Annex I.1
SMALL AND MEDIUM SIZE NUCLEAR REACTORS

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I.1.1. INTRODUCTION

The purpose of this appendix is to provide up-to-date technical information relevant to the deployment of SMRs. It summarizes the status of SMRs and discusses areas of relevance to their utilization, including seawater desalination; and in particular their simplicity, their flexibility for a variety of applications and the use of passive safety features as fundamental to most of these designs. In response to important commercial developments, the energy range of small and medium reactors (SMRs) is now taken as being up to around 700 MW(e). Detailed information on SMR designs can be found in the IAEA report on The Design and Development Status of Small and Medium Reactor Systems 1995 [I.1-1].

The assessment of the world market projection for seawater desalination carried out as part of the options identification programme concluded that a sufficiently large demand in the years 2015 and beyond will support the installation of desalination facilities in the range of 200 000 to 500 000 m^3/d. Plants of this range of production capacity would be required in several countries. In addition, it appears that there is also a sizable market for desalination in the size ranges of 50 000 to 100 000 m^3/d. These ranges correspond to 100~250 MW(e) and 25~50 MW(e) net power output. The most convenient size of the reactor would be in the SMR range, both if the reactor power be used totally for desalination or if the reactor is to operate in a cogeneration mode.

I.1.2. OVERVIEW OF THE SMR MARKET

(1) The SMR market

The current growth of population and energy demand is dominated by developing countries. There are many places and applications where this increased demand will be best met by power plants in the SMR range, due to a small grid system or for application in a remote area or for a special purpose.

The world primary energy consumption amounts to well over 300 000 petajoules and over half of that is used as hot water, steam and heat. Only a few nuclear power plants are being used for heat applications (district heating, heat for industrial processes, and seawater desalination). Potential nuclear heat applications include enhanced oil recovery, petroleum refining, petrochemical industries, and methanol production from hard coal. The need for potable water in some parts of the world is large, vital for sustaining development, and ever increasing. Clearly nuclear heat and power production could play a major and important role.

Nuclear power at present is used mainly for electrical power generation which only forms 30% of the energy market. There have been numerous studies on the use of SMRs for heat applications rather than electrical generation and some of these studies have shown the SMR option to be viable both technically and economically [I.1-2]. Future expansion of nuclear application, beside addressing large power generation demand, may also come from more spread energy market involving smaller units for process heat applications and small scale power generation in remote areas.

(2) SMR projects

With such a range of possible applications in many different parts of the world, a large number of different R&D and design projects have been set up. Figure I.1-1 lists those for which descriptions have been submitted to the latest IAEA review on the subject and indicates the status of their development. LWRs, HWRs, GCRs and sodium cooled reactors all have active development work in various Member States.

Over the past 30 years there have been many market surveys for SMRs. They have shown a potential for sales of a large number of reactors before the turn of the century. These estimates of the market have turned out to be grossly overoptimistic but have encouraged developers to continue their efforts. In spite of a moderate response from the market, there is still a very large development effort continuing but few of the advanced SMR designs have yet been in operation to demonstrate their capabilities. Indeed, few of them have been funded through the detailed design stage to make them ready for construction. They do, however, present a variety of solutions to the problems of reactor design for future designers to draw on and to give an impression to purchasers of the capabilities of current designs, which could be developed to meet their needs. The IAEA is currently involved in a study on the market potential of SMRs which is expected to be concluded in 1997.

There is thus a gap between the designs available but not built, and their exploitation in what appears to be a potentially large market.

(3) Bridging the gap

Possible ways of bridging the gap would be for vendors to collaborate on one design to spread the design and development costs and for users to collaborate to define an SMR requirements document for particular applications. There have been some notable vendor collaborations in industrialized countries demonstrating that this is a possible way forward. Requirements documents have been produced for power generation and requirements have been harmonized on a regional basis (Asia, eastern Europe, western Europe and North America). Developing Member States having similar technological and financial circumstances could establish their version of requirements for an identified market (e.g. desalination). Such requirements could be taken up in some of the developing projects to enhance their prospects for constructions. An other important aspect to the deployment of nuclear power in developing countries is the development of the required manpower and infrastructure for a successful programme.

