Nuclear Power in the 21st Century: Status & Trends in Advanced Nuclear Technology Development

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Abstract

Global demand for energy is going to keep on increasing, especially in developing countries where per capita energy use is only a small fraction of that in industrialized countries. In this regard nuclear energy could play an important role, as it is an essentially unlimited source of energy. However, the nuclear option faces the challenges of increasingly demanding safety requirements, economic competitiveness and public acceptance. Worldwide, a significant amount of experience has been accumulated during development, licensing, construction, and operation of nuclear power reactors. This experience forms a sound basis for further improvements. Nuclear programs in many countries are addressing the development of advanced reactors, which are intended to have better economics, higher reliability, improved safety, and proliferation-resistant characteristics in order to overcome the current concerns about nuclear power. Advanced reactors, now being developed, could help to meet the demand for power in developed and developing countries, not only for electricity generation, but also for district heating, desalination and for process heat.

This paper reviews the status and trends in advanced nuclear power technology development around the world, discusses the challenges it faces, and summarizes the international approach and technical advances made with examples of new designs of reactors.

1. INTRODUCTION

An examination of the global energy use shows that fossil fuels account for nearly 80%, and nuclear power provides only 7%, of our current energy supply. Additionally, around 83% of nuclear power is produced only in a dozen industrialized countries out of 30 nuclear power producing countries. The demand for an increase of standard of living and population growth in developing countries are asking for a considerable increase of this energy supply. However, many factors come into play in specific countries in providing energy to the people - economics, infrastructure, and government policy being the most important factors. The effect on the environment is another crucial factor whose importance, however, has not yet received adequate attention in the energy mix.

The population of the earth, the prime reason for energy use, is increasing although the birth rate has decelerated since the early 1990s. Present trends suggest that total population may not exceed 8 billion people around 2050 and may start to decline shortly thereafter[1]. This is still a large increase from today's population of 6 billion, and energy for these people must be provided. It is important to note that virtually all of this growth will occur in developing countries. Industrialized country populations have peaked or will do so shortly. Moreover, the greater part of the population increase will be urban. The proportion of people living in rural areas has already peaked and will decline in future. An indication of urbanization is that today there are five mega cities of more than 15 million habitants (Tokyo, Mexico City, Mumbai, Sao Paulo and New York), but in 20 years there will be 15, mostly located in developing countries[1]. In energy terms, already we have nearly 2 billion people without access to a regular electricity supply. Even with lower population projections, the challenge to achieve access to energy for all is clearly substantial. An issue here is that concentration of people requires large sources of energy nearby; this needs to be solved in a way that does not create an environmental problem for the city dwellers.

The environmental issues have received prominence since the 1990s, particularly with respect to greenhouse gas emissions, climate change possibilities and their effect on our living conditions. The Third Assessment Report of the Inter-Governmental Panel on Climate Change (February 2001)[2] presented the strongest evidence yet that climate change is occurring (for example, temperatures have risen in the lowest 8 km of the atmosphere, snow and ice cover have decreased, and the sea level has risen between 0.1 and 0.2 meters in the last century). The report also finds that concentrations of atmospheric greenhouse gases have continued to increase as a result of human activities. However, the nations of the world have not unified in their response to this phenomenon.

Nuclear energy is one way to provide bulk electricity supply without greenhouse gas emissions; it is supported by ample uranium resources worldwide and can be made to last almost forever by using the breeder option. The nuclear industry accumulated 10,000 reactor years of operating experience. But nuclear is not without its problems. The challenges facing nuclear power include (1) continuing to assure the highest level of safe operation of current plants, (2) implementing disposal of high level waste, (3) establishing and convincing the public of a sound basis for nuclear power for sustainable development, (4) achieving further technological advances to assure that future nuclear plants will be economically competitive with fossil alternatives, especially in deregulated and privatized electricity markets, and (5) developing economical and non-proliferating small and medium sized reactors to provide nuclear power to countries with small electricity grids and also for non-electric applications such as seawater desalination.

This paper will discuss the status and trends of advanced nuclear reactors, which could help in the solution of the energy problem of the world and, at the same time, address the issues raised by the nuclear critics.

2. CURRENT STATUS

There are only 30 nuclear electricity-generating countries. Table I below shows the total electricity generating capacity in various countries in the world. Note that only 8 countries have total capacity of more than 100 GWe, and of these two of the largest population countries, China and India, have only a few percentage of nuclear to share. However, China and India currently have solid programs for nuclear power. The important part of the table is that there are many dozens of countries with a total capacity of 2 GWe and less, who need the power most. Because of their grid size, these countries cannot add a large plant of the size of 1GWe; plants for these countries would have to be smaller and more cost-effective (and hence more innovative) than existing large plants.

The worldwide operating experience of power reactors is tremendous. Overall 438 reactors were in operation in 2002. The breakdown of these reactors by types and generating capacity are shown in Table II.

TABLE I. TOTAL ELECTRICITY GENERATING CAPACITY (2002)[3]

Total Capacity (GWe)	Countries	No. of Countries	Nuclear Share (%)
More than 100	USA, Japan, China, Russia, India, Canada, Germany, France	8	1 – 80
50 – 100	UK, Brazil, Spain, ROK, Ukraine, Mexico	6	2 - 39
50 – 100	Italy	1	None
10 – 50	S. Africa, Sweden, Argentina, Romania, Netherlands, Pakistan, Switzerland, Finland, Belgium, Czech Rep., Bulgaria	11	2 – 45
10 – 50	Australia, Austria, Denmark, Egypt, Greece, Iran, Indonesia, Poland, Turkey, Kazakhstan,…	23	None
2 – 9	Hungary, Slovakia, Lithuania, Armenia, Slovenia	5	31 – 65
2 – 9	New Zealand, Croatia[†], Vietnam, Bangladesh, …	38	None
1 – 2	Algeria, Albania, Bolivia, Panama, Ghana, Zimbabwe, Myanmar, Iceland, …	18	None
Less than 1	Many small countries	~ 80	None

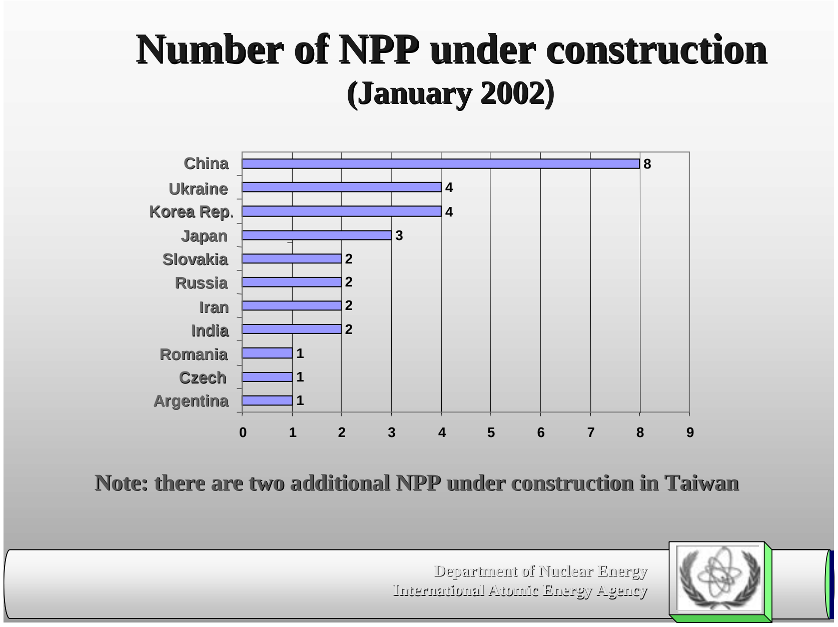
As shown in Figure 1, there are currently 32 nuclear power plants under construction in 12 countries; 8 in China, 4 each in Ukraine and Republic of Korea, 3 in Japan, 2 each in India, Slovakia, Russia, Iran, and Taiwan, China, and 1 each in Romania, Czech Republic and Argentina. China is building six PWRs in the range of 640 to 1000 MWe from Framatome, Russia and their own design, and two 730 MWe PHWRs from Canada. Two 500 MWe PHWRs are under construction in India. India has also announced that four more 220 MWe PHWRs and 2 1000 MWe WWERs and a 500 MWe prototype fast breeder reactor will be under construction soon. In Ukraine Khmelnitski Units 2, 3 and 4 and Rovno Unit 4, all 1000 MWe WWERs, are under construction since 1985 through 1987. Large advanced PWRs and BWRs are being built in Republic of Korea, Japan and Taiwan. Mohovce Units 3 and 4 in Slovakia, WWER 440 plants, are under construction since 1985 and are currently on hold. Atucha Unit 2 in Argentia, 700 MWe Siemens PHWR, is under construction since 1981 but currently on hold. Cernavoda Unit 2, CANDU 700 MWe PHWR, is under construction since 1983. Bushehr Units 1 and 2 in Iran, WWER 1000, are currently replacing the original reactor designs. Temelin Unit 2 in Czech Republic, WWER

[†] Croatia owns 50% of the Krsko 676 MWe Westinghouse PWR plant located in Slovenia.

