CONF-9204157--2

TRENDS IN ADVANCED REACTOR DEVELOPMENT AND THE ROLE OF THE IAEA

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CONF-9204157--2

DE93 006211

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 421 nuclear power plants in operation worldwide with a total net capacity of 326 GW(e). In several countries, nuclear generated electricity has already reached a high percentage of the total generated electricity, e.g. in 1990 in France 74.5%, in Belgium 60.1%, in the Republic of Korea 49.1%. In the USA, the country with the highest amount of installed nuclear power generating capacity in the world (101 GW(e)), 20.6% of the electricity is generated by nuclear power.

* Source: Preliminary non-governmental information as of 31 December 1991, IAEA PRIS data base.

Managed by Martin Marietta Energy Systems, Inc., under contract DE-AC05-84OR21400 with the U.S. Department of Energy.

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 a lack of 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, within the relatively short time since the first controlled nuclear chain reaction, nuclear energy today accounts for 17% of the world's total of 2800 GW(e) of electricity generation capacity. 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. 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. Also, the practice of organizing national economies around the warfare system is hopefully becoming an anachronism. 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, and ultimately a leveling, of demand for electric generation capacity.

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 326 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 a key element 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.

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 is 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 and Approaches for Development of Advanced Reactors

The objectives of the designers of advanced nuclear power plants generally can be categorized into the areas of achieving a high degree of safety and reliability and achieving an economic advantage relative to alternatives. Table 1 summarizes various approaches being taken to assure the objectives are met [6].

The general objective relative to achieving a high degree of safety is to have very low impact on the public, on personnel operating the plant, and on the environment. Achieving a high degree of safety should be considered within the framework of the defence-in-depth principles so as to assure that features proposed to provide safety do, in fact, perform such a function within the total framework.

It is necessary to assure stability of the reactor core under all modes of normal operation and to provide assurance that the reactor core will always tend toward stability under all upset conditions. The reactor core should have sufficient safety margins and an optimum set of inherent temperature coefficients so as to provide for short term self-stability at all times and sufficient available negative reactivity insertion capability to assure shutdown in the long term.

It is also necessary to assure the removal of decay heat from the reactor under shutdown conditions. Such assurance is facilitated by having sufficient decay 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. The ability to limit maximum temperatures in the reactor core below prescribed limits without the need for rapid operator action should be assured.

To assure a high degree of safety, many advanced reactor designs incorporate inherent safety characteristics and utilize 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. Advanced nuclear plant designs are incorporating inherent safety characteristics through selection of materials, their quantity, their physical properties and their configuration in the plant design.

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. A passive safety system relies instead on natural phenomena such as natural convection, heat conduction and heat radiation, on the properties of materials and on internally stored energy. To the extent that passive systems can be shown to be at least as reliable and as effective as active safety systems for the same function, efforts are being made to utilize passive safety systems in many advanced nuclear plants.

Extensive consideration is also being given to human factors so as to enable easier operation of the plant from the main control room. The goal is to minimize both the opportunity and the potential for human error by providing a high degree of automation for all

Table 1: Objectives for advanced nuclear power plants, and approaches to assure that the objectives are met.

1. Achieve high degree of safety
   * assure stability of core
     - select materials, fuel enrichment and configuration to assure
       * sufficient safety margins
       * negative reactivity coefficients
       * long term shutdown
   * assure removal of decay heat
   * incorporate inherent safety characteristics and utilize passive safety systems (for definitions see [7])
     - assure elimination of potential hazzard through material selection, physical properties and configuration
     - provide safety-related functions by reliance on passive systems: i.e. by reliance on natural convection, heat conduction and heat radiation and on material properties
   * incorporate advanced man-machine interface systems
     - utilize advances in technology to design instrumentation and control system and reactor protection system to minimize need for operator intervention
   * achieve very low on site impacts
     - maximize utilization of materials which minimize generation of corrosion products and radioactive activation
     - design plant to allow good accessibility for repair, maintenance and inspection with low occupational doses
   * achieve very low off-site impact of normal operation (e.g. accumulation of radioactive and chemical waste, and thermal discharge)
   * achieve very low off-site impact of accidents
   * achieve very low impacts of external events and internal intervention

