Annex I
OVERVIEW OF GLOBAL DEVELOPMENT OF ADVANCED NUCLEAR POWER PLANTS

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I–1. INTRODUCTION

To assure that nuclear power remains a viable option in meeting energy demands in the near and medium terms, new reactor designs are being developed in a number of countries. Common goals for these new designs are high availability, user-friendly features, competitive economics and compliance with internationally recognized safety objectives. Development of advanced designs is proceeding for all reactor lines - water-cooled reactors, gas-cooled reactors, and liquid metal cooled reactors. Global trends in advanced reactor designs and technology development are periodically summarized in status reports prepared by the IAEA.

Worldwide, considerable efforts are being made to develop advanced nuclear power. Various organizations are involved, including governments, industries, utilities, universities, national laboratories, and research institutes. Expenditures for development of new designs, technology improvements, and the related research for the major reactor types combined is estimated to exceed US $2 billion per year.

I–2. OVERVIEW OF WATER-COOLED REACTOR DEVELOPMENT PROGRAMMES

Worldwide there is considerable experience in light water reactor (LWR) and heavy water reactor (HWR) technology. LWRs include pressurized water reactors (PWRs), boiling water reactors (BWRs) and the Russian type pressurized water reactors (WWERs). Of the operating water cooled reactors, 347 are LWRs totalling 307 GW(e) and 35 are HWRs totalling 16.6 GW(e). The experience and lessons learned from these plants are being incorporated into new water-cooled reactor designs, which are under development in a number of countries.

I–2.1. Light-water reactors

I–2.1.1. Current light-water reactors

LWRs in operation	347
LWRs under construction	23
Number of countries with LWRs	27
Generating capacity, GW(e)	307
Operating experience with LWRs, reactor-years	7 244

I–2.1.2. Evolutionary light-water reactors

Most of the effort on evolutionary LWR designs is aimed at achieving certain improvements over existing designs through small to moderate modifications. Utility requirement documents have been formulated to guide these activities by incorporating this experience with the aim of reducing costs and licensing uncertainties by establishing a technical foundation for the advanced designs. For evolutionary designs, there is a general drive for simplification, larger margins to limit system challenges, longer grace periods for response to emergency situations, improvement of the man-machine interface systems, shorter construction and improved maintainability. All evolutionary designs incorporate features to meet stringent safety objectives by improving severe accident prevention and mitigation. Several evolutionary designs have reached a high degree of maturity: nuclear regulatory authorities have certified some designs, and some are progressing through an optimization phase to reduce capital cost. In some cases design optimization leads to higher plant output to take advantage of the economy of scale, while in other cases, economic competitiveness is ursued through simplification resulting from reliance on passive safety systems. Advanced LWR (ALWR) designs are being developed in a number of countries as summarized below.

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

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

In May of 1997 the System 80+ plant of ABB Combustion Engineering and the ABWR plant of General Electric received Design Certification from the U.S. Nuclear Regulatory Commission highlighting the success of the U.S. Department of Energy's design certification programme for large evolutionary plants. The Westinghouse AP-600 design, a midsize plant with passive safety systems received Final Design Approval, which is the final step before Design Certification, from the NRC in September 1998. 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. The AP-1000 design is being prepared for certification application. Also the first-of-a-kind-engineering, FOAKE, programme was completed for the ABWR in September 1996. The power company in Taiwan, China, selected the USA's ABWR design for two new units slated for operation in 2004. 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.

France and Germany: In Europe, Framatome and Siemens with their joint company, Nuclear Power International, together with Electricité de France and the group of nuclear German utilities have worked out the design of a new advanced reactor, the European pressurized-water reactor (EPR), a large PWR of 1545 MW(e) with enhanced safety features. This reactor is designed to meet utility requirements endorsed by the major utilities of the European countries as expressed in the European Utilities Requirements (EUR) document, and the common safety requirements of the German and French Safety authorities. The basic design was completed at the end of 1997. As a result of a design optimization phase carried out in 1998 to achieve competitive economics, the power rating has been increased to 1750 MW(e) to take advantage of economy of scale. 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.

Siemens was also, together with German utilities, engaged in the development of an advanced BWR design, the SWR-1000, an evolutionary BWR, which incorporates a number of passive safety features for initiation of safety functions, for residual heat removal, and for containment heat removal.

Framatome ANP together with international partners from Finland, the Netherlands, Switzerland and France continues developing the basic design of the SWR-1000.

