-10, BOR-60, and BN-600) has been very good. Efforts are directed towards improving safety and reliability and making the LMFRs economically competitive to other energy sources. While these efforts would take some time, the use of LMFRs over the near-term to burn plutonium and minor actinides is foreseen.

United States. In the United States, the government in 1993 stated that federal funding for reactor development was appropriate only for projects with a potential for near-term commercial application. As a result, the advanced LMFR and integral fast reactor (IFR) programmes were halted. However, the General Electric Company continues its significant design and development programme based on the advanced LMFR and IFR technologies, in collaboration with overseas partners.

IAEA activities supporting development of nuclear power technology

As an international forum for exchange of scientific and technical information, the IAEA plays a role in bringing together experts for a worldwide exchange of information about national programmes, trends in safety and user requirements, the impact of safety objectives on plant design, and the co-ordination of research programmes in advanced reactor technology.

Activities in areas of nuclear power technology development are based on the advice of International Working Groups (IWGs). These are committees of leading representatives of national programmes and international organizations for each major type of reactor.

To support its information exchange function, the IAEA has recently prepared two technical documents — *Status of Advanced Light Water Reactor Designs* and *Fast Reactor Database*. In 1997, topics that will be addressed include improvements in reactor system components and technologies for improving availability and reliability of current and future reactors.

Enhancing communication. Terms such as evolutionary designs, passive designs, and innovative designs have been widely used in describing advanced nuclear power plants, generally without definition and sometimes with usages inconsistent with each other. In view of the importance of communication to the public, and the technical community in general, consistency and international consensus are desirable with regard to the terms used to describe various categories of advanced designs.

In 1991, drawing on advice from reactor design organizations, research institutes, and government organizations, the IAEA issued a document entitled *Safety Related Terms for Advanced Nuclear Power Plants* that is being widely used. More recently, using the same approach to obtain advice from involved parties, the IAEA published *Terms for Describing New Advanced Nuclear Power Plants*. The document's specific purpose is to clarify the meaning of terms by drawing distinctions between design stages reflecting the maturities of designs; for example, whether they are of a developmental nature with some yet untested features or whether they are evolutionary in the sense of retaining many proven features of existing plants.

Co-operative research. The IWGs advise the IAEA to establish international co-operative research programmes in areas of common interest. These co-operative efforts are carried out through Co-ordinated Research Programmes (CRPs), which typically are three to six years in duration, and often involve experimental activities. Such CRPs allow a sharing of efforts on an international basis and benefit from the experience and expertise of researchers from the participating institutes.

As an example, the IAEA has co-ordinated work to collect and systematize a database of thermophysical properties for a broad spectrum of light- and heavy-water reactor materials over a wide range of temperatures; the database has been published. For liquid metal-cooled reactors, the results of co-operative activities on

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.

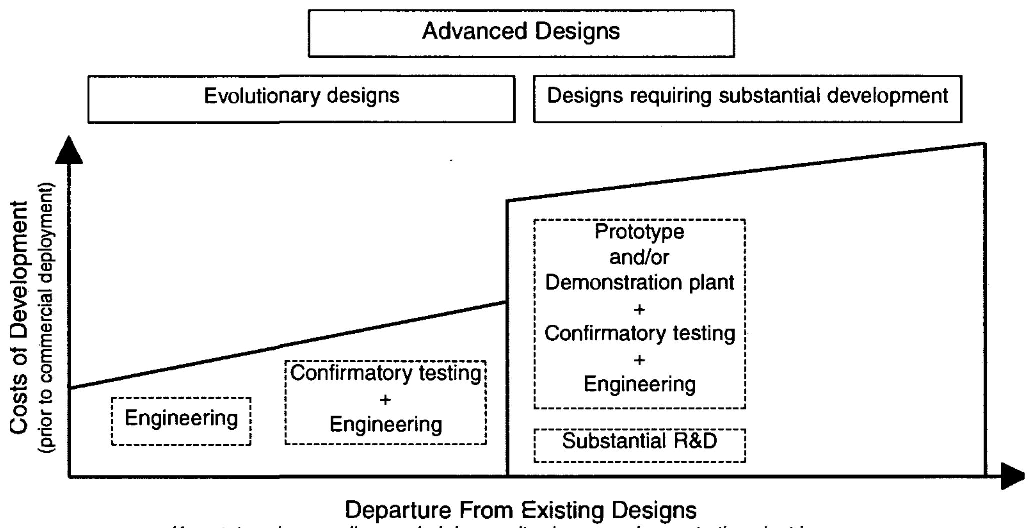
Evolutionary design

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 minimize 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.

Efforts and development costs for advanced designs versus departure from existing designs



(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.)

material behaviour also have been published recently. In other co-operative programmes, the IAEA is establishing sets of thermohydraulic relationships for water-cooled reactors and liquid metal-cooled reactors appropriate for use in analyzing reactor performance and safety. In the field of gas-cooled reactors, the principle focus has been on the four specific technical areas which are predicted to provide advanced HTGRs with a high degree of safety, but which must be proven. These technical areas are: the safe neutron physics behaviour of the reactor core; reliance on ceramic coated fuel particles to retain fission products even under extreme accident conditions; the ability of the designs to dissipate decay heat by natural heat transport mechanisms, and the safe behaviour of the fuel and reactor core under chemical attack (air or water ingress). Activities in HTGR applications focus on design and evaluation of heat utilization systems for the Japanese HTTR.

All these activities are indicative of global co-operation for the development of advanced types of nuclear power reactors. As countries move ahead with plans, and new plants are introduced, further enhancements can be expected in areas of plant economics, reliability, and safety. Through its International Working Groups on advanced reactors, the IAEA will be encouraging the international exchange of information on non-commercial technology and co-operative research. It will also assist countries in harmonizing user requirements, and in the preservation of key technological data on advanced nuclear power systems. ❐