2. Achieve high reliability, availability and capacity factor
   * design to faciliate inspection and maintenance
     - e.g. by use of automated equipment and condition monitoring equipment
   * design to facilitate repair and replacement
   * design for simplicity
   * standardization
   * prove technology prior to application in plant

3. Achieve economic advantage
   * design for long lifetime
     - provision for component replacement
   * assure design stability prior to construction
   * assure regulatory stability

   achieve short construction schedule
     - e.g. by utilizing high degree of factory fabrication
   * minimize operation and maintenance costs
   * design to minimize decommissioning cost
   * design for high degree of investment protection

situations. Instrumentation and control systems and reactor protection systems are being designed to minimize the need for operator intervention. Advances in electronic and information processing technology such as microprocessors, video displays, multiplexing, and fibre optics are being employed.

Advanced nuclear plants are being designed to have a minimal off-site impact as a result of accidents. The intent of development programmes related to this objective is to reexamine each element of the defence in depth concept so as to achieve a high capability to prevent, manage and mitigate accidents and reduce the off-site impact to an insignificant level, irrespective of the seriousness of the accident.

To achieve the objective of high reliability and availability, 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 for cost effectiveness in terms of meeting availability goals. 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 and availability simplicity is being pursued in all aspects of the plant design.

Standardization is another factor which should lead to high reliability and availability. Standardization within the framework of specifying, at least, identical functional specifications if not detailed manufacturing specifications (within proprietary limitations) for components, systems and equipment including instrumentation within a given type of system, of using identical components such as pipe sizes and materials even in various systems is a key goal. In addition, within a broader framework a major objective of standardization is to establish sufficient design detail and qualification testing to enable the certification, or the equivalent thereof, of the design of the plant, or at least the nuclear-related portion, as the reference for replicated application on a worldwide basis.

Regarding use of proven technology, 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 research and prototype testing before they are used in a power plant.

To achieve good economics, in recognition of the large capital investment and the significance of the amortization of this capital investment in economic evaluations, advanced nuclear plants are being designed for as long a life as feasible. Provisions are made in the plant design for component inspection and replacement in order to assure the long life capability.

To give a high assurance that expensive delays during construction will not occur, detailed plant engineering design and proof-testing of equipment and systems should be essentially completed prior to the start of plant construction work.

In recognition of the economic significance of the interest charges on the debt accumulated during construction of the plant, efforts are being made to develop techniques and procedures which can shorten the construction schedule and gain early plant operation. 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, factory-fabrication and pretesting of complete systems or subsystems, piping, control and instrumentation systems.

In recognition that operation and maintenance costs have a significant impact on the competitiveness of a nuclear plant and that, on the average and specifically in some countries, such costs for presently operating plants have been increasing, all contributors to these costs are being critically examined for advanced nuclear plants.

Decommissioning of nuclear plants has only recently been recognized as potentially a significant cost factor for which the preplanning of procedures and the accumulation of an adequate reserve during plant operation to cover the costs requires greater consideration.

For investment protection, the objective is to minimize the time and costs associated with the decontamination, and the replacement or repair of components and equipment in the plant after any accident. In particular, the complete loss of the plant following an accident should be avoided. The measures provided to enhance the safety of the plant provide some degree of enhanced investment protection, particularly if those measures enhance the capability of retaining the fission products in the fuel.

3.2 Development of Advanced Reactor Types

3.2.1 Light Water-Cooled Reactors

The current light water-cooled reactor (LWR) technology has proven to be economic, safe and reliable. The LWR has a mature infrastructure and regulatory base in several countries. Over 75% of all current operating plants are LWRs. LWRs also have the highest percentage of the total world reactor operating experience.