Sweden and Finland: In Sweden, Westinghouse Atom (previously ABB Atom), with involvement of the utility Teollisuuden Voima Oy (TVO) of Finland, is developing the BWR 90 and the BWR 90+ designs as upgraded versions of the BWRs operating in both countries. The BWR 90+ has a capacity of 1500 MW(e) and is an advanced boiling water reactor with improved safety and operability.

Republic of Korea: In the Republic of Korea, an effort started in 1992 to develop an advanced design known as the Korean Next Generation Reactor (KNGR), a 4000 MW(th) PWR design. The basic design is currently being developed by the Korea Electric Power Corporation (KEPCO) with support of the Korean nuclear industry. According to the mid- and-long term construction plan of power plants in the mid 90ties, the first KNGR was scheduled for operation in 2010.

The KNGR is being developed on the basis of experience with the 1000 MW(e) Korean Standard Nuclear Plants (KSNPs). The first two KSNPS, Ulchin 3 and 4, were connected to the grid in January and December 1998, respectively. Four more KSNPs are under construction two at Yonggwang, and two more at Ulchin (as of October, 1999). The accumulated experience is now being used by KEPCO to develop the improved KSNP$^+$.

An optimized design for KNGR, which is now named the Advanced Power Reactor 1400 (APR-1400), was followed by a detailed design for standardization in 1999. A power level of 1400 MWe has been selected to capture economies-of-scale. Recent development of the APR-1400 focuses on improving availability and reducing costs. In March 2001, KEPCO started the Shin-kori 3,4 project for the APR-1400.

Russian Federation: In the Russian Federation, design work is under way on the evolutionary V-392, an upgraded version of the current WWER-1000 (V-320), and another design version is being developed in co-operation with the Finnish company Imatran Voima Oy (IVO). Construction of two 1000-MWe VVERs (V-392) is being planned at the Novovoronezh site. Development of a WWER-1500 design has been initiated. Also being developed is a mid-sized plant, the VVER-640 (V-407), an evolutionary design which incorporates passive safety systems. Construction licenses for VVER-640 units have been issued by the Russian regulatory body Gosatomnadzor for the Sosnovy Bor site (near St. Petersburg) and for the Kola NPP-2 site (Murmansk region). Construction of 1000-MWe VVERs is underway in the People's Republic of China, India and Iran.

Japan: In Japan, the development of the ABWR started in 1978 as an international co-operation between five BWR vendors. The resulting conceptual design was received favourably by TEPCO and other Japanese utilities, and as a result, the ABWR was included in the third standardization programme of Japan from 1981. Preliminary design and numerous development and verification tests were carried out by Toshiba, Hitachi and GE together with six Japanese utilities and the Japanese Government. Two ABWRs, the Kashiwazaki-Kariwa units 6 and 7 were subsequently ordered by TEPCO and have been successfully taken into commercial operation in November 1996 and July 1997 respectively. Two more ABWRs are under construction at Hamaoka-5 and Shika-2, one is under licensing review at Ohma-1, and eight more ABWRs are in the planning stage. Expectations are that future ABWRs will achieve a significant reduction in generation cost relative to the first ABWRs. The means for achieving this cost reduction include standardization, design changes and improvement of project management, with all areas building on the experience of the ABWRs currently in operation.

In addition, a development programme was started in 1991 for ABWR-II, aiming to further improve and evolve the ABWR, with the goal of significant reduction in power generation cost relative to a standardized ABWR. The power level of ABWR-II has been increased to 1700 MWe, and benefits of economies-of-scale are expected. Commissioning of the first ABWR-II is foreseen in the late 2010s.

Also in Japan, the basic design of a large, evolutionary 1530 MW(e) advanced PWR has been completed by Japanese utilities together with Mitsubishi and Westinghouse, with construction of a twin unit being planned at the Tsuruga site (units 3 and 4).

China: In China, the Nuclear Power Institute (Chengdu) is developing the AC-600 advanced PWR, which incorporates passive safety systems for heat removal, based on experience in the design of the 610 MW(e) Qinshan 2 plant. To achieve self reliance in nuclear plant design, the Chinese Government has funded significant research and development supporting the AC-600 design. Experiments on critical heat flux at low flow rates, characteristics of core injection from core makeup tanks, passive containment cooling, passive emergency core heat removal on the secondary side, as well as several other tests, have been completed.

