The Uranium Institute

Twenty-Third Annual Symposium
10–11 September 1998: London

The Role of Small and Medium-Sized Reactors

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In the second half of the twentieth century nuclear power has evolved from the research and development environment to an industry that supplies 17% of the world's electricity. In these 50 years of nuclear development a great deal has been achieved and many lessons have been learned. By the end of 1997, over 8500 reactor-years of operating experience had been accumulated.

The past decade, however, has seen stagnation in nuclear power plant construction in the Western industrialised world, slow nuclear power growth in Eastern Europe and expansion only in East Asia. The prospects for nuclear energy have been affected by a number of factors:

- slower economic development and general reductions in the rate of increase in energy demand, coupled with oversupply in some countries;
- the Three Mile Island and Chernobyl accidents with their effect on public confidence in nuclear power;
- slow progress in properly implementing nuclear waste disposal;
- difficulties for utilities in some countries in transforming from a rapidly growing industry to routine operation of ageing facilities;
- electricity supply deregulation;
- increased competition from natural gas.

The turn of the century is potentially a turning point for nuclear power prospects because of:

- increasing world energy consumption, with nuclear power's contribution to reducing greenhouse gas emissions, nuclear fuel resources sustainability, and improvements in operation of current nuclear power plants;
- advanced reactor designs that will improve economics and availability, and further enhance safety;
- continued strengthening of the nuclear power safeguards system.

Global Issue of Energy Supply

Today's global pattern of energy supply is not sustainable. The provision of affordable energy services is a fundamental prerequisite for economic growth and development. The plentiful energy resources in the past and the enormous efforts in research, development and engineering have produced the high living standards enjoyed today by the industrialised countries. For these countries achieving economically, environmentally, and socially sustainable development is a top priority.

Now and in the near future, better living standards and increased employment opportunities for the developing countries are inevitably linked to the provision of substantially more energy services. Taking into account the population growth, the anticipated increase in energy services will require more than twice as much energy production over the next half century. Over the next two decades India plans to triple and China to double the combustion of coal for electricity generation alone. Where transmission and distribution infrastructures are already in place, natural gas will be the preferred fuel for electricity and heat generation and for households. With the increase in the income per capita, and with growing trade volumes in a global market place, the demand for oil product fuelled transportation will expand rapidly.

There is an international consensus that heavy dependency on fossil fuels – which today account for more than 85% of the total energy supply – must be controlled. Their use adversely affects the atmosphere through emissions of greenhouse gases along with other noxious gases and toxic pollutants, thus becoming an obstacle to sustainable development both on a regional and on a global scale. One specific feature of fossil resources is their uneven distribution around the globe. For example, 60% of proven oil reserves are in the Middle East, while 40% of gas resources are in the countries of the former Soviet Union (FSU) and 40% are in the Middle East. Coal is also very unevenly distributed, with more than 80% of the proven reserves being concentrated in three regions, North America, the FSU and China. The uneven distribution of fossil fuel resources and the high cost of transport systems and infrastructures will be additional issues to be taken into account when deciding on future energy supply.

While energy efficiency in generation, transmission and end use, and the new renewable technologies, are an essential element of the sustainable energy policy of the industrialised countries, they may be far from sufficient and in many cases even inadequate to compensate for the expected increase in the demand for energy in the rest of the world. The global challenge is to develop strategies that foster a sustainable energy future, less dependent on fossil fuels.

Nuclear Power Potential

Though it is not problem free, nuclear power is recognised as having an advantage in contributing to the goals of sustainable development. It has been deployed in the industrialised countries when energy supplies have been insecure and has largely contributed to the stable and predictable energy supply necessary for their economic growth.

From today's point of view of sustainability criteria, the entire energy chain from nuclear fuel production to radioactive waste disposal has very limited emissions of greenhouse gases and other pollutants and does practically no harm to the environment. Furthermore, it is an established technology and commercially available, with 473 nuclear plants currently operating or being built in 32 countries. It can also be reasonably competitive, the resources it uses are plentiful and have no other useful application.

