Annex I
OVERVIEW OF GLOBAL DEVELOPMENT OF ADVANCED NUCLEAR POWER PLANTS

Annex I

OVERVIEW OF GLOBAL DEVELOPMENT OF ADVANCED NUCLEAR POWER PLANTS[1]

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), advanced boiling water reactors (ABWRs), and the Russian type pressurized water reactors (WWERs). Of the operating water cooled reactors, 355 are LWRs totalling 317.10 GW(e) and 38 are HWRs totalling 19.19 GW(e) [suggest to ask Mr. Raatz for updated numbers]. 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

Light Water Reactors	
In operation	355
Under construction	22
Number of countries with LWRs	27
Generating capacity, GW(e)	317.103
Operating experience, reactor-years	8178

In the Republic of Korea, the benefits of standardization and construction in series are being realized with the 1000 MWe Korean Standard Nuclear Plant (KSNP) units. The accumulated experience is now being used to develop the KSNP+. The first units of $KSNP^+$ are planned for Shin-Kori Units 1 and 2 with start of construction in 2004 and 2005 respectively. In addition, the development of the Korean Next Generation Reactor, now named the Advanced Power Reactor 1400 (APR-1400), was started in 1992, building on the experience of the KSNPs. Recent development of the APR-1400 focused on improving availability and reducing costs. A power level of 1400 MWe has been selected to capture economies-of-scale. In March 2001, KEPCO started the Shin-kori 3,4 project for the APR1400. The plan for the first of two APR-1400 units at Shin-Kori is to start construction in June 2005 with commissioning in 2010.

[1] Reactor data are derived from the IAEA's PRIS as of December2003

Benefits of standardization and construction in series are also being realized in Japan with the ABWR units. Two ABWRs are operating at TEPCO's Kashiwazaki-Kariwa site, and deployment programmes are underway for 10 more ABWR units in Japan. Future ABWRs are expected to achieve a significant reduction in generation costs 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 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 France and Germany, Framatome ANP has completed the basic design for a 1545 MW(e) European Pressurized Water Reactor (EPR) in 1998, which meets European utility requirements. 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. In October 2003, Teollisuuden Voima Oy (TVO) announced that it has selected the Olkiluoto site for the new nuclear unit and that the EPR is the preferred alternative.
In Germany, Framatome ANP with international partners from Finland, the Netherlands, Switzerland and France is developing the basic design of the SWR-1000, an advanced BWR with passive safety features.

In Sweden, Westinghouse Atom is developing the 1575 MWe BWR 90+, an advanced boiling water reactor with improved safety and operability.

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 planned in China, India and the Islamic Republic of Iran. Development of a WWER-1500 design has been initiated. Development is also on-going 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 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 in May 1997 by the U.S Nuclear Regulatory Commission. 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 MW(e) 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 under review by the U.S. NRC for design certification. Westinghouse is also designing the IRIS 335 MWe intergral primary system PWR. General Electric is also designing a 1380 MW(e) 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 MW(e) simplified BWR with passive systems. The ESBWR is under pre-application review by the U.S NRC for design certification.

In China, the China National Nuclear Corporation (CNNC) is developing the CNP-1000 plant, which incorporates feedback of experiences of design, construction and operation of Qinshan and the Daya Bay NPPs.

Several countries are developing innovative LWR designs, which represent a greater departure from current systems, and may require a prototype or demonstration plant as part of the development programme. Examples of innovative designs include the SMART integral primary system design of the Republic of Korea and CAREM integral design of Argentina. Developers of each of these designs are planning prototype plants prior to commercial deployment. Examples of innovative LWR designs for high conversion of fertile isotopes to fissile isotopes are the RMWR of JAERI and the RBWR of Hitachi, Japan. Innovative LWR designs also include designs operating thermodynamically in the super-critical regime (above 22 MPa and 374 C). Thermodynamically supercritical water-cooled systems have been selected for development by the Generation IV International Forum.