The China National Nuclear Corporation (CNNC) is developing the CNP-1000 plant. Also for this plant is China 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 2 and Daya Bay NPPs are being incorporated.

I–2.1.3. Innovative light-water reactors

While some experts consider that future nuclear plants will be evolutionary designs building on today’s successful proven systems and incorporating technology advances, other experts consider that development and demonstration of new, innovative designs[1], including their promised short construction and start-up times and low capital costs, are necessary to promote a new era of nuclear power. Innovative designs tend to be in the small to medium size range and would be constructed with factory built structures and components, including complete modular units for fast on-site installation. Small to medium size reactors have the potential to capture economies of series production instead of economies of scale, if several units are constructed. Such smaller and easier to finance systems would be particularly attractive for countries with small electricity grids or remote locations. They could also be used for district heating, seawater desalination and other non-electric applications.

A trend in the design of small and medium sized light water reactors has been simplified designs with long core life and modular design for factory production of standardized components and systems. Several small to medium sized PWR designs are of the integral reactor type in which the steam generator is housed in the same vessel as the reactor core. This approach eliminates primary system piping. A Westinghouse led international team is developing the modular, integral IRIS design with a power level in the 100 – 300 MWe range, with an 8-year core life and with maintenance requirements once in 4 years. The Argentinian CAREM reactor (prototype design 27 MWe) is cooled by natural circulation, and has passive safety systems. The 330 MWth SMART design that has been developed in the Republic of Korea is an integral PWR and, like CAREM, uses no soluble boron. A decision has been made to build a smaller 65MWth pilot plant for the SMART reactor.

In *Japan*, the Japan Atomic Energy Research Institute is developing an extension of the MRX ship reactor design, which is an integral design of up to 300 MWe. The Toshiba Corporation and the Tokyo Institute of Technology are developing a long operating cycle, natural circulation simplified LSBWR with passive safety systems. The power level is in the 100 – 300 MWe range with a target 15-year core life.

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[1] As described in TECDOC-936, an innovative design is an advanced design, which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. Substantial R&D, feasibility tests, and a prototype or demonstration plant are probably required.

Russia has developed several small reactor designs. Notable among them are the barge mounted 35 MWe KLT-40C, a loop-type PWR; RUTA-55, a pool type PWR; UNITHERM, a 15 MWth PWR with a 20 year single core life, ABV-6, a 6 MWe integral PWR based on marine technologies, and VK-300 a scaled up BWR from their VK-50 plant. Also being developed is a mid-sized plant, the VPBER-600, which is a more innovative, integral design with the steam generator system inside the reactor pressure vessel.

In *China*, the Institute for Nuclear Energy Technology near Beijing has developed an integral PWR of 200 MWth, called the NHR-200, for desalination and district heat.

In *Europe*, seven partners [Forschungszentrum Karlsruhe (Germany), Commissariat à l'Energie Atomique (France), Technical Research Center VTT (Finland), KFKI Atomic Energy Research Institute (Hungary), Framatome ANP (Germany), Electricite de France (France), Paul Scherrer Institute (Switzerland)], in co-operation with the University of Tokyo (Japan) are carrying out a co-operative effort funded by the European Commission to assess the merit and economic feasibility a high performance LWR operating thermodynamically in the supercritical regime, similar to some current advanced fossil fired plants. In such concepts, the water exits the reactor core as high-density steam without change of phase at a pressure above 22 MPa and temperatures above 374^{o} C. Thermal efficiencies of 44% are projected with simplified plant designs.

I–2.2. Heavy-water cooled reactors

In addition to light water-cooled reactors, the technology for HWRs has also proven to be economic, safe, and reliable. 7% of all operating plants are HWRs. A mature infrastructure and regulatory base has been established in several countries. Two types of commercial HWRs have been developed, the pressure tube (with horizontal fuel channels and on-line refuelling) and the pressure vessel versions, and both have been fully proven. HWRs with power ratings from a few hundred MW(e) up to approximately 900 MW(e) are available.

The heavy-water moderation yields a good neutron economy and has made it possible to utilize natural uranium as fuel, which leads to lower fuel costs compared with LWRs. The amount of fissile materials is quite limited, however, and the pressure tube designs are therefore using on-load refuelling to achieve adequate reactivity for the plant operation. The effectiveness of this on-load refuelling has been successfully demonstrated; the annual and lifetime load factors of the most of the pressure tube HWRs have been among the best of all commercial reactor types. Safety performance has been also proven to be very good.