(4) Incentives for development

Small and medium size reactor development has many incentives; some are economic others are safety related. The motivation for these developments has included the need to enhance public acceptance of nuclear power. The simplification of designs should improve the transparency of their reactor safety. Another incentive to SMR development has been its suitability for the implementation of new design approaches. Innovative and evolutionary designs with novel features have been implemented in the SMR range. A passive safety approach has so far been the technology of small and medium reactors. SMRs have particular characteristics which can enable them to be economically viable in spite of losing the advantage of the economics of scale.

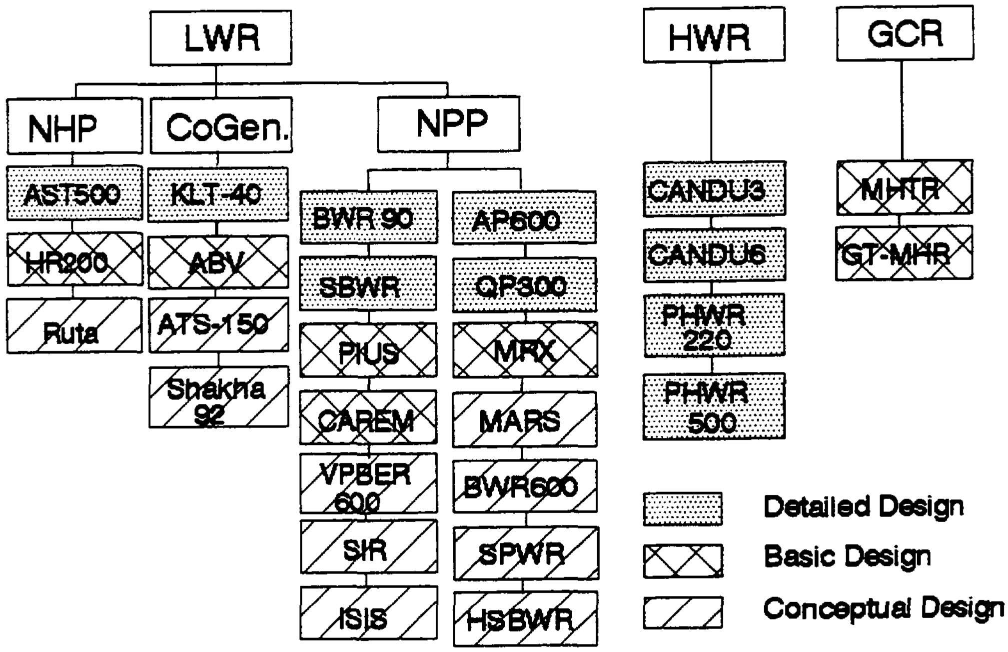

FIG. I.1-1 SMR designs and their design status

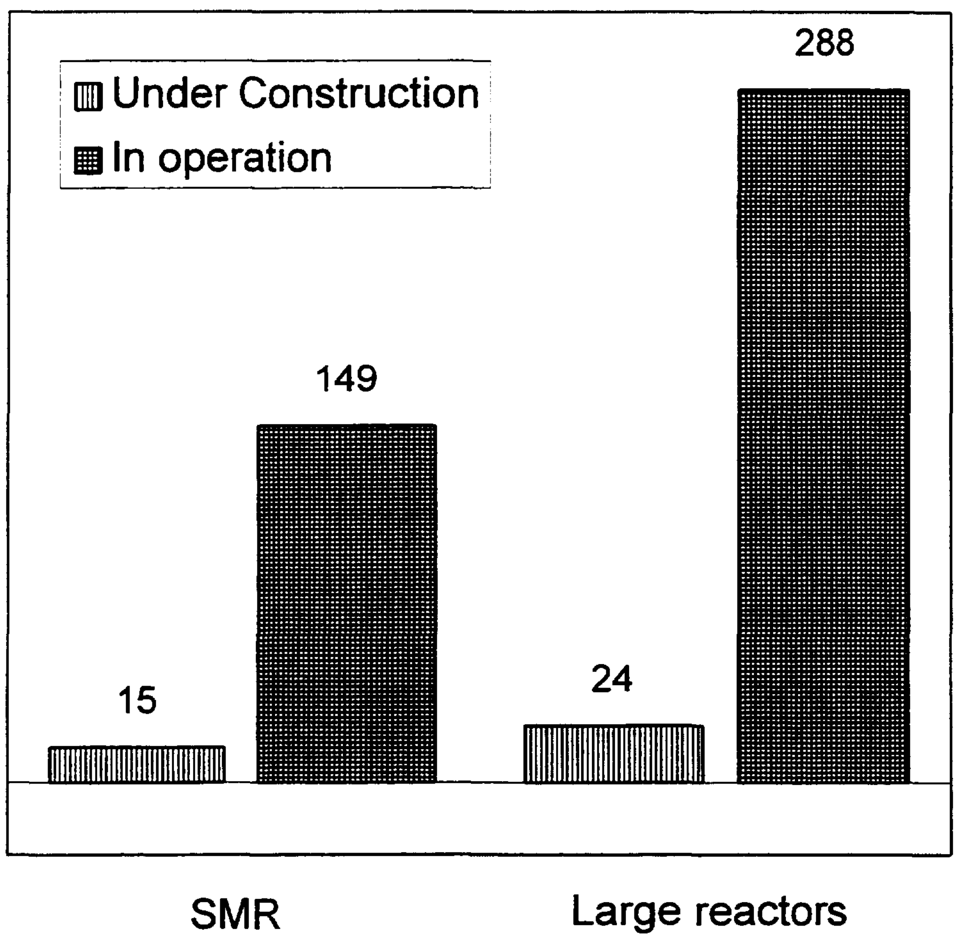

FIG. I.1-2 Nuclear reactors in operation and currently under construction [3]

The incentives for the development of SMRs can be summarized as follows:

- Simpler design,
  An SMR can be modularised more easily and constructed in a shorter time than larger plants, thus reducing constructions costs (including interest during construction) and generating earlier revenues.

- Increased safety margins leading to a longer grace period,
  Passive safety features simplify the design and attain the required safety objective in a different way compared to large plants with more active safety systems. This could reduce cost and facilitate the presentation of the safety of the reactor to both regulatory authorities and the public.

- Lower severe core melt frequency and minimum accident consequences.

- Better match to grid requirements,
  SMRs can provide a better match to small grids or to a slow growth of energy demand. Taking into consideration the potable water demand and the corresponding energy requirement, a SMR would be a suitable candidate for a developing country starting its nuclear programme.