For the advanced LWRs (ALWRs) of the 1990s and beyond most industrialized countries continue to develop large-size units, with power outputs above 900 MW(e). These evolutionary ALWR designs are the result of continuous upgrading and improvement based on experience gained from current models. For example, the N4 model (1400 MW(e)), which is now under construction in France, derives directly from the standardized P4 series (1300 MW(e)), while achieving a reduction of 5% in cost per installed kilowatt compared with the P4 series. The Westinghouse-Mitsubishi Advanced Pressurized Water Reactor (APWR-1350 MW(e)), the British "Sizewell-B" PWRs (1250 MW(e)), the ABB-Combustion Engineering "SYSTEM 80 PLUS" (1300 MW(e)) and the General Electric-Hitachi-Toshiba Advanced Boiling Water Reactor (ABWR-1360

The "REP 2000" programme, initiated in 1989 by Flectricité de France, should lead to the specification of European utilities' requirements. On the vendor side, FRAMATOME and SIEMENS established a joint company, Nuclear Power International (NPI), which is developing a new power reactor with enhanced safety features, and they intend to have it 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 to a broader basis. In Sweden, ABB Atom, in cooperation with the utility Teollisunden Voima Oy (TVO) of Finland, is developing the BWR-90 as an upgraded version of the boiling-water reactors operating in Sweden.

Mid-sized ALWRs in the 600 MW(e) range are also being developed with greater emphasis on passive safety features. In terms of the categories used here, both the larger and mid-sized ALWRs are considered to be evolutionary designs, in that none will require a prototype. Examples of these mid-sized passive ALWRs include the Westinghouse Advanced Passive PWR (AP-600) and the General Electric Simplified Boiling Water Reactor (SBWR).

An important aspect of the US programme was initiated in 1984 by the Electric Power Research Institute, an organization of U.S. utilities. Several foreign utilities have also participated in the programme, which involved developing comprehensive set of user requirements. ALWRs which would meet these requirements are being designed, partly supported by the U.S. Department of Energy. Utility requirements were established for large BWRs and PWRs having power ratings of about 1200 MW(e) and for mid-sized BWRs and PWRs having power ratings of about 600 MW(e). Design certification from the U.S. Nuclear Regulatory Commission is a key feature of this programme and it is contemplated that standardized units could be commercially offered in the 1990s as design certification is obtained.

All of these ALWRs incorporate significant design simplification, increased design margins, and various technical and operational procedure improvements, including better fuel performance and burnup, better man-machine interface using computers and improved information displays, greater plant standardization, improved constructability and maintainab lity, and better operator qualification and simulator training. The result of these improvements are in addition to the improvements already achieved in availability and the lower number of challenges to safety systems.

In the Russian Federation, design work on the evolutionary WWER-92, an upgraded version of the WWER-88, has been started and another design, the WWER-91, is being developed in cooperation with Finland. The Russian Federation is also developing the evolutionary WWER-500 design along the same lines as the AP-600, as well as a more innovative, integral design, the VPBER-600.

An innovative approach for the next generation of light-water-cooled reactors is being taken by ABB-Stom, the developers of the PIUS reactor. The conceptual design for PIUS is for a mid-size power unit of about 600 MW(e), although smaller sizes are certainly possible. The approach to enhanced safety in this reactor is based on the principle that the ability to shut down the reactor and provide continuing core cooling to remove decay heat after accidents could be entirely passive. The PIUS principle is based on having a large volume of borated water available to shut down and cool the reactor core. This borated water is separated from the primary water coolant by density locks during normal operation while naturally convecting through the core during any shutdown. Alo under consideration are several other innovative designs, both of the boiling and pressurized water reactor types, using the PIUS passive core shutdown and cooling principles. The ISER (University of Tokyo) and the SPWR (Japan Atomic Energy Research Institute) concepts use the PIUS principle on smaller units inside steel vessels. Proof of the PIUS principle would probably require a demonstration plant, although considerable loop-type verification work has already been performed.