1000 further modernized by Westinghouse, is currently under startup testing. Figure 2 gives their size breakdown. It is important to note that primarily large size reactors are being built: 22 in the range of 900 – 1350 MWe. Then there are 6 in 600 – 700 MWe range, and 4 between 300- 500 MWe. Thus it is apparent that the utilities will build power plants as large as the grid size will tolerate because that is most economical. However, there is a need for both small and large reactors for flexibility in power management, to suit the grid size and investment capitals, and for remote or special situations such as small localities in Siberia.

TABLE II. REACTOR TYPES AND GENERATING CAPACITY IN THE WORLD AS OF JUNE 2002

	PWR	BWR	HWR	LWGR	WWER	GCR	LMR	TOTAL
No of reactors in operation	208	92	35	17	51	32	3	438
No. of countries	17 Belgium Brazil China France Germany Japan, ROK Netherlands Pakistan S. Africa Slovenia Spain Sweden Switzerland Taiwan UK, USA.	10 Finland, Germany India Japan Mexico Spain Sweden Switzerland Taiwan USA	6 Argentina Canada India, ROK Pakistan Romania	2 Lithuania Russia	8 Armenia Bulgaria Czech R Finland Hungary Russia Slovakia Ukraine	1 UK	3 France Japan Russia	31
Generating capacity, Gwe	198	80	16	13	33	12	1	353
Operating experience of all reactors, Reactor-years	4351	2291	761	469	999	1460	151	10,482

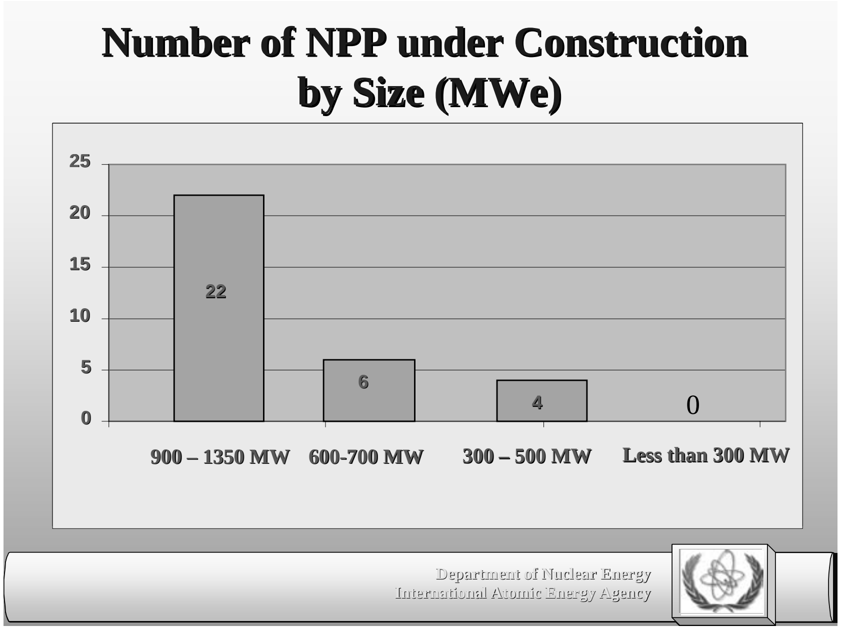


Number of NPP under construction
(January 2002)

Note: there are two additional NPP under construction in Taiwan

Department of Nuclear Energy
International Atomic Energy Agency

Fig. 1 Number of nuclear power plants under construction around the world[4]



Number of NPP under Construction
by Size (MWe)

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Fig. 2 Size breakdowns of nuclear power plants under construction around the world[4]

3. BASIC POWER NUCLEAR REACTOR DESIGNS

The main types of nuclear power reactors are shown in Table III. They are categorized by the material used to moderate the neutrons generated in nuclear fission and the coolants used for the transport of heat.

Pressurized Water Reactor (PWR): Primary water pressurized to about 160 bar act as both the moderator and the coolant. The fuel is up to 5% enriched uranium dioxide in Zircaloy tubes. The primary water heats water in a secondary circuit to produce steam. The reactor is housed in a containment building. The thermal efficiency is about 32%.

Boiling water Reactor (BWR): It is essentially a PWR without the steam generator and the secondary circuit. Water at a pressure of about 70 bar is pumped through the core and, since it is at a lower pressure compared to the PWR, steam is generated in the primary circuit. About 10% of the water is converted to steam and goes to the steam turbine. After condensing it is pressurized and returned to the coolant. The power density of a BWR is about half that of a PWR with lower temperature and pressure, but the efficiency is similar.

CANadian DeUterium Reactor (CANDU): Heavy water is used as both the moderator and the coolant with natural uranium oxide in Zircaloy tubes as the fuel. The fuel tubes pass through a tank of heavy water. Heavy water is pumped through the fuel tubes at about 90 bar pressure and then to a steam generator as in a PWR. The power density is about 1/10th of that of a PWR.

High Temperature Gas-cooled Reactor (HTGR): These are graphite moderated, helium cooled reactors. The fuel is a coated particle to contain the fission products. Water has been used in the secondary circuit to generate steam. Recently a direct cycle (single loop) gas turbine concept has been developed.

Liquid Metal Fast Reactor (LMFR): Liquid metal transports heat very efficiently and only lightly moderates the neutrons from fission. LMFRs consequently need more fissile material to keep the chain reaction going. The core may also contain fertile material to produce new fuel. Since they can breed fuel, they are also known as breeder reactors. Sodium has been used as the most common form of liquid metal for these reactors. Enriched uranium and Plutonium dioxide and metals have been used as fuel. They operate at a much lower pressure compared to the common light water reactors.

TABLE III: CHARACTERISTICS OF NUCLEAR POWER REACTORS RELEVANT TODAY

Reactor type	Fuel	Moderator	Coolant and its pressure in bars (normal atmospheric pressure is about 1 bar)	Steam generation
PWR	uranium dioxide (~ 3.2% U-235)	ordinary water	pressurized ordinary water (160 bars)	separate circuit
CANDU	Natural uranium dioxide (0.7% U-235)	heavy water	Heavy water (90 bars)	separate circuit
BWR	uranium dioxide (2.6% U-235)	ordinary water	pressurized ordinary water which boils and produces steam directly (70 bars)	
HTGR	uranium dioxide in coated particle fuel (approx. 8-19%)	graphite	helium (~ 60 bars)	separate circuit (or direct helium cycle)
LMFR	uranium/plutonium oxide (~ 16-20%), high power density	none	liquid sodium at low pressure (~5 bar)	separate circuit

Other Reactor Types: There are two reactor types developed and built only in the UK, Magnox and AGR, which are still operating. Magnox is a carbon-dioxide cooled (at about 20 bar pressure), graphite moderated reactor. It has natural uranium fuel in a Magnesium alloy cladding. Overall thermal efficiency is about 30%. The AGR, Advanced Gas Cooled Reactor, is a gas-cooled reactor with graphite moderation and carbon-dioxide as the coolant at a pressure of about 40 bar. The fuel is 3% enriched uranium-dioxide and clad in Stainless Steel. Its thermal efficiency is about 40%. It is a unique UK design. Similarly, the Graphite Moderated Boiling Water Reactor (RBMK) is an older Russian design and built only in the former Soviet Union. The RBMK core is an assembly of graphite blocks through which runs the pressure tubes containing the fuel. Water is pumped through these tubes where it boils to steam. The fuel is 2% enriched uranium dioxide in Zircaloy tubes.

An older concept that is receiving new attention is the Molten Salt Reactor (**MSR**), which can generate energy and at the same time considerably burn the long-lived radioactive wastes. It is a circulating, molten salt homogeneous reactor. The fuel is a mixture of fluorides of Li-7, Be, Th, and U-233, U-235 or Pu-239 fissile material. Graphite is used as moderator although some moderation is achieved by the Li, Be and F used in the fuel. Heat is transferred from the fuel leaving the core by an intermediate heat exchanger. Fuel processing is an integral part of the reactor operation. The fuel and the fuel composition can be changed without shutting down the reactor. One 8 MWt Molten Salt Reactor Experiment (MSRE) facility was operated for four years at Oak Ridge, USA, from 1965 – 69.

4. ADVANCED NUCLEAR POWER REACTORS

A lot of work has been done around the world to improve the existing reactor designs. The large base of experience with the current nuclear plants has been used to guide development of the new designs on the basis of User Requirements Documents (URDs) such as the Electric Power Research Institute URD[5] and the European Utility Requirements[6]. Common goals are simplification, larger margins to limit system challenges, longer grace periods for response to emergency situations, high availability, competitive economics and compliance with internationally recognized safety objectives. The new designs are also incorporating features to meet more stringent safety objectives by improving severe accident prevention and mitigation.

Several of these designs have reached a high degree of maturity, and some have been certified by nuclear regulatory authorities. Some are entering a design optimization phase to reduce capital cost. Many of the new design features have been tested to demonstrate technological readiness.

The full spectrum of these advanced nuclear power plants covers different types of reactors with different coolants. They are referred to as evolutionary or innovative designs. An evolutionary design is a design that achieves improvements over existing designs through small to moderate modifications with a strong emphasis on maintaining proven design features to minimize technological risks. It requires at most engineering and confirmatory testing. An innovative design is one, which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practices. They could have new types of coolant, moderator or fuel. Consequently, substantial R&D, and feasibility tests are required, and a prototype or demonstration plant may be necessary to bring the concept to commercial maturity. Figure 3 gives a relative standing of efforts and costs needed for development of advanced reactors[7].