I–2.2.1. Current heavy-water cooled reactors

HWRs in operation	35
HWRs under construction	6
Number of countries with HWRs	7
Generating capacity, GW(e)	16.64
Operating experience with HWRS, reactor-years	673

I–2.2.2. Evolutionary heavy-water cooled reactors

Canada: The continuing design and development programme for HWRs in Canada are primarily aimed at reduction of plant costs through plant optimization and simplification and at an evolutionary enhancement of plant performance and safety. Two new 728 MW(e) CANDU-6 units with improvements over earlier versions of this model are under construction in Qinshan, China. Up-front basic engineering continues on the 935-MWe CANDU-9 reactor, a single unit adaptation of reactor units operating in Darlington, Canada. The two year licensability review by the Canadian Nuclear Safety Commission was completed in January 1997, and found that the CANDU-9 meets the country's licensing requirements. Further studies are being carried out for advanced versions of the next generation CANDU plants (NG-CANDU) to incorporate further evolutionary improvements and to increase the output of the larger reactor up to 1300 MW(e). New features include simple, inexpensive fuel-bundle design based on slightly enriched uranium and light water coolant.

India: India currently has 8 operating HWRs with a total capacity of 1.4 GW(e). In addition, four HWRs of 220 MW(e) each are under construction (the Kiaga-1 and 2 units and the Rajasthan-3 and 4 units). These plants are scheduled to achieve commercial operation in 2000 and 2001. Furthermore, start of construction of two 500 MW(e) units at Tarapur is also scheduled. This HWR design takes advantage of experience feedback from the 220-MWe HWR plants of indigenous design operating in India.

I–2.2.3. Innovative heavy-water cooled reactors

Canada. There are also innovative small heavy water reactors under development. AECL has undertaken a design initiative called CANDU X within which the future steps in CANDU technology are investigated. These include consideration of improved thermodynamic efficiency using supercritical coolant.

India. An Advanced Heavy Water Reactor (AHWR) is under development in India. This is a 235 MWe heavy water moderated, boiling light water cooled, vertical pressure tube type reactor, with passive features, and with its design optimized for utilization of thorium for power generation. The conceptual design and the design feasibility studies for this reactor have been completed and at present the reactor is in the detailed design stage.

I–3. OVERVIEW OF GAS-COOLED REACTOR DEVELOPMENT PROGRAMMES

The initial development of gas cooled reactors was on CO_2 cooled systems beginning in the 1950’s with the Magnox reactors, deployed primarily in the United Kingdom, and later with the Advanced Gas Cooled Reactors (AGRs), deployed exclusively in the United Kingdom. Development of helium cooled High Temperature Gas Cooled Reactors (HTGRs) to achieve higher temperatures began in the late 1960s with prototype power plants constructed in the UK, the USA and Germany. Modular HTGRs utilizing steel reactor vessels and limiting power levels to allow passive heat removal under all conditions within the design basis have been the focus of development since the early 1980’s. Gas-cooled reactors have been in operation for many years.

GCRs in operation	34
Generating capacity, GW(e)	11.8
Operating experience with gas-cooled reactors, reactor-years	1,402

HTGRs are a unique technology offering both highly efficient generation of electricity with direct cycle helium turbines, and production of high temperature process heat enabling nuclear energy to be used for production of H_2 as a clean energy supply. Therefore HTGRs can expand the use of nuclear energy into the process heat market in both industrialized and developing countries. Current development is focused on modular HTGRs with coated particle fuel, inherent safety features and passive systems, coupled with state-of-the-art power conversion technology for electricity production and process heat applications. The safety approach is based on proven technology including inherent safety characteristics of the core that rely on the high heat capacity and negative temperature coefficients of reactivity, passive systems for removing decay heat based on natural convection and heat radiation, and high retention of fission products within the coated fuel particles at accident conditions.

Active development is under way in the European Union, China, Japan, Russia, South Africa and the USA. This development is proceeding on the basis of technology transfer from Germany, the USA, Russia, France and the UK.

*United Kingdom: N*uclear electricity is mostly generated in CO_2-cooled Magnox and Advanced Gas-Cooled Reactors (AGRs). Other countries also have pursued development of high-temperature reactors (HTGRs) with helium as coolant, and graphite as moderator.