Nuclear power is unevenly used in the world. More than 95% of it is deployed in the industrialised countries and the countries of Central and Eastern Europe and Russia. But the contribution of nuclear energy in the energy mix of the rest of the world, and in particular the developing countries, is very small. While nuclear power has reached a level of saturation in several European countries and North America, it continues to expand in Asia. At the same time countries in Eastern Europe and the FSU, heavily dependent on nuclear power, are experiencing serious difficulties due to a breakdown in the economies and the infrastructure necessary to keep the nuclear power plants operational and to further expand their nuclear power programmes.

The future will see a mix of energy sources. The makeup of this mix cannot be precisely defined – it will depend not only on environmental considerations, but also on technological, political and market factors. The experience to date shows that in most of the countries which have reached a quasi-sustainable level of development, nuclear energy has played an important role in supplying a part of the required energy. Most of these countries will try to preserve their nuclear energy generation and capability and probably will seek to renew it in the future when the life of the current plants is exhausted. Inevitably, the countries whose economies will continue to grow rapidly, will be better placed to include nuclear power in their energy supply system for meeting their energy needs but also for security of supply, environmental awareness and access to high technology.

Key Nuclear Power Issues

In an increasingly competitive and international global energy market a number of issues will affect not only the choice of nuclear power, but also the extent and manner in which it will be used in a sustainable mix of energy sources:[1]

- enhancing reactor safety;
- improving nuclear power generation economics;
- minimising environmental impact;
- improving resource utilisation.

Enhancing Reactor Safety

With over 8500 reactor years of operation worldwide, nuclear power generally has an excellent safety record. But the Chernobyl accident demonstrated that one very severe nuclear accident has a potential to cause national and regional radioactive contamination. Although safety and environmental impacts are becoming a key issue for all energy sources, many in the general public perceive nuclear power as particularly and intrinsically unsafe. In order to reduce the risk of accidents a number of approaches are used:

- international collaboration to promote internationally accepted safety and engineering standards;
- enhancement of the integrity of the reactor vessel and reactor systems (such as double containment);
- development of advanced reactor designs with enhanced safety systems.

Unquestionably, the most convincing demonstration of safety will be through the safe performance of existing plants and the avoidance of any major incident in the future.

Improving Nuclear Power Economics

Success in meeting this challenge is critical to maintaining a role for nuclear power as a viable energy option. Without getting the economics right, its potential environmental benefits may well become irrelevant. Nuclear power plants will increasingly have to compete directly, in an open energy market, with other suppliers of electricity. This competitive environment has significant implications for plant operations, including among others the need for efficient use of all resources, including personnel; more effective management of plant activities, such as outages and maintenance; and sharing of resources, facilities and services among utilities. The ultimate objective is to provide electricity services at competitive costs without compromising operational safety.

Nuclear energy also has the potential to provide an economic source of heat for non-electricity applications, including district heating, desalination and high temperature process heat, especially through development and application of small and medium-sized reactors.

Minimising Environmental Impact

Although nuclear energy has distinct advantages over today's fossil burning systems – in terms of fuel consumed, pollutants emitted and waste produced – a further reduction in environmental concerns can positively influence public attitudes. As the overall health and environmental impact of the reactor and nuclear fuel cycle is small, attention is directed at techniques to deal with spent fuel, accumulated plutonium and radioactive waste. Reprocessing of spent fuel and recycling of most dangerous actinides in future fast reactors is being analysed in some countries as a solution for the fuel cycle back-end issues.

Improving Resource Utilisation

Known and likely resources of uranium should assure a sufficient nuclear fuel supply in the short and medium term even with reactors operating primarily on once-through cycles with disposal of spent fuel. However, as uranium demand increases and reserves are decreased, to meet the requirements of increased nuclear capacity, there will be economic pressure for the optimal use of uranium in a manner that utilises its total potential energy content per unit quantity of ore. Recycling of generated plutonium in thermal reactors and introduction of fast reactors in the longer term is considered in some countries as a solution.