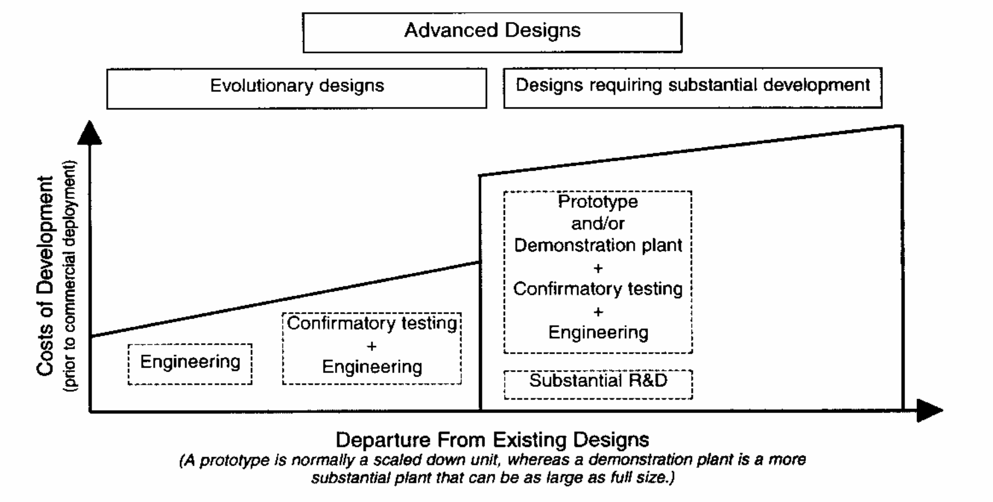


Fig.3 Relative indication of cost of development of advanced reactor designs

For new plants, the basis for achieving high performance is also being laid down during the design phase[8]. These include design for on-line maintenance and short outages. Many other aspects such as better man-machine interface using computers and improved information displays, and better operator qualification and simulator training, which have been applied at current plants, will contribute to high performance of future plants. The advanced designs also desire plant lifetimes of 60 years.

A new terminology is being used for the advanced reactors. Bill Magwood first introduced this from the US Department of Energy[9] and is shown in Table IV, which also describes the evolution of reactor designs. First generation reactors (Generation I) were those introduced early in the prototype stage of nuclear power. Generation II reactors were the commercial PWR, BWR, HWR, and WWER reactors built in the 70s and 80s. Generation III are the evolutionary advanced reactors. These could be divided into two categories: (1) those whose designs have been completed such as AP600/1000, SWR 1000, and the EPR, and (2) those which have been built such as ABWR, System 80+, KSNP. The next generation or Generation IV reactors are those designs that are beyond the current advanced designs and are "revolutionary" in nature. However, no Generation IV reactors have been built or even demonstrated, and so from a utility perspective, we may think of the next generation reactors as those just beyond the near term deployment designs. In other words, those are reactors that still need demonstration or some significant tests before commercial operation.

TABLE IV. EVOLUTION OF NUCLEAR POWER REACTORS

Evolution	Example
Generation I Early 1950s to late 1960s	Early Prototypes . Shippingport . Dresden, Fermi I . Magnox . VK-50, BiNPP
Generation II (1970 – 90)	Commercial power reactors . LWR – PWR & BWR . CANDU . RBMK/WWER
Generation III Improvements of designs started in late 1980s	Evolutionary and Advanced designs . ABWR . APWR . WWER 1000 . AP 600/1000 . GT-MHR, PBMR
Generation IV 21st century	Innovative designs .Molten salt reactors; supercritical water-cooled reactors; lead alloy, sodium and gas-cooled fast reactor systems; and very high temperature reactors.

4.1. Light Water-cooled Advanced Reactors

Worldwide, LWRs (PWRs, BWRs and WWERs) are the major types of nuclear power plants. They represent approximately 88% of today’s global nuclear power capacity, and evolutionary designs, based on this experience base, are being developed in several countries. The major evolutionary LWR designs are shown in Table V.

TABLE V. MAJOR EVOLUTIONARY LWR DESIGNS

Reactor	Power (MWe)	Organization	Status/Significant Features
System 80+ PWR	1350	Westinghouse (formerly ABB Combustion Engineering)	Design certified by US NRC.
APWR	1530	Mitsubishi, Japan Westinghouse, USA	First unit planned at Tsuruga site in Japan.
AP 1000	1000	Westinghouse	Upgraded from AP-600; under licensing review
EPR	1545	Framatome ANP, France/Germany	Design complete; meets European Utility Requirements
WWER	1000 640	Gidropress & Atomenergoproject, Russia	Several planned in Russia, China, India and Iran. Design of WWER 640 with passive safety features is complete and 2 construction sites in Russia have been located.
KSNP	1000	Korea Electric Power Co., Republic of Korea (ROK)	Six operating in ROK and two under construction.
APR-1400	1400	KEPCO and Korean industry, Republic Of Korea	Based on System 80+ design; has received design certification and is expected to be built by 2010.
AC-600/1000	600/1000	NPIC, China	Similar to AP-600/1000 designs; expected in 2010.
ABWR	1360	General Electric, Hitachi-and Toshiba	2 operating and 10 planned in Japan; design based on well- proven active safety systems.
ABWR-II	1700	Japanese utilities and GE-Hitachi-Toshiba	Economy of scale design under consideration
ESBWR	1380	General Electric, USA	Incorporates economy of scale with passive safety, design based on earlier SBWR effort.
SWR-1000	1000	Framatome ANP, Germany	Design complete, based on German utility experience; active and passive safety systems.
BWR 90+	1500	Westinghouse Atom, Sweden	Evolutionary version of earlier ABB Atom designs.

The evolutionary LWR activities in different countries are briefly described in the following[10]:

In the USA, designs for a large sized advanced PWR (the Combustion Engineering System 80+) and a large sized BWR (General Electric's ABWR) were certified by the U.S. NRC in May 1997. Westinghouse's mid-size AP-600 design with passive safety systems was certified in December 1999. Efforts are currently underway by Westinghouse on a 1090 MWe plant called the "AP-1000," applying the passive safety technology developed for the AP-600 with the goal to reduce the capital costs through economies-of-scale. A certification application for the AP-1000 design has been made to the US NRC this year. General Electric is also designing a 1380 MWe ESBWR applying economies-of-scale together with modular passive safety systems. The design draws on technology features from General Electric's ABWR and from their earlier 670 MWe simplified BWR with passive systems.

In France and Germany, Framatome ANP completed the basic design for a 1545 MW(e) European Pressurized Water Reactor (EPR) in 1998, which meets European utility requirements. The EPR design includes the mitigation of core melt and vessel penetration accident scenarios ensuring the avoidance of evacuation of people in the vicinity of the plant. Accidents with molten core material outside the reactor pressure vessel are handled via a spreading concept in the basement of the containment. The EPR's higher power level relative to the latest series of PWRs operating in France (the N4 series) and Germany (the Konvoi series) has been selected to capture economies of scale. Framatome ANP's SWR 1000 is based on German BWR experience with added features to increase safety. It is an advanced BWR with active and passive safety features which allows for extended grace period for accident control and consequences of a core melt accident is limited to the immediate vicinity of the plant. This has been achieved by providing cooling of the reactor pressure vessel exterior. The essential elements of the SWR safety concepts are shown in figure 4.

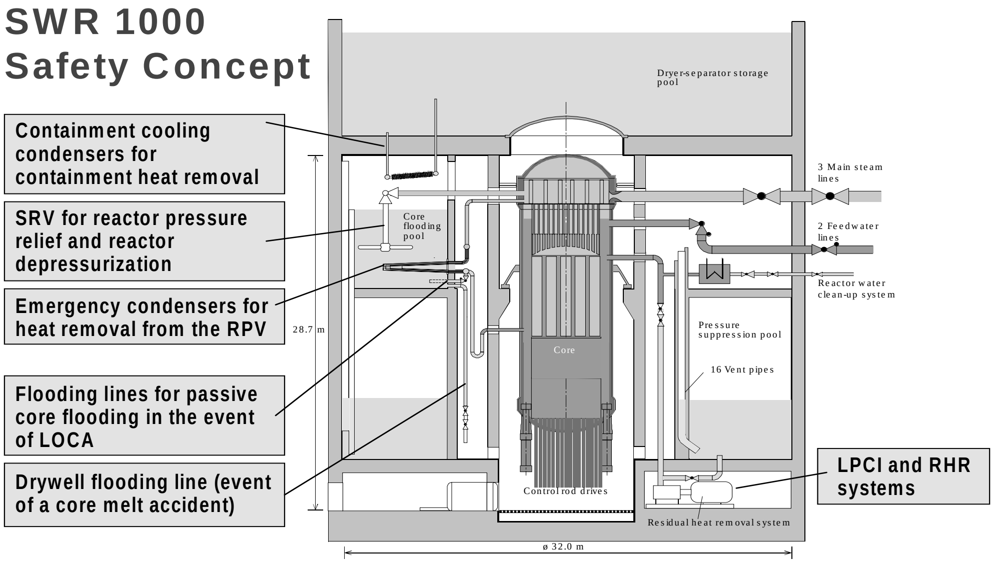


Fig. 4. A schematic drawing of SWR 1000 safety features

In Sweden, Westinghouse Atom is also developing the 1500 MWe BWR 90+, an advanced boiling water reactor with improved safety and operability. This is an upgraded version of the BWR operating in Sweden and Finland.