Germany: The 13 MW(e) AVR reactor was successfully operated for 21 years demonstrating application of HTGR technology for electric power production. Another helium-cooled, graphite-moderated reactor is the 300 MW(e) Thorium High Temperature Reactor, now shut-down.

United States: Helium-cooled, graphite-moderated reactors in the United States include the 40 MW(e) Peach Bottom and 330 MW(e) Fort St. Vrain plants, both reactors are shut-down. Exelon is collaborating with Eskom (South Africa, see below) in the development of the helium-cooled pebble bed modular reactor (PBMR). Following this development, Exelon has initiated pre-application interactions with the Nuclear Regulatory Commission (NRC) regarding construction of a multi-unit PBMR plant. Discussions with the NRC are also under way regarding licensing of a commercial version of the GT-MHR design.

France: In France, the Atomic Energy Commission CEA has recently set up a comprehensive R&D programme on promising technologies for future nuclear systems, the main axis of which relies on HTGRs with hardened neutron spectra and refractory fuel possibly compliant with on-site reprocessing.

Russian Federation, United States, France, and Japan: MINATOM, General Atomics, Framatome and Fuji Electric have combined their efforts for the co-operative development of 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. The net efficiency of this advanced nuclear power concept is 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 future consideration in the production of electricity. This plant is under consideration for the purposes of burning weapon grade plutonium and for commercial deployment.

South Africa: In South Africa, the large national utility, Eskom, is in the process of performing a technical and economic evaluation of a helium-cooled pebble bed modular reactor (PBMR) directly coupled to a gas turbine power conversion system. Now Eskom, Exelon (USA) and BNFL (UK) are collaborating in the development of the PBMR, with plans to initiate construction of a prototype in South Africa in 2003.

The Netherlands: Design and assessment studies are being made on a small, simplified version of the South African PBMR for the purpose of heat and power cogeneration. It is named ACACIA (AdvanCed Atomic Cogenerator for Industrial Applications), has a 40 MW(th) pebble bed reactor with a direct cycle helium turbine and produces 13.6 MW(e) and 17 t/h steam of industrial quality.

China: In China, the HTGR development focuses on construction and operation of a test reactor. China’s High Temperature Reactor (HTR-10) at the Institute of Nuclear Energy Technology (INET) reached initial criticality in December 2000. This pebble bed reactor of 10 MW(th) will be utilized to test and demonstrate the technology and safety features of the HTGR. Initial operation will be with a steam turbine, with prospects for later conversion to a gas turbine configuration. Development of the HTGR by INET is being undertaken to evaluate a wide range of applications. They include electricity generation, district heat production, steam and gas turbine cycle operation, and the generation of process heat. The HTR-10 is the first HTGR to be licensed and constructed in China.

Japan: In Japan, the HTGR development focuses also on construction and operation of a test reactor. The principle focus of Japan's HTGR development programme is the High Temperature Engineering Test Reactor (HTTR) at the Japan Atomic Energy Research Institute (JAERI) site in Oarai, Japan. Initial criticality of the HTTR was achieved in November 1998. This 30 MW(th) helium-cooled reactor is being utilized to establish and upgrade the technology for advanced HTGR development, and to demonstrate the effectiveness of selected high temperature heat utilization systems. The reactor continued power ascension operation during 2001, achieving 20 MWth in February and projecting to reach full power later in the year. Also, a project has been initiated to develop a 600 MWth gas turbine design for electricity production.

I–4. OVERVIEW OF LIQUID METAL-COOLED REACTOR DEVELOPMENT PROGRAMMES

The feasibility of a nuclear chain reaction involving only fast neutrons was recognized from the earliest days of nuclear power in the 1940s. As a matter of fact, a fast reactor, the EBR-1 in the USA, delivered the first electrical current ever produced through fission processes. The driving force behind the R&D work in the field of fast reactors was the realization that fast reactors could be used for breeding fissile material from fertile. This provided the key to utilizing the enormous worldwide energy reserve represented by uranium-238, opening the prospect of a virtually non-exhaustible source of energy.

The development of civil fast reactors started in several countries, notably the USA, the USSR, the UK and France, in the late 1940s. This involved test reactors such as CLEMENTINE and EBR-l in the USA, and BR-2 in the USSR. Subsequently, experimental reactors such as EBR-2, Fermi and FFTF (USA), BR-10 and BOR-60 (USSR), Rapsodie (France), KNK-II (Germany), JOYO (Japan), FBTR (India), and DFR (UK) were constructed from the 1950s to the early 1970s, leading to demonstration or prototype power reactors such Ph6nix (France), PFR (UK), BN-350 (USSR-Kazakhstan), BN-600 (USSR-Russia), MONJU (Japan) and PFBR (India), and finally to the only full-scale power plant, Superphénix (France).