Development of Advanced Nuclear Plants

Worldwide, considerable efforts are being made to develop advanced nuclear power plants with the aim of addressing the above mentioned issues. Various organisations 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$2 billion per year.

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 an innovative concept 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. Different tasks have to be accomplished and their corresponding costs in qualitative terms are a function of the degree of departure from existing designs. In particular, a step increase in cost arises from the need to build a reactor as part of the development programme.

Through activities within the framework of its nuclear power programme, the International Atomic Energy Agency (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.

Characteristics of Energy Use

Worldwide, about 30% of total primary energy is used to produce electricity. Most of the remaining 70% is either used for transportation or converted into hot water, steam and heat. Nuclear plants are now being used to produce about 17% of the world's electricity. Yet only a few of these plants are being used to supply hot water and steam. The total capacity of these few plants is about 5 GW of thermal power, and they are operating in just a few countries, mostly in Canada, China, Kazakhstan, Russia and Ukraine.

For heat applications, specific temperature requirements vary greatly. They range from low temperatures, just about room temperature, for applications such as hot water and steam for agro-industry, district heating and seawater desalination, to up to 1000°C for process steam and heat for the chemical industry and high pressure injection steam for enhanced oil recovery, oil shale and oil sand processing, oil refinery processes and olefine production, and refinement of coal and lignite. The process of water splitting for the production of hydrogen is at the upper end. Up to about 550°C, the heat can be supplied by steam; above that, requirements must be served directly by process heat, since steam pressures become much higher above 550°C. An upper limit of 1000°C for nuclear-supplied process heat is set on the basis of the long term strength capabilities of metallic reactor materials.

Water-cooled reactors offer heat up to 300°C. These types of reactors include pressurised water reactors (PWRs), boiling water reactors (BWRs), pressurised heavy water reactors (PHWRs) and light water cooled, graphite-moderated reactors (LWGRs). Organic-cooled, heavy water moderated reactors (OCHWRs) reach temperatures of about 400°C, while liquid metal fast reactors (LMFRs) produce heat up to 540°C. Gas-cooled reactors reach even higher temperatures, about 650°C for the advanced gas-cooled, graphite-moderated reactor (AGR), and 950°C for the high temperature gas-cooled, graphite-moderated reactor (HTGR).

As noted before, the primary conversion process in a nuclear reactor is the conversion of nuclear energy into heat. This heat can be used in a "dedicated" mode of operation for direct heating purposes. In this case, no electricity is produced.

The other mode is co-generation of heat and electricity. Parallel co-generation is achieved by the extraction of some of the steam from the secondary side of the steam generator, before the entrance to the turbine. Series co-generation is achieved by the extraction of some or all of the steam at some time during steam expansion in the turbine, when it has the right temperature for the intended application. During this cycle, the extracted steam also has been used for electricity production. Series co-generation is ideally suited to industrial processes related to district heating, desalination and agriculture.

More than 80% of the world's energy use is based on fossil energy sources, namely coal, oil and gas. Burning these fuels is known to cause serious environmental problems from emissions of sulphur oxides, nitrogen oxides and carbon dioxide. To help solve such problems, one approach that has been proposed is the integration of energy systems. A typical example for one future integration is the application of nuclear heat for the reforming of natural gas. Synthesis gas, methanol, hydrogen, heat and electricity would be produced from natural gas and uranium, using what is known as the HTGR-reforming process. In the process, natural gas is decomposed into mainly hydrogen and carbon monoxide. The main products are methanol, a liquid hydrocarbon, and hydrogen. Side products are heat and electricity.

Another example of this integrated approach is seen in the oil industry. Several studies have been performed on the use of nuclear power as a heat source for heavy oil exploitation. They have shown that under favourable oil market conditions, the nuclear option presents economic and environmental benefits, as compared to conventional methods.