The first two ABWRs in Japan, the 1360 MWe Kashiwazaki-Kariwa 6 and 7 units, have been in commercial operation since 1996 and 1997, respectively. ABWR plants are under construction at Hamaoka Unit no. 5 and Shika Unit no. 2, and under licensing at Ohma Unit no. 1. Another eight ABWR plants are in the planning stage in Japan. The benefits of standardization and construction in series are being realized with the ABWR units. Expectations are that future ABWRs will achieve a significant reduction in generation cost due to standardization, design improvements and better project management. In addition, a development programme was started in 1991 for 1700 MWe ABWR-II, aiming to further improve and evolve the ABWR, with the goal of significant reduction in power generation cost. Commissioning of the first ABWR-II is foreseen in the late 2010s. Also in Japan, the basic design of a 1530 MWe advanced PWR has been completed by Mitsubishi Heavy Industries and Westinghouse for the Japan Atomic Power Company’s Tsuruga-3 and –4 units.

In the Republic of Korea, the benefits of standardization and construction in series are also being realized with the 1000 MWe Korean Standard Nuclear Plant (KSNP). The first two KSNPs, Ulchin 3 and 4, have been in commercial operation since 1998 and 1999, respectively, and four more units (Yonggwang 5 and 6 and Ulchin 5 and 6) were under construction in 2001, with Yonggwang 5 and 6 scheduled to begin commercial operation in 2002. In addition, ROK is developing the Korean Next Generation Reactor, now named the Advanced Power Reactor 1400 (APR-1400), which is focusing on improving availability and reducing costs. It has received design certification and is expected to be constructed by 2010.

In the Russian Federation, efforts continue on evolutionary versions of the currently operating WWER-1000 (V-320) plants. This includes the WWER-1000 (V-392) design, of which two units are planned at the Novovoronezh site, and WWER-1000 units are also planned in China, India and the Islamic Republic of Iran. Development of a WWER-1500 design has been initiated. Development is also ongoing on a mid-size WWER-640 with passive safety systems, and on an integral design with the steam generator system inside the reactor pressure vessel.

In China, the China National Nuclear Corporation (CNNC) is developing the CNP-1000 plant. China is pursuing self-reliance both in designing the plant to meet Chinese safety requirements, and in fostering local equipment manufacture with the objective of reducing construction and operation costs. Lessons learned from the design, construction and operation of the Qinshan and Daya Bay NPPs are being incorporated. Two ABWRs are under construction in Taiwan.

4.2. Heavy Water Advanced Reactors

Heavy water reactors (HWRs) at the beginning of 2001 represented about 8% by number and 4.7% by capacity of all operating power reactors. With many years of operating experience Canada has developed the 700 MWe CANDU-6, which has been built in several countries outside Canada. India has also built a series of 220 MWe HWRs. Work on evolutionary HWRs is ongoing in Canada, India and Russia and is briefly described below.

The new Canadian evolutionary Heavy Water Reactor[11] is the 935 MWe CANDU-9. Canada is also working on a 400 – 650 MWe Next Generation CANDU. The NG CANDU design features major improvements in economics, inherent safety characteristics and performance. It optimises the design by utilizing SEU fuel to reduce the reactor core size, which minimizes the amount of heavy water required for moderation, and allows light water to be used as the reactor coolant. It is expected that the potential for offsite releases of radioactive material in NG CANDU will be sufficiently low that a target of “no evacuation” can be achieved. In June 2002, Atomic Energy of Canada renamed the NG as Advanced Candu Reactor (ACR) and announced that the ACR-700 will be “market-ready” by 2005.

In India, a continuing process of evolution of HWR design has been carried out. In 2002 construction began on two 500 MWe units at Tarapur which incorporate feedback from several indigenously designed and built 220 MWe units. The Advanced HWR (AHWR), under development in India, is a 235 MW heavy water moderated, boiling light water cooled, vertical pressure tube reactor with its design optimised for utilization of thorium for power generation. The conceptual design and the design feasibility studies for this reactor have been completed and the detailed design is in progress. The design incorporates a number of passive systems and the overall design philosophy includes achievement of simplification to the maximum extent.

A reactor design concept for an 'Ultimate Safe' reactor with 1000 MW output is being developed by the Russian Institute ITEP, in conjunction with other Russian organizations[12]. The prototype for this conceptual design is the KS150 reactor in Bohunice in the Slovak Republic. Low temperature heavy water is used as the moderator, and the design incorporates gaseous coolant, either CO_2 or a mixture of CO_2 and helium, and low fissile content fuel. The entire primary system, including main gas-circulators, steam generators and intermediate heat exchangers are contained within a multi-cavity, pre-stressed concrete pressure vessel. The design is said to be super safe, for example, accidental withdrawal of all control rods will add a relatively small amount of reactivity to the system compensated by the negative reactor power coefficient.

4.3. Gas-cooled Reactors

South Africa, Japan, China and a consortium of US, Russia, France and Japan are developing small gas-cooled reactor designs and technologies. Coated fuel particles are used in these reactors and they retain fission gases even under accident conditions. Modularization, inherent safety characteristics, direct cycle, and high temperature applications have generated renewed interest in High Temperature Gas-cooled Reactors (HTGR). Japan and China have made the most recent progress in the technology development as they have already constructed and are operating two research reactors; South Africa and the above-mentioned consortium are developing innovative power reactor designs with direct cycle gas turbine for power conversion.

China: The 10 MWe helium-cooled, pebble bed reactor (HTR-10) reached criticality in December 2000. It will initially have steam turbine for phase 1 and later helium turbine for phase 2. Preliminary design of the helium turbine is in progress. It will deliver He at 950 C for electricity generation and for heat applications for coal gasification/liquefaction.

Japan: A High Temperature Engineering Test Reactor (HTTR) with prismatic fuel elements has reached full power this year. This 30 MW_{th} reactor will be the first of its kind to be connected to a high temperature process heat utilization system with an outlet temperature of 850 C. The system will operate as a test and irradiation facility, and be utilized to establish the basic technology for advanced HTGR designs for nuclear process heat applications.

Russian Federation: MINATOM, General Atomics, Framatome and Fuji Electric have combined their efforts to develop the Gas Turbine Modular Helium

Reactor (GT-MHR). This plant features a 600 MW(th) helium cooled reactor as the energy source coupled to a closed cycle gas turbine power conversion system. This is under consideration for the purposes of burning weapon grade plutonium and for commercial deployment. The net efficiency of this advanced nuclear power concept is expected to be 47%. Substantial progress in the development of components such as magnetic bearings and fin-plate recuperators makes this type of HTGR plant a feasible alternative for commercial production of electricity.

South Africa: S. Africa is developing a Pebble Bed Modular Reactor (PBMR) based on technology developed in Germany. The design is a single loop direct gas cycle system that utilizes a helium cooled and graphite-moderated nuclear core as a heat source. The coolant gas transfers heat from the core directly to the power conversion system consisting of gas turbo-machinery, a generator, gas coolers and heat exchangers. The reactor has a thermal power of 268 MW with an electrical output of 110 MW. Improvements of the design are underway to increase the electrical output. The inlet and outlet Helium coolant temperatures are approximately 500 ºC and 900 ºC, respectively. The important design feature of PBMR is its tennis ball sized pebbles containing the silicon carbide coated HTGR fuel particles, which is expected to contain all fission products for the PBMR[13] during all accident conditions, and hence requires no separate containment building.

4.4. Liquid Metal-cooled Reactors

There has been renewed interest in recent years in liquid metal cooled reactors particularly for smaller sized designs and from a sustainable development point of view. They are significant because they can breed new fissile material and extend the potential of nuclear energy. Because of their fast neutron spectrum, which can be used as a burner or a breeder, they have also received recent attention for incinerating weapons plutonium, thorium utilization, partitioning and transmutation of actinides and burning nuclear waste. First used in Russian submarines, liquid lead and lead-bismuth have received worldwide attention in the last few years for power reactors and also for accelerator driven transmutation systems. Russia, India, and Japan have remained most active in recent years in liquid metal power reactor development[14]. The Republic of Korea is developing a pool-type sodium-cooled 150 MWe KALIMER plant with metal fuel and a passive safety decay heat removal system.