- Better use of nuclear industry infrastructure and manpower skills in countries with small nuclear programmes.
  One 600 MW(e) unit every 2 years is preferable to one 1200 MW(e) unit every 4 years.

- SMRs could open up energy markets,
  SMRs can be used for process heat, desalination, district heating and enhanced oil extraction as well as power generation.

- Lower financial risk due to:
  · lower financing requirements per unit,
  · shorter and better predictable construction schedule.

(5) Objectives and requirements for SMRs

Development or deployment of SMRs could take place in a programme under the following general objectives:

1. The size of reactor is appropriate to a geographical location, distribution network or application.
2. It should be economic within the constraints of the other objectives.
3. It must be demonstrably safe and licensable.

These general objectives are applicable to reactors of any size but there are particular aspects of SMRs which help in meeting them.

1. Size. SMRs are appropriate for remote regions with limited load. They are appropriate for utilities with small grid systems. They are appropriate for some dedicated applications such as desalination, district heating or process heat possibly in a co-generation mode.

2. Economics. SMR designs all aim to simplify the design to reduce costs and offset to some extent the economies of scale. Modularisation allows a greater element of factory construction and assembly and is generally less expensive than work on site. It leads to shorter construction times and savings in interest during construction. The reduced capital requirements compared with large plants may well be attractive to purchasers.

3. Safety. Most SMRs make extensive use of inherent safety features and passive safety systems. Such systems are appropriate to SMRs and are harder, if not impossible, to engineer on large reactors. They tend to be simpler than active systems resulting in a simpler safety case and easing the problems of public acceptability.