A third example is the integration of coal and nuclear energy in the steel industry. From the technological point of view, this is the most ambitious integration. It involves gasification of hard coal heated by hot helium from an HTGR. The intermediate products are synthesis gas and coke, which is used for iron ore reduction. The final products are methanol and pig iron.[2]

Reactor Size Ranges

The choice of ranges is somewhat arbitrary but it has been the usual practice to take the upper limit of the range of small and medium-sized reactors (SMRs) as approximately half of the power of the largest reactors in operation. Accordingly, reactors up to 700 MWe are currently considered as SMRs. Other limits are defined by continuing to take similar reductions. The ranges adopted therefore are:

- Very small reactors: <150 MWe.
- Small reactors: 150–300 MWe.
- Medium reactors: 300–700 MWe.
- Large reactors: >700 MWe.

For heat-only or co-generation reactors, the range limits are applied to the electrical equivalencies of the thermal power. For very small heat-only reactors, for example, the upper limit adopted is 500 MWth.

It is understood that very small, small, medium or large reactors are relative concepts, related to the power level of the largest reactors in operation. That is, at the time when the largest reactors in operation were of the order of 200 MWe, the corresponding upper limit of the SMR range was 100 MWe, when 600 MWe units came into operation, the SMR range increased to 300 MWe, and so on. As there are no ongoing efforts to further increase the power level of the largest units, the currently accepted SMR range is assumed to prevail for a considerable period.

Applying the current definition of the SMR range, a third of the operating nuclear power reactors would qualify as SMRs. However, it should be noted that at the time when most of these plants were designed and built, they were considered large reactors according to the then-prevailing definition of the term.

The above defined ranges for medium, small and very small reactors expressed in power levels (MWe), are to be interpreted more as orders of magnitude and less as precise numbers. The large variety of reactors with different characteristics which are included in each of these ranges, are intended to respond to different requirements and uses, which need to be taken into account in order to facilitate the assessment of the potential market.

Medium-sized reactors are eminently power reactors whose objective is electricity generation. They can also be applied as co-generation plants supplying both electricity and heat, but the main product remains electricity. As such, they are intended for introduction into interconnected electricity grid systems of suitable size (at least six to 10 times the unit power) and operated as baseload plants. If operated in the co-generation mode, the heat supply would be up to about 20% of the energy produced. Economic competitiveness with equivalent alternative fossil fuelled plants is expected to be achievable under most conditions.

Small reactors are either power or co-generation reactors which may have a substantial share of heat supply. Due to the size effect, small reactors for electricity generation only, or operated in the co-generation mode, are not expected to be economically competitive with medium or large size nuclear power plants. They are therefore intended for special situations where the interconnected grid size does not admit larger (medium or large size) units and where alternative energy options are relatively expensive.

Very small reactors are not intended for electricity production under commercially competitive conditions as baseload units integrated into interconnected electrical systems. Clearly, very small reactors of current designs are not to be regarded as competitors of large, medium or even small power reactors, of which they are not scaled-down versions. Very small reactors address specific objectives such as the supply of heat and electricity or heat only (at either high or low temperature) for industrial processes, oil extraction, desalination, district heating, etc., propulsion of vessels or for energy supply of concentrated loads in remote locations. They could also serve as focal projects and a very effective stimulus for the development of nuclear infrastructures in countries starting a nuclear power programme.

The consideration of the specific objectives of the reactors corresponding to each power range has major relevance for the assessment of the respective markets.[3]

SMR Development Programmes

Several countries, notably in East and South Asia, believe strongly that nuclear power will be a principal source of energy in years to come.[4] Small and medium reactors form a major part of this activity. The People's Republic of China has a well developed nuclear capability, having designed, constructed and operated reactors. In many cases, these reactors can be regarded as SMRs and the skills needed to implement them are the same as those needed for terrestrial power plants. China has some 10 000 nuclear engineers in three major centres in different parts of the country, as well as other centres which make a major contribution. There is a particular interest in district heating reactors to help ease the current enormous logistical problems of distributing 11 billion tonnes of coal around the country each year.