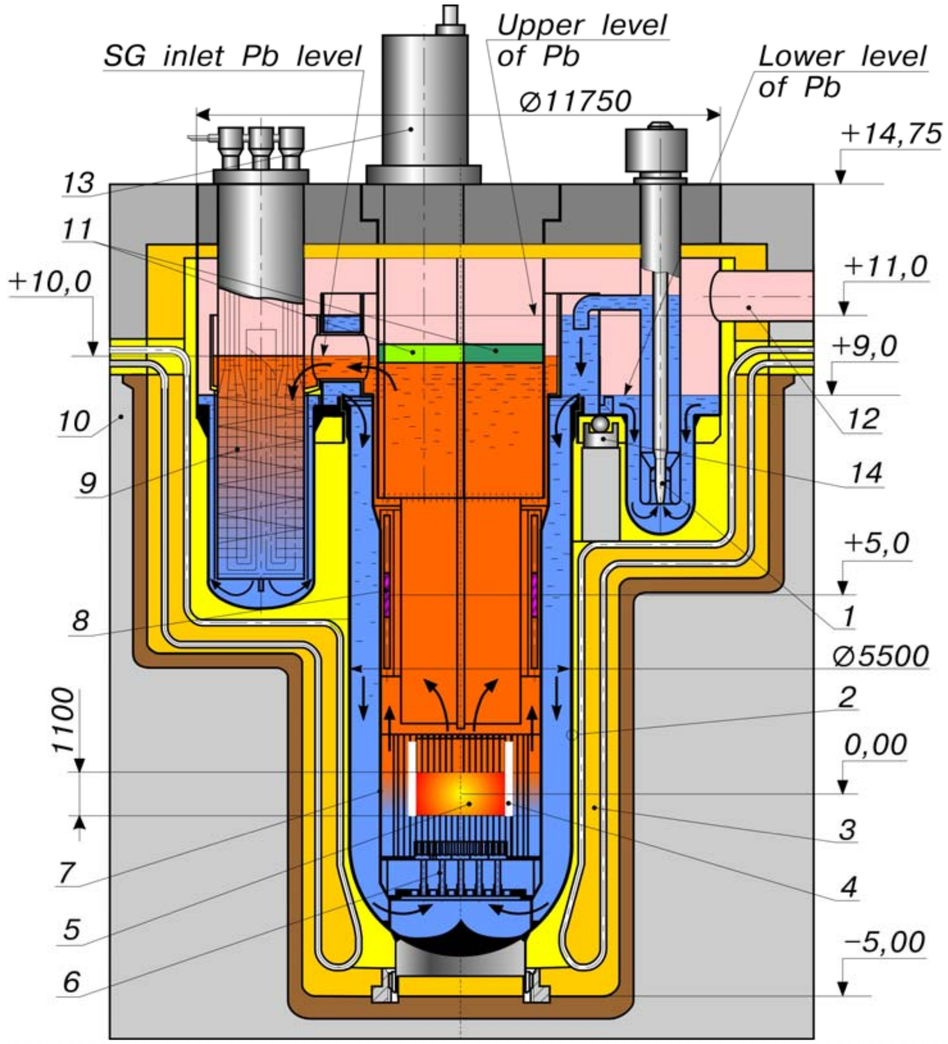
India: India’s sodium-cooled Fast Breeder Test Reactor (FBTR), has been operating in Kalpakkam for several years. It has a unique mixed uranium carbide-plutonium carbide fuel. It was designed for 40 MWt but has only recently reached a power level of 17.4 MWt. It has achieved a fuel burnup of 90 GWd/t. Thorium blankets have been used in the breeder reactor in Kalpakkam. A 500 MWe sodium-cooled pool type Prototype Fast Breeder Reactor (PFBR) design is under development, also for the Kalpakkam site. It will use U-Pu MOX fuel. The Preliminary Safety Analysis Report for this reactor is nearing completion.

Japan: The two sodium-cooled fast reactors, the Experimental Fast Reactor "Joyo" and the prototype fast breeder reactor "Monju" are not operating at this time. Joyo will start operation in 2003 with a new high-flux core, and Monju is waiting for governmental approval for improvement work for sodium leaks, leading to its eventual startup in 3 more years. However, several small and medium size designs are being developed in Japan, the most prominent one being the 50 – 100 MWe sodium-cooled fast reactor design known as Super Safe, Small and Simple (4S)[15]. In this reactor, Burnup of the core is controlled by the annular reflector surrounding the core, and a long life is achieved by the long length of the core and upward movement of the reflector. The Modular Double Pool (MDP) is another concept of 325 MWe sodium-cooled fast reactor, which has steam generator and secondary pumps in the sodium filled annular space between the primary and the secondary vessel thereby reducing the secondary piping system. Metallic fuel is used for both of these two designs. MDP has been designed to reduce the construction cost and improve reliability by factory manufacture of most components, and 4S has been designed to obtain a long life core. A concept of Multipurpose Fast Reactor (MPFR) has also been proposed which has liquid plutonium-Uranium metallic fueled core. It has 300MW thermal power and does not require fuel reloading[16].

A Pb-Bi cooled Long-life, Safe, Simple, Small, Portable, proliferation-resistant reactor (LSPR)[17] has also been proposed. This is a 35 MWe (150 MWt) integral type design where the steam generators are installed within the reactor vessel. Nitride fuel is used. Natural or depleted Uranium fuel assemblies are placed at the center of the core and Pu fuel assemblies at the outside. In this composition, the burnup will progress from the outer core into the inner blanket region.

Russian Federation: Russia's experience in the construction and operation of sodium-cooled experimental and prototype fast reactors (the BR-10, BOR-60, BN-350 in Kazakhstan and BN-600 with hybrid core) has been very good. Efforts have been directed towards further improving safety and reliability, and making the Liquid Metal Fast Reactors (LMFRs) economically competitive to other energy sources. While these efforts would take some time, LMFRs are being considered to burn weapons plutonium and minor actinides. The current main efforts in sodium cooled fast reactors in Russia have been the lifetime extension for BOR-60 and BN-600, decommissioning of BR-10 and designing BN-800. By 2010, Russia wants to complete construction of the BN-800 fast reactor at Beloyarsk. Russia has also developed three small sodium-cooled reactor designs: MBRU-1.5, MBRU-12 and BMN-170 for production of 1.5, 12 and 170 MWe of electricity[18].

The design from Russia that has received the most recent attention is the BREST reactor, which uses lead coolant, uranium-plutonium mono-nitride fuel and indirect cycle for heat removal to a supercritical steam turbine. Owing to unique combination of the thermo-physical properties of the lead coolant and mono-nitride fuel, BREST can boast of a very high level of natural safety. Two conceptual designs have been developed for the 300 MWe and 1200 MWe BREST reactors. Figure 5



1 — pump
2 — reactor vessel
3 — termal protection
4 — CPS
5 — core
6 — support pillars
7 — dividing barrel with a support
8 — in-pile FA storage
9 — steam generator
10 — concrete vault
11 — rotating plugs
12 — emergency to throw of steam
13 — transfer machines
14 — vessel support

Fig. 5. BREST-300 reactor. Vertical section

gives the schematic details of the 300 MWe BREST design. Russian fast reactor R&D activities are concentrating on advanced concepts with enhanced safety features and designs with alternative coolants, as well as on the development of the basic design, and experimental confirmation, of the lead cooled BREST-300 demonstration reactor with on-site closed fuel cycle[19].

Studies of small fast spectrum reactor modules cooled by lead-bismuth eutectic are also being pursued. These designs, called SVBR-75/100, are based on the reactor operation experience with nuclear submarines. The designs could be used for electricity production, seawater desalination, or the utilization and transmutation of actinides. The SVBR-75 is a Pb-Bi cooled 75 MWe (268 MWt) fast reactor with two-circuits, the primary Pb-Bi circuit and the steam-water secondary loop[20]. Two other heat removal systems are provided for both scheduled and emergency cooling. The reactor operates for 8 years without refueling. Average fuel enrichment is 15.6%.

USA: Although the U.S. had a strong sodium cooled reactor program for many years, it has essentially halted. Recently, however, because of impetus in research for new generation of reactors, one innovative liquid metal cooled design called the Encapsulated Nuclear Heat Source (ENHS) has been proposed[21]. The ENHS is a Pb-Bi natural circulation cooled, 50 MWe (125 MWt), modular, fast reactor concept. It is designed that the fuel is installed sealed into the reactor module at the factory and transported to the site to be inserted into a secondary pool of Pb-Bi that contains the steam generators. Major components, such as the pool vessel and steam generators, are permanent and remain at the site while the reactor module is replaced every 15 or 20 years. The heat generated in the core is transferred through the primary coolant vessel wall to the secondary pool. The natural circulation avoids the need for active components but it requires a tall 19m primary vessel. A design with a lift pump reduces the height to 10m and reduces the coolant mass. The fuel considered is metallic Pu-U-Zr fuel with 11-12% of Pu. The peak fuel Burnup is approximately 105,000 MWD/t. The autonomous control and no fuel handling reduce the nuclear operations onsite to a minimum. Figure 6 gives a schematic description of ENHS.