While objectives provide for general and long-term applicable targets for nuclear reactors of present and future designs, requirements provide more specific, clear and complete statements by utilities in a given country. The requirements are usually grounded on well proven technology and long experience of commercial operation. The design requirements usually take into consideration problems of the past and incorporate new features assuring simple, robust, and more forgiving designs. They also provide for a common ground for regulators and vendors on licensing issues. Well defined requirements agreed upon by regulators, vendors and utilities provide for investor confidence. The design requirements usually cover the whole plant (i.e. NSSS, BOP, safety systems, etc.) and provide clear specifications with regard to performance, maintainability and plant economics. Taking into consideration infrastructure and experience, requirements in most developing countries and some industrialized countries are expected to be easily fulfilled by a small or medium reactor.

I.1.3. PROGRAMMES FOR SMR DEVELOPMENT

(1) Current activities in Member States

Nuclear energy plays an important role in supplying a significant portion of the world electricity demand. Reactor generated heat has been utilized in several parts of the world for district heating, process heat application, and seawater desalination. It should be noted here that over 50% of the world energy demand is utilized for either hot water or steam production. Such processes could be carried out more efficiently and cleanly utilizing nuclear energy.

Some South and East Asian countries believe strongly that nuclear power will be a principle source of energy for many years to come. Small and medium reactors form a major part of this activity. China has a well developed nuclear capability having designed, constructed and operated nuclear reactors. A 300 MW(e) PWR (QP300) has been in operation for three years and two 600 MW(e) reactors are under detailed design and site preparation. Longer term plans call for development of a 600 MW(e) passive reactor (AC600). A 5 MW(th) integrated water cooled reactor has been built and operated for five winter seasons (since 1989) for district heating. Another purpose of the 5 MW(th) reactor is the development work for other applications such as desalination. Construction of a 200 MW(th) demonstration heating reactor has been started aiming at start of operation by the year 1998. A 10 MW(th) high temperature gas cooled reactor for process application is also under construction.

India has adopted a prime policy target of self reliance in nuclear power development, based on heavy water moderated reactors. Five units of the 220 MW(e) PHWR type are under construction and all are expected to be in operation by the year 1997. An additional four units of the same type and an extra four units of a scaled up 500 MW(e) type are planned.

Japan has a preference for large reactors on the available sites to maximize the power output from them. There is a very strong and diverse programme of reactor development supported by the big industrial companies, by the national laboratories and by the universities. At least seven different designs are currently being worked on in the SMR range; namely SPWR, MRX, MS 300/600, HSBWR, MDP and 4S. SPWR and the marine reactor MRX are integrated PWRs. The MS series are simplified PWRs. HSBWR is a simplified BWR. MDP and 4S are small sodium-cooled fast reactors. Preliminary investigations have shown a high level of safety, operability and maintenability. The economics of these systems are promising and they are expected to form part of Japan's next generation of reactors.

Japan has also a development programme where gas cooled reactors in the small and medium size range are under development. A High Temperature Engineering Test Reactor (HTTR 30 MW(th)) has been under construction since 1991 at Oarai.

Korea has ten PWRs and one PHWR in operation and has an ambitious programme for the further development of nuclear power. Most of the existing plants are of the large PWR type, but, since April 1984, there has been a policy to install medium size PHWR (~700 MW(e)) to diversify supply and operation. Three more PHWRs are under construction. In addition, a relatively small 330 MW(th) integral reactor is also currently under development for a cogenaration purpose.

Indonesia has a very rapid growth of population spread over 13 000 large and small islands. There is a clear future potential for reactors in the SMR range. However, the main island has over half the current population and could take a large station; a feasibility study covering this and other aspects of Indonesia's possible nuclear programme has been undertaken. The outcome is in favour of the nuclear power option. 7000 MW(e) of nuclear capacity is being considered up to the year 2015. Optimal plant size is being looked at and a number of 600 to 900 MW(e) units are being considered. Indonesia has deposits of tar sands for which extraction based on nuclear heat using HTGRs is being investigated. A programme on public acceptance is being executed.

Thailand has just started a feasibility study on the construction of a nuclear power plant.

The current Russian programme is largely based on 1000 MW(e) units but the 500-600 MW(e) range is well represented in the development programme. Two units of 600 MW(e) each are planned in the Far East region of the country for the period 2000~2010. Two others in Karel'ska are planned for the same period.