With delays apparent in the large-scale deployment of breeder reactors, mostly because of considerations, improvement in uranium resource utilization has become another element in the evolutionary development of LWRs. Some improvements involve relatively limited changes to optimize core designs for improved uranium utilization with the once-through cycle. These approaches should have low economic risks and some have been incorporated in existing plants. Further improvement in resource utilization could be obtained by more widespread application of plutonium recycling in LWRs. Confirmation of the technical and economic feasibility and safety of evolutionary LWR developments is expected soon from validation studies and development work in progress in several countries, including the USA, Japan, Germany and, in particular, France. Many of these modifications, if proven satisfactory, could be applied to existing reactors within the next three to five years.

3.2.2 Heavy Water-Cooled Reactors

Heavy water-cooled reactor (HWR) technology has also proven to be economic, safe and reliable. A mature infrastructure and regulatory base has been established in several countries, notably in Canada, the pioneer in the development of the HWR concept. Approximately 7% of all current operating plants are HWRs. Two types of commercial pressurized heavy water-cooled reactors have been developed, both the pressure tube and pressure vessel variants, and have been fully proven. HWRs with power ratings from a few hundred MW(e) up to 900 MW(e) are available. Lifetime capacity factors of most of them have been among the best of all commercial reactor types. Safety performance has also proven very good. The promise of low fuelling costs arising from the inherent neutron economy of heavy water moderation has been demonstrated.

The continuing design and development programmes for HWRs in Canada are primarily aimed at reduction of plant costs and an evolutionary type of enhancement of plant performance and safety along lines similar to the LWR programme. These designs include the 450 MW(e) CANDU 3 and the 665 MW(e) CANDU 6 MK2. Also under development are the 500 MW(e) reactor in India and the 380 MW(e) ARGOS under joint development by an engineering firm in Argentina and Siemens in Germany. Work is also proceeding in Japan on 600 MW(e) and 1000 MW(e) ATRs, a heavy-water moderated, boiling light-water-cooled, pressure tube reactor.

3.2.3 Gas-Cooled Reactors

In the United Kingdom and France, considerable operating experience with carbon-dioxide-cooled reactors has been obtained. In the United Kingdom, about 20% of the total electricity is generated by gas-cooled reactors. However, with the completion of the Heysham 2 and Torness Stations in the UK the Advanced Gas-Cooled Reactor (AGR) programme appears to have come to an end. Further development work on this carbon-dioxide-cooled system will be concentrated on improvements in plant performance and life extension studies of existing plants.

The experience with the early helium cooled High Temperature Gas-Cooled Reactors (HTGRs), the Dragon plant in the United Kingdom, the AVR in Germany and Peach Bottom in the USA was very satisfactory and proved the capability of several of the unique features of this type of reactor. The experience with the later HTGRs, Fort St. Vrain (330 MW(e)) in the USA and the THTR-300 (300 MW(e)) in Germany, was not entirely satisfactory. The problems which resulted in the termination of operation of these plants were not related to the basic reactor concept of helium cooling, graphite neutron moderation and the use of graphite as a structural material, or from any safety concerns but were primarily related to technical and economic problems with first-of-a-kind systems and components.

The development of HTGRs is proceeding in the USA, Germany, the Russian Federation, Japan and China. Most of the effort is concentrated on small modular HTGR designs with individual power ratings from 80 to about 170 MW(e). The motivation for the present effort comes almost entirely from a critical examination of the goal of achieving enchanced safety for future nuclear plants. Satisfying this goal formed the basis for the smaller power output of individual power-producing modules and the reactor core configuration of each module. Emphasis has also been placed on other modular design features with a maximum use of factory fabrication, as opposed to field construction, for better quality control and savings in construction time and costs. Separation of the HTGR nuclear systems from the majority of the plant is intended to yield significant cost savings.

The key features of the HTGR which permit these characteristics are the benign helium coolant, a low power density, the large mass of graphite moderator closely coupled to the fuel, the power coefficient which is always negative and, in particular, the fuel itself, which is in the form of small particles individually coated with multiple layers of ceramic material. Along with the graphite moderator, this fuel is capable of withstanding very high temperatures without losing integrity.