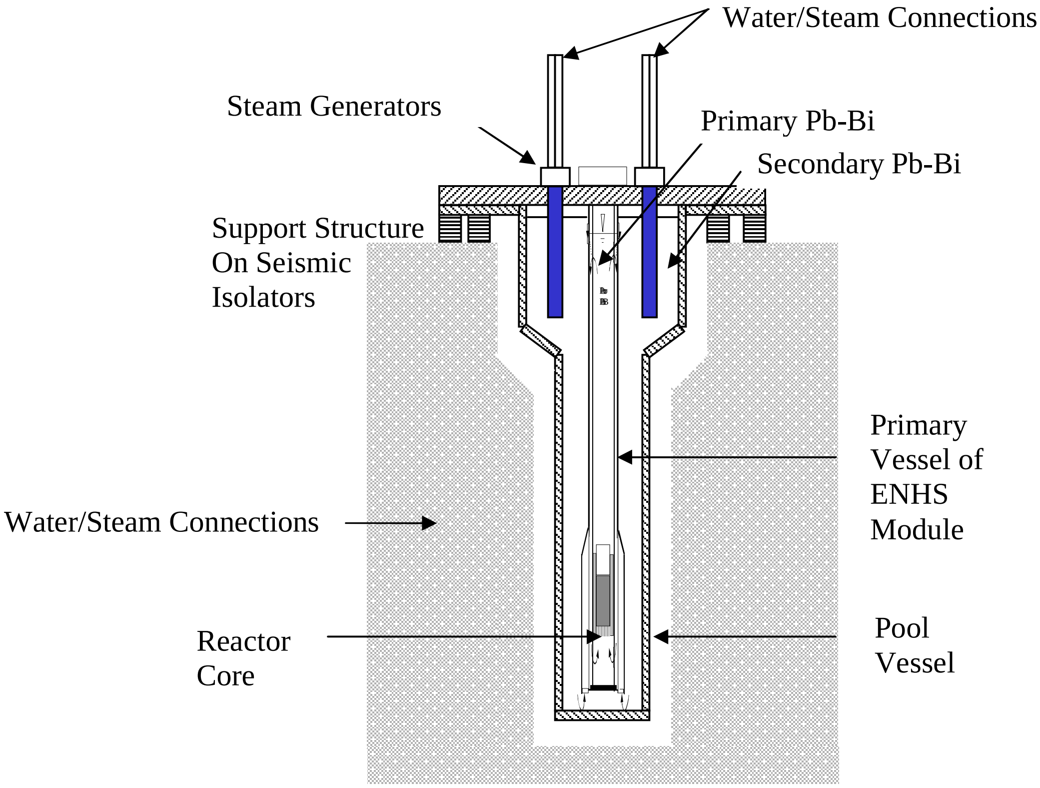


Fig. 6. A Schematic Vertical View of a Single ENHS (Not to Scale)

4.5. Molten Salt Reactors (MSR)

No molten salt reactor is operating now but a considerable interest has been generated among several investigators in the US, Japan and Russia for this concept. This is primarily due to the good operating record of the MSRE in Oak Ridge and to find innovative ways to (1) eliminate fissile material from dismantled nuclear weapons, (2) burn actinides and help in the solution of the nuclear high level waste problem, (3) utilize its inherent safety features, (4) flexibility of using any fissile fuel in continuous mode, (5) higher thermal efficiency from higher temperature operation, and (6) improve non-proliferation. Two types of designs are being pursued: one with fuel mixed with the molten salt coolant (Fig. 7) and the other where molten salt is used only as a coolant (Fig. 8). In the latter case prismatic or pebble bed type HTGR fuel has been advocated. Table VI describes[22] the list of currently known MSRs.

TABLE VI. SOME MSR DESIGNS

Country	Design	Power (MWt)	Primary circuit		Secondary Circuit	Status
			Coolant & Structure	Inlet/Outlet Temp C		
USA	Aircraft Reactor Experiment (ARE)	2.5	NaF ZrF_4UF_4 Inconel	655/800	Helium	Operated in 1954 at ~750 C
USA	Molten Salt Reactor Experiment (MSRE)	8.0	$LiFBeF_2$ ZrF_4UF_4 Hastalloy-NM	632/654	$LiFBeF_2$ Hastalloy-N	Operated during 1965-69
USA	Molten Salt Breeder Reactor (MSBR)	2250	$LiFBeF_2$ ThF_4UF_4 Hastalloy-NM	566/705	$NaFNaBF_4$ Hastalloy- NM	Th-233 U fuel cycle. Design effort discontinued in 1976
Japan	Fuji-II[23]	350	$LiFBeF_2$ ThF_4UF_4 Hastalloy-NM	566/705	$NaFNaBF_4$ Hastalloy- NM	Conceptual design
Russian Federation	High Temperature Molten Salt Reactor (MARS)	300	$LiFBeF_2$	600/750	Air	Conceptual Design
Russian Federation	Gas-cooled Molten Salt Reactor	2000	$LiFBeF_2$ ThF_4UF_4	600/750	$NaFNaBF_4$	Designed especially for industrial applications
France	CCDP	2000	$LiFBeF_2$ ThF_4UF_4	550/700	Plumbum	Conceptual Design
China	MSGR	2250	$NaFBeF_2$ Hastalloy-NM	566/705	$NaFNaBF_4$	Conceptual design

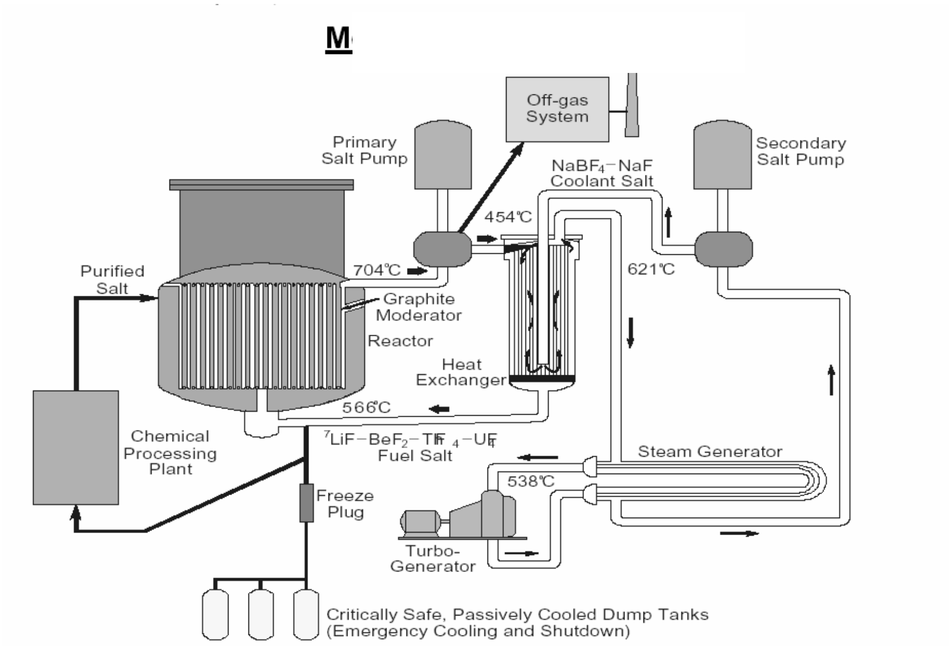


Fig. 7. Schematic diagram of a molten salt reactor such as the MSRE[21]

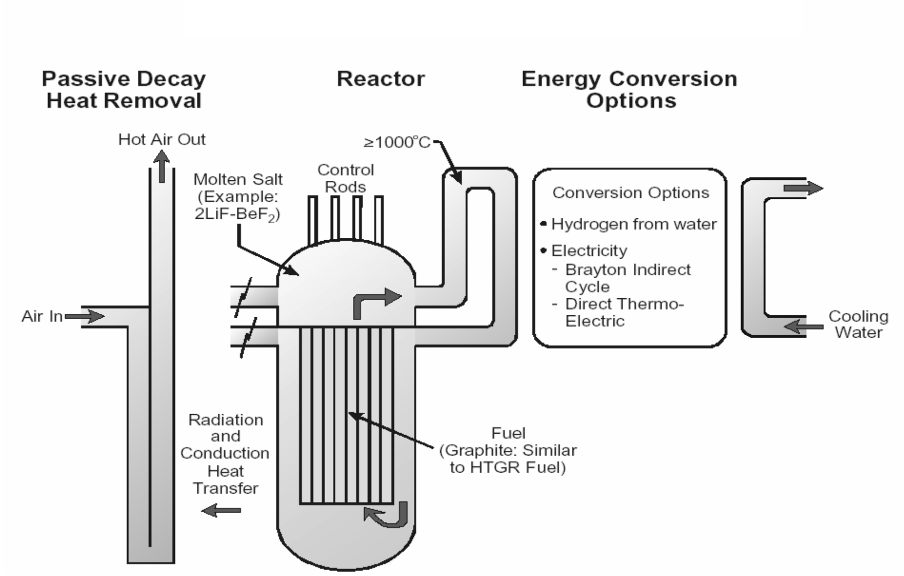


Fig. 8. Schematic diagram of a molten salt cooled reactor such as MARS[24]

4.6. Small and Medium Sized Reactors

Although a considerable progress has been made in the evolutionary designs of LWRs, these are large reactors and many believe[25] that development and demonstration of new, smaller, innovative designs with short construction and start-up times and low capital costs are necessary to usher a new era of nuclear power. Since the early 1990s, the interest of developing countries, mainly in Asia, has resulted in increased efforts on the design of small and medium sized power reactors. This is because in the next 50 years, electric demand is expected to be tripled, most of which will come from developing countries with small grid capacities. Also, in industrialized countries, electricity market deregulation is calling for power generation flexibility that smaller reactors may offer. Small and medium reactors (SMRs) are also of particular interest for non-electric applications such as seawater desalination and district heating, fuel synthesis, and, in the future, hydrogen production.

Small and medium sized reactors are, however, not new. We have currently 150 SMRs operational in the world, 41 of these with power levels less than 300 MWe and 109 having power levels between 300 and 700 MWe. The detailed breakdown show 32 gas cooled reactors in UK (AGR and GCR), 32 PWR, 24 BWR, 29 WWER and 27 HWRs.

Recent major drive for innovation in light water reactors has been toward integral reactors, where the core, pumps, pressurizers, and steam generators are contained inside a single reactor pressure vessel (RPV). They are of enhanced safety because there is no large break LOCA; they also endure less fluence on the reactor pressure vessel and employ passive safety systems. Three primary examples of these reactors are CAREM (Argentina), IRIS (USA), and SMART (Republic of Korea). Being small, they allow more shop-fabrication and hence improved quality. These are being designed primarily for sizes up to 700 MWe due to easy constructability of Reactor Pressure Vessels and to better match smaller electric grids.