In the SMR range, a 300 MWe PWR is in operation in China, and two 600 MWe reactors are under construction. All three reactors are of the evolutionary reactor type. Longer term plans call for development of a 600 MWe passive system. A 5 MWth integrated water cooled reactor has been built and operated for several winter seasons for district heating. A 200 MWth demonstration heating reactor project has been started. A 10 MWth high temperature gas cooled modular reactor for process application is under construction. Technical, safety and economic objectives of the programme have been defined. The test module HTR has been constructed and is expected to go critical by 1999. The system will be used to accumulate experience in plant design, construction, and operation. Several applications, such as electricity generation, steam and district heat generation are planned for the first phase. A process heat application, “methane forming”, is planned for the second phase. China is also constructing a 300 MWe LWR in Pakistan.

India has some early reactors of the CANDU type developed by Canada but has adopted a prime policy target of self reliance in nuclear power development, based on heavy water moderated reactors. Four units of the 220 MWe PHWR type are under construction. Additional similar units and two units of a scaled up 500 MWe type are planned. The main objective is to make the most economical use of uranium natural resources in the first phase. In the second phase it is planned to utilise fast breeder reactors fuelled by plutonium generated in phase one. A 500 MWe prototype is in a detailed design stage. India also has large reserves of thorium which exceed its reserves of uranium. The heavy water reactor with its very good neutron economics is well suited to the thorium / U-233 cycle and a programme of R&D work for phase three, aiming at utilisation of the this cycle in an advanced heavy water reactor, has been initiated.

Japan has a high population density and a shortage of suitable sites for nuclear reactors due to the large fraction of the landmass covered by mountainous terrain. This has led to a preference for large reactors on the available sites to maximise the power output from them. In spite of this, there is a very strong and diverse programme of reactor development supported by the big industrial companies, by the national laboratory and by the universities. Three large industrial companies have developed their own LWR designs in the SMR range and the Japan Atomic Energy Research Institute (JAERI) has several more innovative designs.

At the end of 1996 two large reactors were under construction in Japan. The Monju fast breeder reactor (280 MWe), a prototype demonstration plant, is currently undergoing a safety review as a follow up of the incident in 1995. Several different designs are currently being worked on in the SMR range; namely SPWR, MRX, MS-300 / 600, HSBWR, MDP, 4S and RAPID. SPWR and the marine reactor MRX are integrated PWRs. The MS series are simplified PWRs. HSBWR is a simplified BWR. MDP, 4S and RAPID are small sodium-cooled fast reactors. Preliminary investigations have shown a high level of safety, operability and maintenance. The economics of these systems have been promising. These systems are expected to form part of Japan’s next generation of reactors.

Japan has also a development programme for the gas cooled reactor of the small and medium-sized range. A High Temperature Engineering Test Reactor (HTTR) has been under construction since 1991 at Oarai. The 30 MWth reactor will be the first of its kind to be connected to a high temperature process heat utilisation system with an outlet temperature of 850°C. The system will be used as a test and irradiation facility and also utilised to establish the basic technology for advanced HTGRs for nuclear process heat applications. The system is expected to go critical in 1998. However, the main trend in power generation is still taking the line of larger (1000–1300 MWe) evolutionary light water reactors. The guidelines of the programme put user-friendliness, improvement in operability, and flexibility of core design as prime design objectives.

Korea has twelve nuclear power plants (10 PWRs, 2 PHWRs) in operation and has an ambitious programme for the further deployment of nuclear power. The country is not well blessed with indigenous sources of fossil fuel and has to rely on imports. Furthermore, 80% of the countryside consists of mountainous terrain which encourages the installation of large stations to make optimum use of the available sites. Most of the existing plants are of the PWR type, but, since April 1983, PHWRs (679 MWe each) have been added to the grid to give some diversification in supply and operation. Six large PWRs (1000 MWe each) and two medium-sized PHWRs (700 MWe each) are under construction. Large PWRs are expected to form the main component of nuclear power installation in Korea until well into the next century. The optimal combination of PWRs and PHWRs will help to maximise the usage of uranium resources through the utilisation of spent fuel in the future. This choice has been the first phase of a strategy of reactor development in Korea.