I–2.2. Heavy-water cooled reactors

Heavy Water Moderated Reactors	
In operation	38
Under construction	8
Number of countries with HWRs	7
Generating capacity, GW(e)	19.19
Operating experience, reactor-years	822

Heavy water reactors are a significant proportion of world reactor installations. They provide fuel cycle flexibility for the future and can potentially burn the spent fuel from LWRs, with no major reactor design changes, thus extending resources and reducing spent fuel arising.

New HWR designs are being developed mainly in Canada and India.

In China, the Qinshan CANDU project, a partnership between AECL, Canada and the Third Qinshan Nuclear Power Company (TQNPC), has proceeded successfully since construction began in June 1996. This multinational endeavour uses the combined global expertise of companies from Canada, China, Japan, the Republic of Korea, and the USA to build two 700MW(e) CANDU 6 units. Qinshan Unit 1 reached full power 2002 December 17 and commenced commercial operation 2002 December 31, after a 54 month construction period. Unit 2 is also on schedule and is expected to achieve full power in 2003.

On April 1, 2000, construction started on China's first CANDU nuclear fuel manufacturing plant located in Boatou City in Northern China. By 2003, the plant will provide nuclear fuel for the two CANDU 6 units. The new production facility, which will produce approximately 200 tonnes of fuel annually, furthers China's efforts towards energy independence.

In Canada, AECL is continuing to adapt the basic CANDU design to develop the Advanced CANDU 700 MWe Reactor (ACR-700), focusing on improvements in economics, inherent safety characteristics and performance, while retaining the features of the earlier family of PHWR nuclear power plants. The unit size has been selected to match the requirements, in increasingly deregulated electrical power markets, for plants with lower plant capital and operating costs, plus reduced project schedules, through the use of improved design and construction methods and operational improvements. However, the basic concept described is suitable for a range of plant sizes with gross outputs in the range of 400 MWe to 1200 MWe. The design is optimised by utilizing SEU fuel to reduce the reactor core size, which reduces the amount of heavy water required to moderate the reactor and allows the use of light water in place of heavy water as the reactor coolant.

AECL is also developing the innovative CANDU-X, operating at higher thermal efficiencies, which implies high temperature coolant or supercritical water as coolant. Such reactors would also incorporate passive high temperature fuel channels, natural circulation heat removal wherever possible, and passive containment heat removal.

A cooperative research project on intercomparison of techniques for pressure tube inspection and diagnostics and an international standard problem exercise on intercomparison and validation of computer codes for thermalhydraulics safety analyses are in progress. A Technical Report Series document on “Heavy Water Reactors, Status and Projected Developments” that presents the status of HWR advanced technology in the areas of fuel cycle flexibility and sustainable development, safety and economics, and the advanced technology developments needed in the future, was published in 2002. A document entitled “User Requirements for Heavy Water Reactors” is in preparation.

India began construction of two 500 MW(e) units at Tarapur, in late 1998. Also, a boiling light water cooled Advanced Heavy Water Reactor (AHWR) is under development in India. This innovative design burns thorium and incorporates many passive features, including natural circulation cooling.

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.

Gas Cooled Reactors	
In operation	26
Generating capacity, GW(e)	10.86
Operating experience, reactor-years	1547

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.

South Africa: In South Africa, the large national utility, ESKOM has completed its feasibility study on the Pebble Bed Modular Reactor (PBMR), currently rated at 168 MWe,. In 2003, the South African government has taken a positive Record of Decision (ROD) on the environmental impact assessment report submitted by ESKOM. A safety analysis report is to be submitted to the regulator authorities during 2004. BNFL continues to be a shareholder in the project and ESKOM is currently seeking new partners.

Russian Federation: MINATOM, together with General Atomics of the US and Fuji Electric of Japan continue their efforts on the development of the gas turbine modular helium reactor (GT-MHR). This plant, rated at 288 MWe, is under consideration for the purposes of burning weapon grade plutonium and for commercial deployment. Activities are currently focusing on R&D related to fuel, turbo-machinery and calculation methods.