SMR designs are also attempting to increase the fuel core life to enhance proliferation-resistant features and also to reduce the O&M costs. Eight to even 20 years of single core life has been envisioned. Another idea in this regard is to have refueling services provided by a central refueling organization, with crew dedicated to refueling, visiting each site as required. This would also improve efficiency. Similarly, barge mounted reactors could be returned to a central location for refueling.

Some designs have proposed to make extensive use of modularization, in which a significant portion of the plant is built as modules, which are fabricated outside of the principal buildings of the nuclear power plant. In some cases, the modules are fabricated off-site, to take advantage of existing fabrication facilities. Modularization serves to transfer a significant portion of the construction labor from the nuclear power plant to more easily controlled manufacturing environment. This reduces the site construction infrastructure and shortens the construction schedule, and hence the capital cost.

In order to improve economics, small reactor designs strive to minimize the manpower costs associated with the operation of the reactors. The inherent reactor shutdown and passive decay heat removal capability of some designs, in combination with modern advanced communication systems, may even facilitate remote operation with fewer operators, or even unattended, for some applications.

New research is underway to utilize the unique thermo-physical properties of supercritical water to enhance nuclear plant thermal efficiency to 40 – 45% from the current 33 –34%. This will also lead to considerable plant simplification. Because there will be no change of phase in the core, the need for steam separators and dryers as well as for BWR-type recirculation pumps is eliminated, which will lead to smaller reactor vessels. In a direct cycle steam generators are not needed. However, to make this possible, advances are required in high temperature materials to improve corrosion, stress corrosion cracking, and wear resistance.

Major innovative reactors in the world[26] are tabulated in Table VII. Key features of SMRs include simplification and streamlining of designs as well as emphasis placed on safety features avoiding off-site impacts in case of accident. Such characteristics should facilitate their acceptability by local communities. However, none of these reactors have been built; only recently announcements have been made for beginning the preparatory phase for construction of KLT-40 in Severodvinsk in Russia and of a 65 MWt pilot version of SMART in KAERI, Republic of Korea. Two KLT-40 nuclear submarine reactors will be built on a floating barge with a displacement capacity of 20,000 tonnes. It is expected that the floating nuclear plant in Russia will produce power in 2006 and the pilot plant in Korea in 2008.

TABLE VII. MAJOR INNOVATIVE REACTOR DESIGNS UNDER DEVELOPMENT AROUND THE WORLD

Reactor	Power (MWe)	Country of origin	Status/imp. features
A. Light Water Reactors			
IRIS	100 – 300	USA-led multinational	Integral, 8-year core; under design.
Triga Power System	64	USA, General Atomic	Commercial design
CAREM-25	27	Argentina	Integral, self-pressurized; Regulatory approval received.
SMART	300 MWt	Republic of Korea	Integral. 65 MWt pilot plant to be built.
KLT-40	35	Russian Federation	Floating NPP, ready for construction
UNITHERM	15 MWt	Russian Federation	Based on marine reactor; 20 years core life, dual purpose.
RUTA-55	55 MWt	Russian Federation	Low-temp, Pool type at atm. pressure
VK-300	250	Russian Federation	Based 0n VK-50 BWR. Dual use possible.
ABV-6	6	Russian Federation	Compact, based on marine reactor; land or sea use.
ATU-2	40	Russian Federation	Water-graphite reactor.
MRX-based designs	Various	Japan	Integral; 8 year core life for PSRD. Some for heat only.
IMR	<300	Mitsubishi, Japan	Integral PWR
HABWR	600	Hitachi, Japan	Forced circulation BWR
HSBWR	300 – 600	Hitachi, Japan	Natural Circulation BWR
SSBWR	150	Hitachi, Japan	Small BWR with natural circulation
LSBWR	100 – 300	Toshiba, Japan	Long life core.
NHR-200	200 MWt	China	Upgrade from NHR-5; designed for non-electric.
B. Other Reactors			
PBMR	110	ESKOM, S. Africa	Pebble Bed Gas-cooled Reactor
GT-MHR	286	US, Japan, France, Russia	Gas-cooled prismatic reactor with direct gas turbine
4S	50 –100	Japan	Sodium-cooled fast reactor
Brest	300	Russian Federation	Lead-cooled, mono nitride fuel.
ENHS	50	USA	Lead-Bismuth-cooled, modular fast reactor.

5. UTILIZATION OF THORIUM FUEL

There has been a recent renewed interest in thorium fuel cycles. The reasons for this are to (1) burn excess weapons Pu without creating more, (2) generate less long-lived radioactive waste, (3) design reactors to operate in a safer mode, (4) reduce U-235 enrichment, (5) go to higher temperatures, and finally having large thorium deposits.

Thorium-232 is three times more abundant than uranium and available in India, Brazil, USA, Turkey and China. It is not a fissile material but it can produce U-233 in a reactor, which, from a neutronic standpoint, is an excellent nuclear fuel among the three nuclear fuels – U-235, Pu-239 and U-233. It also produces much less minor actinides from fission. Thorium dioxide is the only stable oxide of thorium, which accounts for its greater stability compared to uranium dioxide. It is also much more resistant to chemical interactions and has a high thermal conductivity. The melting point of thorium dioxide is 3050 degree centigrade. Thorium contains naturally up to about 100 ppm of Th-230; this and other neutron reactions of Th-232 and U-233 produces U-232, which decays with emission of hard gamma rays. Thorium fuel fabrication is similar to U-fuel but it requires remote operation because of the gamma emission from U-232 decay chains. In addition high chemical inertness of thorium dioxide makes it very difficult to be dissolved and reprocessed. Because of these drawbacks the thorium fuel cycle is considered a more proliferation-resistant fuel.

Thorium fuel cycles have been studied in the past in several countries on a smaller scale but its importance has increased in recent years as a non-proliferating fuel and also for reducing the inventory of Pu. Germany had used Thorium fuels for several years on the AVR, a pebble-bed high temperature research reactor, and on the THTR, Thorium High Temerature Reactor. Both in Germany and the US the fuel fabrication technology has been developed under high temperature reactor programs to a well proven, industrial process. The coated fuel particles for the HTGRs have shown excellent performance under irradiation and reactor operation. In Russia also tests of thorium-based fuels for WWER and LMFBRs have shown an excellent irradiation behavior.

The US has shown new interest in thorium fuel and has initiated four projects under the Nuclear Energy Research Initiative. Their primary motive is to develop an advanced proliferation-resistant, low cost uranium-thorium dioxide fuel. The Radkowski Thorium Reactor (RTR), being investigated in the US, Russia and Israel, revives the seed-blanket concept of the US Light Water Breeder Reactor design that operated in Shippingport in the late 50s. The concept assumes a once-through fuel cycle with no reprocessing; U-233 is bred and mostly burned in the reactor.

Most prominently, India has been pursuing a strong program on thorium fuel cycle activities. India has a closed fuel cycle strategy, which calls for using U-Pu fuel cycle for fast breeder reactors and a closed Th-U-233 fuel cycle in the next stage with advanced heavy water reactors. The Advanced Heavy Water Reactor (AHWR), currently under design, plans to use thorium for 75% of the power. Utilization of thorium is their focal point for development. All aspects of the fuel cycle including the back end are being studied in India. Activities for Thorium fuel development in India include studying: (1) dissolution of irradiated thorium fuel, (2) effective utilization of recovered fissile and fertile material, and (3) thorium fuel fabrication.

6. PARTITIONING AND TRANSMUTATION OF RADIOACTIVE WASTE

A lot of attention has been given in recent years on the subject of partitioning and transmutation of the actinides and some long-lived fission products contained in the spent fuel as it has the potential of easing operational and safety requirements of a repository. Some would even like this to become an important alternative to direct disposal of spent fuel. Separation of the long-lived isotopes and transmutation of these into less hazardous materials have several advantages. It allows a reduction of the volume, toxicity, and fissile content of waste and supports a simpler repository. The issues related to long-term disposal of spent nuclear fuel is attributable to only ~1% of its content, namely plutonium, neptunium, americium, and curium (the transuranic elements) and long-lived isotopes of iodine and technetium. When transuranics are removed, the toxic nature of the spent fuel drops below that of natural uranium ore within a period of several hundred years. The removal of neptunium, technetium, and iodine also makes the waste safer for the biosphere. Removal of plutonium eliminates the relevance of the waste from the point of view of nuclear proliferation. Thus if the nuclear waste can be partitioned and transmuted economically to more benign materials, the waste can be disposed of in controlled environments having time scales of a few centuries rather than millenniums.

Partitioning and transmutation requires advanced reactor and fuel cycle technologies, including multiple recycle strategies. That is the spent fuel must be reprocessed. Partitioning of waste can be accomplished by both aqueous and non-aqueous methods. The Argonne National laboratory in the US has developed an electrometallurgical non-aqueous process that can separate fissile material from fission products. This process can be used for both metallic and oxide fuels. For transmutation, both accelerator driven systems (ADS) and fast reactors are being considered for actinide burning. The ADS has the potential of providing both plutonium and minor actinide utilization, and enhanced safety of sub-critical operation. It has been recognized that a pure accelerator driven system for transmutation of waste is too costly, and hence a dual concept of power production and transmutation is being envisioned. This option combines the accelerator and fission reactor technologies; neutrons are generated by directing a beam of high-energy protons from an accelerator against a heavy target such as lead or lead-bismuth eutectic and these neutrons are then used in a surrounding blanket to fission the actinides and transmute the long-lived fission products. Unlike a conventional reactor the blanket is sub-critical and cannot sustain a chain reaction without the accelerator generated neutrons. Power is generated from this sub-critical facility while transmuting the waste.