The medium-sized PHWR plants form part of the Korean power source, but the standard nuclear power plant, KSNP, with 1000 MWe rating, is expected to form the main stream of the nuclear power generation industry in Korea. On the basis of PWR technology, an advanced integral reactor, the System Integrated Modular Advanced Reactor (SMART) is being conceptually developed. The power output of the reactor will be in the range of 100–600 MWe depending on the purpose of utilisation, such as desalination or power generation. It is expected that the export of nuclear technology to the rest of the world will form part of Korean trade. Streamlining of standardisation, modularisation, prefabrication, and substantial reduction in the construction schedule of small and medium-sized reactors will make Korea a potential nuclear power exporter in the twenty-first century.

In the Russian Federation, there is substantial experience from the development, design, construction and operation of several reactors in the small and medium-sized category. These reactors have been used for electricity generation, heat production and ship propulsion. Reactors that have been used for icebreaker and submarine propulsion are planned to be made available for other applications, not only within Russia but also to other countries that are interested in their application for electricity generation for remotely located areas or for non-electricity applications.

Currently a project is being implemented that consists of two reactors (KLT-40) mounted on a barge. These reactors have been earlier used for propulsion of icebreakers. The barge is supposed to provide electricity to Pevek in Northern Siberia. Barge mounted reactors may become a near term solution for other countries that need energy, but do not yet have the infrastructure for the introduction of large nuclear power plants. The barge mounted reactors could be operated under the supervision of the vendor and be pulled back to the vendor's location for maintenance and refuelling, thereby avoiding the need for on-site refuelling. Besides KLT-40 (up to about 160 MWth) there are other small reactors under design in Russia for mounting on barges, including the NIKA 75 (75 MWth), UNITHERM (15 MWth) and RUTA-TE (70 MWth).

The CAREM-25 reactor is under development in Argentina by the Atomic Energy Commission (CNEA), which has subcontracted the design and development of the reactor to INVAP SE. The design and development of the fuel elements is carried out by CNEA. The power level of CAREM is 100 MWth, approximately 25 MWe. The intended uses of the reactor are electricity generation, industrial steam production, seawater desalination or district heating. The reactor is also intended to bridge the gap between a research reactor and a larger nuclear power plant, by serving as a focal project for infrastructure development and the transfer of technology, in order to facilitate the launching of a nuclear power programme in a country with no previous nuclear power experience.

The main features of the reactor are light water cooling by natural circulation, low enriched uranium fuel, an integrated and self-pressurised primary system, and a passive heat removal system. The achievement of high levels of safety, simplicity and reliability are the main design criteria. The basic design of CAREM-25 has been completed. The detailed design of the reactor is being performed, and there is a comprehensive research and development effort going on. This consists of various relevant studies and of testing rigs and installations, such as a critical facility, natural convection loop, full scale hydraulic control rod drives, protection system simulator, etc. A preliminary safety analysis report has been completed and presented to the national regulatory authority. It is intended to construct a first project in Argentina.

Examples of SMR Designs

The AP-600

The Westinghouse Advanced Passive PWR (AP-600) is a 600 MWe design which is conservatively based on proven technology, but with an emphasis on passive safety features. It has been designed by Westinghouse of the United States, under the sponsorship of the US Department of Energy (DOE) and the Electric Power Research Institute (EPRI). The design team includes a number of US and foreign companies and organisations. The AP-600 passive safety-related systems include the passive core cooling system (PXS), the passive containment cooling system (PCS), and the main control room habitability system.

The PXS protects the plant against reactor coolant system breaks, providing the safety functions of core residual heat removal, safety injection, and depressurisation. It uses three passive sources of water for safety injection: the core makeup tanks, the accumulators, and the in-containment refuelling water storage tank (IRWST). These injection sources are directly connected to nozzles on the reactor vessel. Long term injection water is provided by gravity from the IRWST, which is normally isolated from the reactor coolant system by check valves.

The PXS includes a 100% capacity passive residual heat removal heat exchanger, which is connected through inlet and outlet lines to one reactor coolant system loop. The IRWST provides the heat sink for this heat exchanger. Once boiling in the IRWST starts, steam passes to the containment. This steam condenses on the steel containment vessel and, after collection, drains by gravity back into the IRWST. The heat exchanger and the PCS provide indefinite decay heat removal capability.