United States: HTGR reactors in the United States included the 40 MW(e) Peach Bottom and 330 MW(e) Fort St. Vrain plants, both shut-down. In 2003, the US government has proposed $1.2 billion for research funding on the hydrogen economy roadmap for the next decade. The idea is to eventually make a transition from fossil fuel dependence to the use of cleaner hydrogen, primarily in transportation and fuel cell applications. The funding will mainly go into building the Next Generation Nuclear Plant (NGNP), a co-generation HTGR-type plant coupled to a hydrogen production unit. The NGNP project is set for construction by 2010 in Idaho.

China: In China, the HTGR development is focusing on operation and safety demonstration of the HTR-10, a 10 MWt high-temperature test reactor. at the Institute of Nuclear Energy Technology (INET). 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, including electricity generation, district heat production, steam and gas turbine cycle operation, and the generation of process heat. A conceptual design of a 300-400 MWt pebble-bed nuclear power plant, featuring a steam-cycle, is currently being considered for construction.

Japan: In Japan, the HTGR development is focusing on operation, safety testing and high-temperature applications such as hydrogen production. The principal tool is the High Temperature Engineering Test Reactor (HTTR), a 30 MWt HTGR operating at the Japan Atomic Energy Research Institute (JAERI) site in Oarai. A 300 Mwe nuclear power plant of the prismatic HTGR design (GTHTR-300) is also being considered for construction with hydrogen production in mind.

France: In France, the Atomic Energy Commission CEA continues its comprehensive R&D programme on HTGR technology, including design methods, fuel technology, material studies and helium loop tests. Long-term interest has been expressed in hardened neutron spectra and refractory fuel possibly compliant with on-site reprocessing. France is also cooperating with the European HTGR program currently focusing on fuel, design, material and licensing aspects of the technology.

United Kingdom: Nuclear 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. Several UK institutes are currently cooperating with the European HTGR program currently focusing on fuel, design, material and licensing aspects of the technology.

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 was the 300 MW(e) Thorium High Temperature Reactor, now shut-down. Institutes such as Juelich are currently cooperating with the European HTGR program currently focusing on fuel, design, material and licensing aspects of the technology.

The Netherlands: Design and assessment studies have been 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.NRG of the Netherlands is currently cooperating with the European HTGR program currently focusing on fuel, design, material and licensing aspects of the technology.

Korea (Rep. Of): The republic of Korea has recently shown increased interest in HTGR technology, with an eye on high-temperature applications, in particular hydrogen production. An R&D program focusing on HTGR fuel technology has been initiated.

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

Energy production with fuel breeding is the main goal of liquid-metal-fast-reactor (LMFR) development to ensure long-term fuel supply. LMFRs are also being investigated to reduce the actinide content of nuclear waste, and to take advantage of their high thermal efficiency. LMFRs have been operating successfully in several countries to produce energy and to demonstrate the first nuclear power plant for sea water desalination in the world (BN-350 in Kazakhstan, which was commissioned in 1964, generated first electricity in 1973, and was shut down in 1998).

In China, the 25 MW(e) China Experimental Fast Reactor (CEFR) is under construction, as the first step in the Chinese FR engineering development. The main components of the primary, secondary and tertiary circuits and of the fuel handling system have been ordered. The construction of the reactor building with about 40,000m^2 floor surface has been completed.First criticality of CEFR is scheduled for 2006.

As a second step in the Chinese FR technology development effort, a 300 MW(e) Prototype Fast Breeder Reactor (PFBR) is presently under consideration. The role of minor actinide transmutation is also being evaluated taking as reference the PFBR.For the Accelerator Driven Sub-critical System (ADS), China is undertaking great efforts to accomplish the research tasks defined in the work plan of the first phase (1998-2002). The emphasis in this phase is on system optimisation, reactor physics and technology, accelerator physics and technology, and nuclear and material data. At the same time, considerable effort is being put into the preparation of the second phase. The highlight of this phase will be the ADS concept verification study (2000-2007). As regards Fusion/Fission Hybrid System, in the near-term the emphasis will be put on the experiments performed at the two large testing facilities, HL-1M and HT-7. In parallel, scope and objectives for both the medium-term and long-term development of Fusion/Fission Hybrid System will determined, and the respective R&D programs developed.