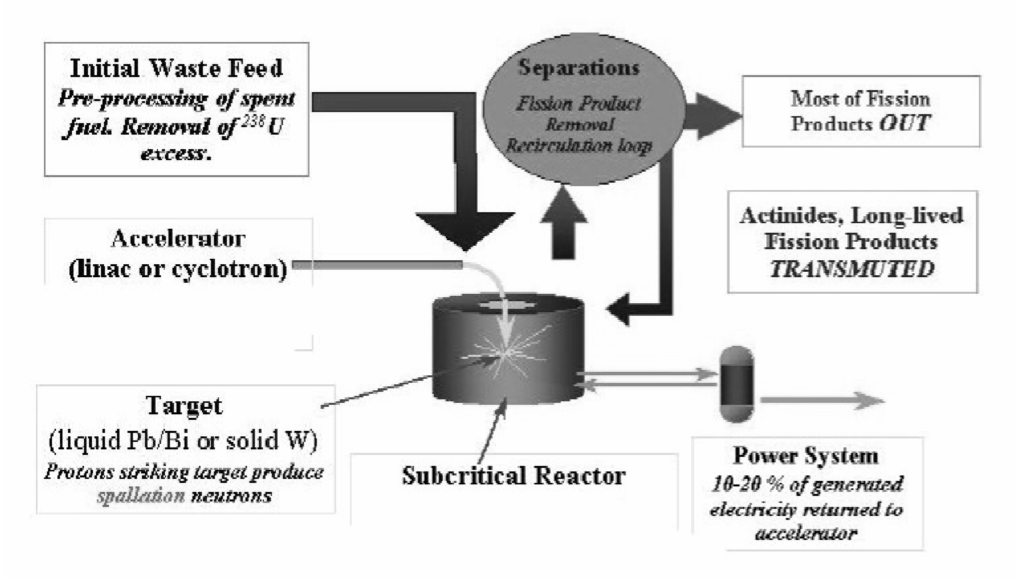


Fig. 9. A schematic diagram of an Accelerator Driven System to incinerate waste and produce electricity.[27]

Various ADS schemes are being studied in several countries: the OMEGA (Option Making Extra Gain from Actinides) project in Japan, Advanced Accelerator Applications (AAA) program in the US, HYPER (Hybrid Power Extraction Reactor) project in the Republic of Korea, European Industrial Partnership and other projects at CERN, and CEA, France, and China. Russia is also participating in international collaboration activities. Carlo Rubbia’s “Energy Amplifier” is one ADS design that provided a strong, early impetus in developing a system to generate more energy than needed for the accelerator.

There are many technical problems to be solved; ADS is only at the beginning stage of investigation. It is very likely that the best results in terms of high level waste radio-toxicity reduction will be achieved by symbiotic systems, including critical fast reactors and hybrid systems (e.g., accelerator driven concepts).

7. CURRENT ISSUES

Although fuel diversity and energy security are important items for a country, economic competitiveness with alternate sources of electricity has been recognized as the critical element for the survival of nuclear power. Hence consorted efforts are being made with design, construction, operation and maintenance of new nuclear power plants to reduce its capital and operation costs. Currently nuclear production costs (fuel and O&M) of existing plants are low, approaching 1 cent/KW-hr; hence the critical issue is capital cost for new plants. Also, investors expect a short-term payback of capital costs such as within 20 years of operation. It appears that capital costs in the range of $1000 – 1200 per KWe are needed for competition with natural gas. In this regard, construction of large nuclear power plants, if allowed by the infrastructure of a country, provides an advantage. At the same time, new generation of small, innovative plants are needed for specific markets and especially for developing countries.

Non-proliferation and physical protection have become more important for nuclear power plants since the September 11, 2001 terrorist event in New York. In spite of the demonstrated effectiveness of the international safeguards regime, the risk of proliferation of nuclear weapons remains a social and political concern. A significant deployment of nuclear power would lead to building a large number of reactors in many different countries and sites, and there may not be sufficient resources to safeguard all reactors. Therefore, gaining acceptance will require specific efforts of designers to enhance the proliferation resistance characteristics, particularly for the SMRs. It has also been argued that since no country has made nuclear weapons from the civilian nuclear power program and we surely have the international, scientific and regulatory mechanisms to handle the proliferation question, we should move forward as rapidly as possible to build nuclear power where it can meet human and environmental needs. In any case, the world must remain vigilant and the suppliers, verifiers, and buyers must assure safeguarding of nuclear materials.

The September 11, 2001 event has highlighted the importance of protecting nuclear facilities from sabotage and stealing of nuclear material by terrorist organizations. Even if the actual impact of a potential terrorist activity is very minimal, the occurrence of such an event will create havoc from the public perception point of view; hence nuclear facilities including spent fuel storage facilities must be secured. An issue here is how to achieve this in a cost-effective manner and how much security effort is good enough.

Disposition of spent fuel is a challenge and a roadblock for nuclear power. However, great progress has been made this year when the governments of Finland and USA have approved the construction of geologic repositories in Olkiluoto in Eurajoki, Finland and at Yucca Mountain, Utah, USA. Finland is now set to become the first country in the world to build a final repository for spent fuel from nuclear power plants. Sweden and the US are also well ahead with similar plans.

8. INTERNATIONAL EFFORTS

Several countries and groups are working on innovative reactor technology development. However, to develop a cost-effective innovative reactor design a large amount of research is required, particularly for the design and testing of new fuel and other materials and the final demonstration. In the deregulated market no one company or even a country can afford to or willing to allocate the expenses necessary to bring a design to the market place. Hence international development and partnership may be required. From this perspective two efforts are already underway – the US-initiated Generation IV International Forum (GIF) and the IAEA-initiated International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO).

The time frame of interest to the GIF is two or three decades from now, and their goal is development of suitable technology for nuclear power (reliable and safe, sustainable, and economic). They also want to increase the assurance that the reactor system is a very unattractive and undesirable route for diversion or theft of weapons-usable materials. The US DOE has conducted wide-ranging discussions on the development of next-generation nuclear energy systems, engaging governments, industry and the research community of several countries. Ten countries have joined in this effort; they are Argentina, Brazil, Canada, France, Japan, Republic of Korea, South Africa, Switzerland, UK and the US. After long deliberations, the GIF has selected six areas for further research and collaboration among interested countries. These are gas-cooled fast reactor, molten salt reactor, liquid sodium metal-cooled reactor, lead alloy-cooled reactor, supercritical water-cooled reactor and very high temperature reactor systems.

The objective of INPRO is to support the safe, sustainable, economic and proliferation-resistant use of nuclear technology to meet the global energy needs of the 21st century. INPRO is mainly focusing on developing user's requirements for nuclear power for the long term – fifty years time frame. As of January 2002, there were 13 members in INPRO: Argentina, Brazil, Canada, China, Germany, India, Republic of Korea, Russian Federation, Spain, Switzerland, The Netherlands, Turkey and the European Commission. The INPRO is developing a report to identify global user requirements for economics, safety, spent fuel and waste, non-proliferation and the environment, and establishing the criteria and methodologies for examination of nuclear reactor and fuel cycle technologies. The INPRO developed criteria are expected to be used by individual countries to assess their situation with respect to nuclear power introduction or expansion.

Conclusion

The global energy market is rapidly increasing and is expected to triple in about 50 years. Nuclear energy is free from greenhouse gas emissions and is excellent from an environmental perspective. In a closed cycle mode of operation, nuclear energy is almost an infinite source of energy; it could help improve the standard of living of all countries in the world. So nuclear power should expand, especially in developing countries, and could contribute to sustainable energy development for the world. With this in mind, many evolutionary designs of nuclear power plants have been developed to meet the high performance and the safety goals. The efficiency and economics of these new plants are excellent and are beginning to compete with other base load alternatives. These larger plants are currently being constructed in Japan, Republic of Korea and Taiwan, China. New small and medium sized designs are underway. They are of interest to many countries for many reasons. Due to population growth and demand for a higher standard of living, they are of primary importance to countries with a shortage of electric power and low grid capacity. Work is progressing on several innovative reactor and fuel cycle designs in several countries. However, these innovative, smaller reactor designs must be demonstrated in the near future because the time frame for the availability of commercial SMRs is very important as most developing countries can not wait for another two or three decades to increase their installed electricity generation capacities.

Many challenges remain for nuclear power to become an acceptable source of energy throughout the world. Notable among these are (1) implementing the disposal of high level waste, (2) making nuclear generated power economically competitive with fossil fuel alternatives in the deregulated market place, (3) continuing to assure non-proliferation and physical safety of nuclear plants, (4) developing economic reactors for small electricity grids and non-electric applications, and finally (5) continuing to assure the safety of nuclear reactors. The new evolutionary and innovative designs are responding to these challenges. Let us hope that the new surge of interest in nuclear power and the new activities that have been initiated in several countries will lead to a solution of the nuclear issues and provide adequate energy for all humanity.

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