The PCS provides the ultimate heat sink for the plant. The steel containment vessel provides the heat transfer surface that removes heat from inside the containment and rejects it to the atmosphere. Heat is removed from the outer surface of the containment vessel by natural circulation of air. During an accident, the air cooling is supplemented by evaporation of water, which drains by gravity from a tank located on top of the containment shield building.

To contain core damage, the AP-600 design provides the operators with the ability to drain the IRWST water into the reactor cavity in the event that the core has uncovered and is melting. The objective is to prevent reactor vessel failure and relocation of the molten core debris into the containment.

The VVER-640

This design of the VVER-640 (V-407) is being developed in Russia by OKB “Gidropress”, the Russian National Research Centre “Kurchatov Institute”, and LIAEP. The VVER emergency core cooling system (ECCS) includes the following automatically initiated subsystems:

- hydrotanks with nitrogen under pressure;
- hydrotanks under atmospheric pressure;
- deliberate emergency depressurization.

The passive ECCS provides long term residual heat removal in loss of coolant accidents (LOCAs) accompanied by a station blackout. In the first stage, the nitrogen-pressurised hydrotanks will be actuated. When these are empty, the tanks holding cooling water under atmospheric pressure begin to operate. Active elements of the system needed for the function of emergency heat removal are provided with electrical power from storage batteries.

The design basis for the passive residual heat removal system (PHRS) is also a station blackout situation, including loss of emergency power supply. The PHRS consists of four independent trains, each comprising a steam–water heat exchanger, piping for steam supply and condensate return, and battery-operated valves. The heat exchangers are installed in a tank of demineralised water. They are connected to the secondary side of the steam generators in such a way that the steam from the steam generator will flow to the heat exchanger where it condenses, transferring its heat to the water. The condensate will flow back to the steam generator. Coolant motion occurs by natural circulation.

The system for passive heat removal from the containment includes coolers, storage tanks of cooling water and connecting pipelines. Steam released to the containment condenses on the heat exchange surface of the cooler giving heat to the water of a storage tank via natural circulation. Construction of a first pilot plant at the Sosnovy Bor site, near the Leningrad nuclear power station site outside St Petersburg, is under consideration.

The Indian AHWR

A 220 MWe Advanced Heavy Water Reactor (AHWR) is being developed at the Bhabha Atomic Research Centre in India. The AHWR utilises heavy water moderator and light water coolant with a fuel cycle based on thorium, and a safety approach based on the incorporation of passive safety systems.

Boiling light water in vertical tubes in the reactor core enables heat removal through natural circulation so primary circuit pumps are unnecessary. The required flow rate is achieved by locating the steam drums about 32 m above the centre of the core. An experimental programme is underway to confirm the analysis leading to the loop height and to study the thermal-hydraulic stability of the primary heat transport (PHT) system.

The top of the primary containment shell contains the gravity-driven water pool (GDWP). The inventory in the GDWP is sufficient to cool the reactor for three days following an accident. The GDWP inventory is connected to the core through a series of rupture discs and does not involve the use of external power, moving parts or instrumentation.

Isolation condensers (ICs) positioned in the GDWP will transfer decay heat to the GDWP during short, planned reactor shutdowns or following a reactor trip. This is achieved by diversion of the steam flow between the steam drums and the turbine to the ICs. Another set of condensers in the GDWP will cool the primary containment following a LOCA. Simple experiments have demonstrated the feasibility of the passive containment cooling system and more detailed experiments are in progress.

Emergency core cooling is provided from accumulators pressurised with nitrogen, with separation from the PHT system achieved with rupture discs that rupture when post LOCA depressurisation of the PHT system reaches a preset level. Passive containment isolation following a LOCA is achieved by U-bends in the reactor building air supply and exhaust ducts. In the event of a LOCA, pressure acts on the GDWP inventory and pours water, by establishment of a siphon, into the ventilation duct U bends, thus providing seals. Experiments have confirmed the effectiveness of this innovation.