It is recognized that the unique features and characteristics of the modular HTGRs will likely require prototype demonstration prior to design certification and commercialization. With the relatively small size of each power-producing module it is possible to contemplate such a demonstration with just one module, later expanding into a multi-module plant at the same site for commercial purposes.

The HTGR programme in Japan, although recognizing the potential for higher quality steam production and higher efficiency electricity generation, is nevertheless aimed primarily at proving the capability for even higher core outlet temperatures for the helium coolant (up to 950°C) with the view to a large number of industrial process heat applications. The 30 MW High Temperature Test Reactor (HTTR) is presently being constructed in Japan for tests related to this objective.

3.2.4 Liquid Metal-Cooled Reactors

More than 200 reactor-years of operating experience from experimental and mid-size LMFR power units has been accumulated up to now. However, the deployment of liquid metal fast reactors (LMFR) as breeder reactors as well as for electricity generation has not gained the momentum expected, owing to the availability of adequate low cost uranium resources to meet near and mid-term demands. Nevertheless, there is an awareness in the industrialized countries that breeder reactors will be needed in the early decades of the next century particularly if large scale deployment of nuclear energy is necessary to meet growing energy demands.

The development of advanced Liquid Metal Cooled Fast Reactors (LMRs) is continuing, with due recognition to the requirements for the next generation of nuclear power plants. Work is also continuing on fuel cycle development with emphasis on extending fuel burnup and demonstrating fuel cycle closure.

Design development in Europe, Japan and the Russian Federation is focused on large-scale designs fuelled with mixed oxides. In Europe and in the Russian Federation, 1500-1600 MW(e) units are being developed with component design, plant design and fuel cycle following an evolutionary pattern from the operation of the Phenix and Superphenix in France, the PFR in the UK and the BN-350 and BN-600 in the Russian Federation. Major efforts are under way at this time to make better use of passive safety in these designs. One example is the European Fast Reactor (EFR) design, which includes a passive decay heat removal system via air coolers.

Efforts in Japan and India are concentrated on smaller units as the next step in design evolution. With the 280 MW(e) MONJU prototype reactor expected to go critical in 1992, Japan's next step is the development of a loop-type demonstration reactor. India is proceeding from its Fast Breeder Test Reactor (FBTR) with the follow-up design of a 500 MW(e) pool type prototype (PFBR).

Most of the fuel cycle development is on mixed oxide fuels, but recent developments in the USA on the use of ternary metallic (U-Pu-Zr) fuel and the associated pyroprocessing of spent fuel are showing promise. A notable feature of pyroprocessing is that the majority of the long-life actinide elements which accompany plutonium through the process can subsequently be recycled into reactors for burning, where they are converted by fission into short-lived fission products and thus removed from the waste stream to facilitate waste disposal activities.

The main thrust of the liquid metal reactor programme in the USA is on a modular type concept, PRISM, originated by the General Electric Company. The development activities are focused on providing a reactor with improved safety and economics and an attractive waste management option. Each power block of the proposed system comprises three 471 MW(th) reactor modules connected to a single 465-MW(e) turbine generator. The plant has many innovative characteristics, including the use of the ternary metallic fuel cycle, inherent reactor shutdown by thermal and reactivity response, passive decay heat removal, and other construction and operational type characteristics associated with such modular concepts. The programme is proceeding with the conceptual design and prelicensing stage of this concept, to obtain design certification after extensive testing of a full-scale prototype module.

3.3 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 POWER

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.

Up to about 550°C, the heat can be supplied by steam at reasonable working pressures; above that, the heat must be supplied by other energy carriers. The long-term strength capabilities of metallic reactor materials set an upper limit of about 1000°C for nuclear-supplied process heat. Industrial processes, e.g., steel production, which require temperatures above 1000°C can utilize nuclear energy only via secondary energy carriers such as electricity, hydrogen and synthesis gas.

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-temperarture 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, Czechoslovakia, 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.