Russia is a country with a clear scope for the deployment of smaller plants due to its huge land mass with remote communities living in areas with harsh winters. The nuclear energy option seems to have favourable economics compared to conventional sources for application in remote areas, including domestic heating. Several reactors of small size (5~35 MW(e)) are planned for construction around the year 2000.

Eastern Europe has WWER units of the 440 MW(e) size but for the future larger units are considered. In western Europe, most utilities have opted for large nuclear power plant (1000-1500 MW(e)) if they have opted for nuclear at all. On the basis of several different national development programmes on SMRs, many innovations using a wide variety of coolants, fuel, containments and safety features have been worked out. More recently, SMR-specific development effort in western Europe has decreased because of reductions in governmental funding.

In the USA, the AP600 in the SMR range is being supported and aggressively marketed worldwide, in addition to a large reactor design (ABWR). In Canada a perceived need for a simpler, cheaper reactor which could be more easily demonstrated to the public as safe has led to the development of a smaller version of the CANDU line. Design and safety requirements for the next generation of reactors have been identified both in Canada and in the USA by the utilities and governmental agencies. In North America, medium size reactors are expected to supply a significant share of nuclear electricity in the future.

In Argentina the work on Atucha 2 (745 MW(e) PHWR) is continuing. Argentina has carried out a development effort for the design of a small pressurized water cooled reactor "CAREM". The system has a total power of 100 MW(th) and it is of the modular integrated type. The basic design of the system is complete and it is currently undergoing detailed design.

North African and Middle Eastern countries have identified a strong need both for electricity and for power for desalination and several of them are looking at the nuclear option. The reserves of fossil fuel are massive in some countries but others rely largely on imports. The water problem is compounded by low rainfall, a rising population with increasing expectations for its standard of living and by a lowering of the water table in the traditional sources under the desert sands. A study for the North African countries of the economic feasibility for nuclear desalination has been completed [I.1-3]. A feasibility study for a demonstration facility for seawater desalination in Morocco is expected to start in 1996. In Egypt, a feasibility study has been completed for a medium sized NPP [I.1-4].

From information provided by Member States (see Table I.1-1), it can be seen that several nuclear power plants in the SMR range are under construction around the world. Nuclear power investment on a worldwide basis has preferred large units due to the economy of scale, especially in the industrialized countries. This can be clearly seen from the number of nuclear power plants in operation today (Fig. I.1-2). The number of units currently under construction in the SMR range is in the same range as that of the big power plants. These data show that SMRs could play an important role in many industrialized and developing countries.

Table I.1-1 SMRs UNDER CONSTRUCTION

Country	Number of units	Name	Type	Capacity (net)	Expected date of commissioning
Argentina	1	AtuchaII	PWR	692 MW(e)	1998
India	4	PHWR 220	PHWR	202 MW(e)	1998-1999
Rep. of Korea	3		PHWR	650 M(e)	1997-1998-1999
Pakistan	1	Chashnupp	PWR	300 MW(e)	1999
Romania	2		PHWR	650 MW(e)	1996-2002
Slovak Rep.	4	Mochovce	PWR	388 MW(e)	?
Russian Federation	2	AST 500	PWR	500 MW(th)	1998

I.1.4. SUMMARY OF TECHNICAL DEVELOPMENT

(1) Passive safety features

The use of safety systems operating on passive principles is a feature of many SMR designs. The original incentive was to produce designs which could cope with any accident initiating event coupled with the failure of all engineered safety systems. Reliance would be on natural processes, such as gravity and natural convection, only. There should be no need for operator intervention for a long, perhaps indefinite period. Two reactors have achieved this in their design, the Swedish PIUS reactor and the Modular HTGR. In these two designs, the safety systems are passive both in initiation and in operation. Other designs need some form of stored energy (e.g. batteries, springs or hydraulic reservoirs) to initiate the passive systems but are then passive in operation, requiring no safety grade power sources such as diesel generators. There are thus different degrees of passivity and the recent IAEA document on reactor terminology has gone to some lengths to include all the different types of system for which their designers claim passivity [I.1-5].