South African PBMR

Eskom, the state electricity utility of South Africa, has initiated a detailed economic and technical evaluation of the Pebble Bed Modular Reactor (PBMR) as a potential candidate for future additions to its electricity generation system. The requirements set by Eskom for the installation of new generation capacity include a capital and operation cost which must match (or improve upon) that being achieved by their large coal stations. This currently represents a retail power cost to the customer of approximately two US cents per kWh. Other requirements for the plant include an availability approaching 90%, location and plant size to match the load, public acceptance and environmental cleanliness.

High temperature gas cooled reactors (HTGRs) feature a high degree of safety through reliance on passive safety features. All HTGRs incorporate ceramic coated fuel capable of handling temperatures exceeding 1600°C with core helium outlet temperatures approaching 950°C under normal operating conditions. Consequently, the primary focus for this reactor type is to investigate the generation of electricity via the direct coupling of a gas turbine to the HTGR (resulting in a net plant thermal efficiency approaching 47%), and to evaluate the application of this high temperature primary coolant for industrial applications such as steam and CO_2 reforming of methane for the production of hydrogen and subsequent synthesis to other fuels such as methanol.

The conceptual design of the South African PBMR features a helium cooled pebble bed reactor with a power output of 103 MWe (228 MWth) coupled to a closed cycle gas turbine power conversion system consisting of two turbo-compressors, a turbo-generator, a recuperator, pre-cooler and an intercooler all located within three steel pressure vessels. The three turbo machines are equipped with magnetic bearings and the recuperator is of a fin-plate design for compactness. The overall net efficiency of this Brayton cycle system is expected to be ~45%, based on a reactor outlet helium temperature of 900°C and a maximum system pressure of 70 bars.

The PBMR reactor basically builds on German reactor designs utilising the experience from the Thorium High Temperature Reactor and the AVR. These plants utilise a steam cycle in contrast to the Eskom design for a direct cycle helium turbine. The choice of a core design limited to 228 MWth with a diameter of 3.5 m, and the use of graphite constrictions for nuclear control and shutdown outside of the pebble bed, provide conservatism in maintaining the maximum accident fuel temperature to 1600°C. Also, the PBMR is to use a multiple pass regime for on-line constant fuelling of the reactor.

Other design considerations for the PBMR include the components for the power conversion unit (PCU). The Atomic Energy Corporation (AEC) of South Africa is developing the initial design for the two turbo-compressors and the power turbine. GEC Alsthom of France is providing the preliminary design of the electricity generator and the associated exciter. The three rotating shafts of the PCU are to be supported by magnetic bearings. The recuperator is of the compact perforated fin-plate type with the pre-cooler and intercooler being of conventional finned tube design. The thermodynamic loadings of the pre-cooler and intercooler are anticipated to be nearly identical which may allow for interchangability of components. The electricity generator will basically be of standard design with the additional requirements of operating in a vertical configuration on magnetic bearings and with a high pressure helium atmosphere. However, these requirements are not considered to represent significant design concerns.

Activities of the IAEA

The IAEA has witnessed a considerable renewal of interest by its member states in the development of SMRs. This is particularly evident in the developing countries where large power plants are not a viable consideration due to the size of the existing electrical grid. This interest was strongly expressed in the 1997 IAEA General Conference and subsequently reaffirmed at the March 1998 Board of Governors meeting.

Many member states have active programmes associated with nuclear power development in the SMR size range. These programmes involve a wide variety of reactor designs, and include plants whose status ranges from being in long term operation to currently undergoing initial conceptual design. The vast majority of these plants are for the production of electricity.

Although nuclear power seems to be focused predominantly on the generation of electricity, the wide range of plant types provides the possibility for nuclear power as an energy source for other applications, such as desalination, district heating, and industrial processes such as hydrogen production through the reforming of methane.

The IAEA has an extensive programme to help support member states in their national SMR efforts. This programme has, as its basic objective, the requirement to provide a venue for international exchange of information on the development of technology and designs of SMRs, in order to enhance their performance, safety and economics.

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