A 10-MW(th) SLOWPOKE energy system is being developed by Atomic Energy of Canada Ltd. as a heat source specifically designed to satisfy the needs of local heating systems in building complexes, institutions and of municipal district heating systems. Hot water at 85°C is provided for these purposes. A 2 MW(th) demonstration unit has been in operation since 1987 at the Whiteshell Laboratories in Manitoba.

In the Peoples' Republic of China, the HR-5 Nuclear Heating Test Reactor, developed by the Institute of Nuclear Energy (INET) in Beijing, is a 5-MW(th) water-cooled reactor which began operation in 1989 and supplies hot water, in the range of 60 to 90°C, to the INET centre. This reactor is establishing a technology base for possible future applications of nuclear district heat in China.

In the Russian Federation the AST light-water-cooled reactor has been designed specifically to provide hot water for district heating. Designs with power levels from 50 to 500 MW(th) have been developed.

The Shevchenko complex has made an important contribution to solving the water and electricity supply problems of West Kazachstan, enabling the natural resources in its arid regions to be developed and utilized. Shevchenko includes a fast breeder reactor (type BN-350), three thermal power stations and a desalination plant with thermal distillation equipment. The complex constitutes the world's first, and for the time being the only demonstration plant where a nuclear reactor is used for the desalination of seawater.

As a nuclear heat source, the HTGR has the unique capability of providing temperatures up to 950 to 1000°C. In addition to generating electricity by conventional steam turbine systems, the HTGR can provide helium gas at about 850°C for highly efficient gas turbine electric generating units, and up to 1000°C for high-temperature process heat. Extensive research, development and demonstration programmes have been conducted on components and systems for using nuclear process heat in the refinement and conversion of coal, oil and gas, to produce environmentally benign liquid-energy carriers which can be used as fuel for transportation and heating. The advantages are: use of nuclear energy rather than fossil fuels for the process heat; and reduction of certain environmental impacts, particularly concerning the releases of carbon dioxide into the atmosphere. 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 produce a core outlet temperature of 950°C and 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 cooperation is playing a greater role, and the Agency promotes international cooperation in their development. Especially for designs incorporating innovative features, international cooperation 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 cooperation 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 coordinated 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 cooperative Coordinated 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 cooperative programmes in areas of common interest in order to pool efforts on an international basis. These cooperative efforts are carried out through Coordinated 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.

One example of a CRP is the international project underway at the PROTEUS critical experiment facility of the Paul Scherrer Institut (Villigen, Switzerland) where an international team has been assembled to plan, conduct and analyze a new series of critical experiments focused on the needs for validation data for HTGR designs being developed by the participating countries. Another example is the CRP on Acoustic Signal Processing for the Detection of Sodium Boiling or Sodium/Water Reaction in LMFBRs which is examining experimental data and acoustic signal processing techniques to establish methods of detecting sodium boiling or sodium/water reactions rapidly and with high sensitivity.

Examples of recent Specialists and Technical Committee Meetings convened by the IAEA to promote information exchange are:

Advanced Water Cooled Reactors:
- Progress in Development and Design Aspects
- Cost Reduction Guidelines
- Structural Materials
- Nuclear Process Steam Applications

Liquid Metal Cooled Reactors:
- Steam Generator Failure and Failure Propogation
- Acoustic/Ultrasonic Detection of Sodium-Water Leaks in Steam Generators
- Instrumentation for Supervision of Core Cooling
- Advanced Controls for Fast Reactors

Gas-Cooled Reactors:
- Uncertainties in Core Physics Calculations
- Status of Graphite Development
- Fuel Behaviour during Accident Conditions

Several forms of IAEA support are available to Member States that do not have major reactor development programmes. Through the Agency, technical assistance is arranged for developing countries for providing expert advice, training, fellowships and special equipment for research. This will assist developing countries to establish the expertise to be able to incorporate advanced reactor technologies into their power generation programme when these technologies are ready for introduction.

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 are finding an advantage to cooperate internationally in technology development. The IAEA's programme in nuclear power technology development encourages international cooperation through technical information exchange and cooperative 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. Cooperation 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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