The important feature of all these systems, however, is not their degree of passivity but their performance and reliability in carrying out the function for which they were designed. All reactors have to achieve the same standards of safety as a minimum but the passive systems may be able to achieve this standard more easily provided their performance and reliability can be demonstrated. The driving forces of natural convection are generally lower than those of pumped circulation systems and the flow in natural convection does not always follow the path which a first analysis might suggest. Programmes of experimental verification are needed. There are further issues on whether a single natural convection system, relying only on the force of gravity for its operation, would be adequate or if some element of redundancy would still be needed.

(2) Dedicated nuclear heating reactors (NHRs)

The power range of nuclear heating reactors is generally lower than SMR power reactors. They are rated from about 2 to 500 MW(th). Apart from the high temperature reactors, their outlet temperature is aimed mainly at district heating or sea water desalination and does not exceed 130°C. This corresponds to a primary circuit temperature of around 200°C, and a power density ranging from 2 to 60 kW(th)/l.

The smaller size and lower pressure resulting from these requirement leads to simplification of the overall design and allows for the maximum utilization of natural processes. Simplifications have been achieved through a less massive RPV, through integration of the primary circuit in the RPV, and in the safety systems and containment. Further simplifications have been made in the use of natural circulation for normal heat removal (made possible by the large safety margins in the NHR design) and by the use of passive safety systems.

Over a dozen reactor designs are known worldwide, most of which have originated in developing Member States. The economics of these reactors, however, can only be justified in remote regions isolated from a national grid. Only a few of the concepts have been constructed (e.g. AST-500 in Russia, HR5 in China and SLOWPOKE in Canada). As a result there is only little operational experience.

(3) Water cooled and moderated nuclear power plants

It is this area of SMR development to which most attention has been given. Common to most SMR developments is the pursuit of passive safety systems based on the premise that such systems are easier to implement in plants smaller than the current 1000 ~1500 MW(e) units and that they will lead to savings in overall plant cost. The prime objective is to prolong the grace period in case of an accident from the current 30 minutes, which is commonly required by safety authorities, to a period of several days before active measures initiated by operators are required for long-term cooling of the reactor core. Generally, the grace period is directly proportional to the amount of water in the passive cooling systems and inversely proportional to the nominal thermal power. During this time, the decay heat is removed from the core by natural circulation. Heat removal from the core cooling water is accomplished by the emergency heat removal loops which also operate by natural circulation. The ultimate heat sink is either the atmosphere or large water tanks within or outside the containment.

Designers have sought innovation in the areas of:

- Shut-down,
- Residual heat removal,
- Make up water supply,
- Protection against LOCA.

In addition the goal of simplification has been pursued with vigour.

In the PWR field there have been two main approaches; by development of smaller loop type reactors or through the integral reactor route. There are more designs of the integral type (SPWR, MRX, VPBER-600, NHR-200, SIR, SBWR, etc.), but the loop approach (AP-600, AC-600) is more advanced in terms of market readiness. Boiling water reactors are by their very nature of the integral type and some of their traditional features, such as pressure suppression containment systems have been adopted by some of the PWRs.

In the pursuit of more readily demonstrable safety, design objectives have been to increase the design margins and to enhance operating flexibility in comparison with larger reactors. The SMR designs envisage larger specific pressurizer volumes and water inventories above the core (in terms of m^3/MW(th)). Contributions to this end are also expected from the 10 to 60 per cent lower power densities of the SMR cores than those of large reactors.

Simplification

Generally, the term plant simplification means simplification of the arrangement of systems and equipment, of operations, inspections, maintenance and quality assurance requirements, resulting in significant reductions in equipment and bulk material quantities. Significant simplification of the systems throughout the plant as well as an increased application of modularised and prefabricated construction are key design features of the advanced SMR technologies. All new designs lay emphasis on simplification and its benefits. Most designs have sought to reduce the number of components, such as valves or the number of cable runs, by as much as 80% in the most favourable cases. Factory prefabrication of modularised components, including sections of reinforced structures, and ease of decommissioning (small components, cast iron vessels, boron tanks) are further key claims of the SMR technologies. All principal components are to be built in a factory where full quality control and production line techniques can be used. They are completed as modules which are then installed on site.