In the earliest days great importance was attached to the breeding of fissile material, but the increasing availability of low cost uranium from the 1980s onwards shifted the emphasis to include other uses for fast reactors both in the critical and subcritical mode, particularly for the control of plutonium stocks (incineration) and the treatment of radioactive wastes (partitioning and transmutation). In spite of these additional functions the main long-term importance of fast reactors as breeders, essential to world energy supplies, remains unchanged.

LMRs in operation	3
LMRs under construction	2
Number of countries with LMRs	3
Generating capacity, GW(e)	1.04
Operating experience with LMRS, reactor-years	142

Various types of fast neutron spectrum reactors and hybrid systems (e.g. accelerator driven systems (ADS)) are under investigation in several Member States. The claimed advantages of some new concepts, for example ADS, are low waste production, high transmutation capability, enhanced safety characteristics and better long-term utilization of resources (e.g. with thorium fuels). R&D programmes are underway to substantiate these claims and to advance the basic knowledge in this innovative area of nuclear energy development. Common goals of these R&D efforts are lower cost, improved efficiency, and safety and proliferation resistance enhancements, and simplification of the nuclear fuel cycle. These goals are facilitated by co-ordinated R&D efforts. Technology development programmes for LMFRs are proceeding in several countries:

China: In China, the basic research work on LMFRs was started in 1964. Since then and up to 1987, the major work has been on neutronics, thermalhydraulics, and sodium technology. During 1991-92, the conceptual design of the 15 MW(e) Chinese Experimental Fast Reactor (CEFR) was completed and during 1992-93, the conceptual design was confirmed and optimization studies were carried out. Since 1993 onwards, major work has involved the preparation of a detailed design. A preliminary design has been completed in 1997 and a 25 MW(e) Chinese Experimental Fast Reactor (CEFR) is under construction. First criticality is scheduled for the end of 2005.

France: In France, the commercial introduction of LMFRs is being postponed. The 1200 MWe Superphénix reactor has been shut down. Meanwhile, the application of an additional important aspect of these reactors -to transmute long-lived nuclear waste and to burn plutonium- is being developed (CAPRA and CADRA projects). The current programmes on operation of the 250 MW(e) Phénix reactor reflect these requirements. One objective of extending the lifetime of the Phénix reactor till 2004 is to perform the necessary irradiation experiments. The CEA has launched an R&D programme to study promising technologies for future nuclear energy systems, addressing in the first place the issues of enhanced safety, sustainability, and economics. The reference concept is based on a gas-cooled fast reactor with on-site closed fuel cycle.

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

Japan: In Japan, the experimental fast reactor (JOYO) has been operated from 1982 to 2000 with MK-II core (100 MWt). The reactor and its cooling system is currently being upgraded to the MK-III core (140 MWt). The initial criticality of the MK-III core is scheduled in 2002. The prototype LMFR MONJU with the capacity of 280 MW(e) reached initial criticality in April 1994 and was connected to the grid in August 1995. Reactor operation was interrupted in December 1995 due to a leak in the non-radioactive secondary cooling system. The legal application on improvement of the MONJU plant mainly for countermeasures against sodium leakage has been launched in June 2001. The MONJU reactor is considered to be a corner stone for R&D activities and considerable effort is made to resume its operation. In addition to this main stream of development work, a Feasibility Study on Commercialized Fast Reactor Cycle Systems is in progress with the objective of presenting an optimal commercialization vision of LMFR technologies and a research and development programme.

Republic of Korea: In the Republic of Korea, the LMFR development programme is considered as an important part of the national long-term R&D programme. The Republic of Korea plans to develop the conceptual design of its first fast-breeder reactor, the 330 MW(e) Kalimer plant, by 2002, and the basic design by 2006, for construction soon after 2010. The ADS HYPER concept development roadmap will be finished in 2001 and the conceptual design will be completed by 2007.