The use of passive safety systems leads directly to simplification in design since it eliminates the need for multiple redundant safety systems with their redundant safety grade power supplies. A system which relies only on gravity for its operation has no problem about the availability of its power supplies and has a reliability determined only by the integrity of its piping and flow channels.

Traditional control rod drives require a lot of space either above or below the core. There are possibilities to use liquid absorber materials, which do not require the space for rod drives and for in vessel storage when withdrawn. There have also been designs for in vessel mechanical drives (PSR, MRX, HR 200). These eliminate the need to consider control rod ejection which is one of the main, but unlikely, reactivity accident initiators. A more radical solution is in the SPWR design where liquid filled tubes are used instead of control rods.

The elimination of large primary circuit pipes in integral PWRs allows an easing of the containment specification. Pressure suppression systems for PWRs become feasible and several versions have been proposed.

There are very significant developments in instrumentation and control systems allowing simplification and an increase in reliability at the same time. Many proposals use process computers and digital electronics leading to a complete redesign of the architecture of the control system.

(4) Heavy water reactors

Heavy water reactors have demonstrated their safety, reliability and economical viability in several countries. Their neutron economy gives them a wide flexibility in the choice of the fuel cycle paving the way for a better uranium utilization. Natural uranium, slightly enriched uranium, recovered uranium from reprocessing MOX fuel, thorium or spent LWR fuel form options for the fuel cycle of PHWRs. Most of the PHWR designs are of the channel type allowing on power refuelling making the excess reactivity of the core small at all times. The Canadian CANDU design and the Indian PHWR type reactor form the main technology development activities at the commercial level.

(5) Gas cooled reactors

Gas cooled Magnox reactors have been operated in the UK since 1956. They are based on uranium metal fuel rod technology with magnesium alloy cladding and CO_2 as the coolant. This design puts a limitation on maximum outlet temperature and consequently on the efficiency of the plant. The later AGR reactors (also in the SMR range) obtained much higher efficiency through a high gas temperature and stainless steel clad UO_2 fuel rods.

High temperature gas cooled reactors on the other hand are based on ceramic coated particle fuel allowing for high outlet temperature. The basic fuel design utilizes a uranium oxide or carbide particle coated by pyrolytic carbon and silicon carbide able to withstand 800 bar of internal pressure. The stability of this fuel at high temperatures has permitted the design of reactors with a truly passive response to loss of all safety systems, including all gas cooling, provided the overall diameter of the reactor and its vessel is small enough.

(6) Liquid metal reactors (LMRs)

A fast neutron spectrum allows production of more fissile material than that consumed for heat generation. In a fast reactor liquid metal such as sodium is normally used to remove the heat, and it has a minimum effect on the moderation of fission neutrons. Sodium as a coolant has an excellent heat capacity, low operating pressure and natural convection capability.

Sodium coolant has very good thermal conductivity. In the event of failure of the main sodium pumps, heat can be transferred to the vessel boundary by conduction and natural convection without large increases in temperature. Provided the reactor is small enough, decay heat can then be transferred through the vessel wall to a natural convection air flow. Alternatively a small additional heat exchanger in the sodium pool can be used to take heat to an external heat sink by natural convection. Thus the sodium and the small size permit a passive decay heat removal system.

I.1.5. CONCLUDING REMARKS

Small and medium reactor systems provide an attractive option for a wide range of applications worldwide. The design approach and design characteristics of the SMRs with regard to size, economics and safety appear to provide favourable conditions. Specific requirements on these topics will provide a common ground for the suppliers and interested users to further the discussion on specific design requirements such as performance, operability, maintainability, reliability. For successful deployment, overall cost must be competitive with other alternatives, taken into consideration the main objectives.

Among existing reactor designs, the pressurized water reactor of the integral type seems to be well suited for a wide range of low power applications, including seawater desalination. Integral reactors using natural circulation of the primary coolant and utilizing passive safety systems appear to be technically capable of achieving a high degree of safety and reliability.

An important aspect to the introduction of nuclear power in a developing country is a well planned and executed programme on the development of the required infrastructure according to the objectives of the programme.

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