Russian Federation: Russia's experience in the operation of experimental and prototype fast reactors (the BR-10, BOR-60, and BN-600 with hybrid core) has been very good. Efforts are directed towards further improving safety and reliability and making the LMFRs economically competitive to other energy sources. While these efforts would take some time, the use of LMFRs over the near-term to burn plutonium and minor actinides is foreseen on the basis of new BN-800 fast reactors. By 2010, Russia wants to complete construction of the BN-800 fast reactor at Beloyarsk. The fast reactor R&D activities are concentrating on advanced concepts with enhanced safety features, including a large size (~1600 MWe) sodium cooled fast reactor, designs with alternative coolants (e.g., lead), 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. 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, sea-water desalination, or the utilization and transmutation of actinides. In the field of ADS, Russia is conducting research on the physical processes and performing design studies.

United Kingdom: BNFL is examining core design, thermal-hydraulics design, and fuel design for gas cooled Accelerator Driven Systems (ADS).

Europe: The European Organization for Nuclear Research (CERN), as well as the EC's JRC are supporting ADS studies being pursued within the framework of the European Technical Working Group on ADS by institutes in the UK, Belgium, France, Germany, Italy, Sweden, Finland, and Spain. Efforts are undertaken to include some of the R&D into the European Commission's 6th and 7th Framework Programme. ENEA, Ansaldo, and INFN in Italy have contributed substantially to the preparation of the "European Roadmap on ADS".

United States: A promising integral fast reactor (IFR) concept, comprising the LMFR and its entire fuel cycle, has been developed at the Argonne National Laboratory (ANL) and General Electric Company over the past two decades. A distinguishing element of the IFR concept is its unique fuel cycle based on metallic fuel and pyrometallurgical processing. At ANL, an effective fuel cycle technique has been developed whereby spent fuel is reprocessed and new fuel is fabricated at the reactor sites. The plutonium is not separated from the higher radioactive actinides; these are recycled together in the reactor and never leave the reactor site. Advantages of the IFR system are in areas of (i) fuel performance, (ii) passive safety, (iii) economics, (iv) waste management potential, and (v) proliferation resistance.

When the first LMFRs were constructed in the 1950s, it was expected that the bumup potential of metallic fuel would be limited to 3-5% of heavy atoms. In fact, by using a U-Pu-1-% Zr alloy and ferritic-martenistic HT9 cladding and duct, a burnup of about 20% has been achieved in EBR-II. All irradiation results in EBR-II and FFTF have demonstrated reliable performance of metallic fuel and the potential to achieve high burnup in prototypical fuel elements. The EBR-II Electrometallurgical Treatment programme is presently processing about 25 t of EBR-II spent fuel with later R&D planned to improve processing rates and to qualify the waste for repository acceptance.

In one of the NERI activities, a 50 MWe modular design with Pb-Bi coolant, called the Encapsulated Nuclear Heat Source, which has a 15-year core life, is being developed. The Advanced Accelerators Applications (AAA) programme includes a 10-year R&D plan for defining the key technologies to be used for transmutation of nuclear waste (plutonium, minor actinides and long-lived fission products) and the construction of the Accelerator Driven Test Facility (ADTF). This facility will serve as the principal test station for a proof of performance series of tests, to demonstrate the safety and operation of Accelerator Driven Systems, and to demonstrate efficient transmutation and recycling of minor actinides and long-lived fission products. The U.S. fast reactor programme includes also examinations of whether to restart or deactivate the FFTF.

I–5. SMALL AND MEDIUM SIZED REACTORS

Small sized reactors are defined by the IAEA as reactors having power levels less than 300 MW(e) or the equivalent thermal power (1000 MW(t)). Medium sized reactors are defined as having power levels from 300 to 700 MW(e). Recently there has been an increasing emphasis on the development of small and medium reactors (SMRs), with the prospect of better matching to load demand in industrialized countries and meeting needs in developing countries where electrical grids cannot accept the additional capacity of a large nuclear plant. Small and medium sized reactors (SMRs) are also of interest for non-electrical applications of nuclear energy, such as desalination of seawater and district heating. SMR concepts of interest in IAEA Member States include a wide range of water, liquid metal and gas cooled designs. Water reactors include derivatives from ship propulsion reactors, integral pressurized water reactors, low temperature heating reactors, and heavy water reactors. Numerous liquid metal reactors using sodium, lead or lead/bismuth as coolant are under study over a wide range of power ratings. Gas cooled reactor concepts are focused on gas turbine concepts with either prismatic block or spherical fuel elements. Typical SMR design developments are included under the four mainstream reactor lines in the Sections I-1 to I-3.