Liquid Metal Fast Reactors	
In operation	3
Under construction	0
Number of countries with FRs	3 (+1 with a test reactor)
Generating capacity, GW(e)	1.039
Operating experience, reactor-years	156

In France, decommissioning work that started in 1999 is underway at the Superphénix FR. The last fuel subassembly has been unloaded on 19 March 2003. At Phénix, after completion of the plant renovation programme, power operation was resumed on 15 June 2003. The reactor will be operated for 6 irradiation cycles of 120 EFPD each. Its main mission will be to perform the irradiation tests in support of the CEA transmutation R&D programme in the framework of the 30 December 1991 law on long-lived radioactive wastes management. As regards R&D, CEA has launched a comprehensive R&D program to study promising (with regard to enhanced safety characteristics, sustainability and economics) technologies for future nuclear energy systems. The reference system is based on a gas cooled fast reactor with on-site closed fuel cycle. However, many of the long-term options investigated are believed to be of generic interest, and to offer the chance of developing high performance fuels and materials.

In Germany, Forschungszentrum Karlsruhe (FZK) participated in the European CAPRA/CADRA Project (plutonium and minor actinides (MA) burning in critical Fast Reactors). This work is nearly finished, and FZK is pursuing now R&D activities in the area of actinide burning in sub-critical systems (ADS). For ADS, the topics of interest cover neutronics, safety analyses, lead bismuth technology (thermalhydraulics, corrosion), and the development of the spallation target.

In India, the detailed design, R&D, manufacturing technology development, and safety review for the 500 MW(e) Prototype Fast Breeder Reactor (PFBR) were continued. Manufacture of the fuel handling transfer arm was completed and is undergoing tests. The Atomic Energy Regulatory Board has given excavation clearance. Clearance has been also given by the Ministry of Environment and Forests. R&D in reactor physics, engineering development, structural mechanics, metallurgy, non-destructive evaluation, chemistry and reprocessing was continued. Important works include PFBR shielding experiments, in-sodium testing of control and safety rod drive mechanism, testing of secondary sodium pump model in water, boron enrichment, structural integrity testing and readiness for FBTR carbide fuel reprocessing. The small-size Fast Breeder Test Reactor (FBTR), located at Kalpakkam and used for various test irradiations, attained peak burn-up of 101.5 GWd/t.

In Italy, nuclear fission R&D is pursued on a limited scale by ENEA in its twin role of advisor to the Italian Government and applied R&D organization. ENEA's nuclear activities contribute to solving open questions of nuclear energy, maintenance and improving expertise in the field of nuclear data, neutronics, shielding, fuel, thermal-hydraulics, safety, structural and system analysis. The most important effort is the national initiative focused on the European ADS programme. The R&D activities on nuclear energy that are not part of the ADS programme are performed by Italian universities and ENEA in the framework of international collaborations, in particular within the framework of European Commission projects, or of bilateral agreements, such as ENEA-CEA and ENEA-IPSN.

In Japan, the direction of the R&D efforts in the field of fast breeder reactor (FBR) cycle technology is determined, apart from the constant pursuit of further safety enhancements, to a large extent by the goal of economic efficiency at the commercialisation stage of this technology. In March 2001, the first phase of the "Feasibility Study on Commercialised Fast Reactor Cycle Systems" has been completed, and the second phase initiated. This ongoing study, undertaken by JNC with the cooperation of electric utilities and other interested parties, will be continued to examine such aspects as reactor type selection, spent fuel reprocessing methods, and fuel fabrication technologies, with the objective of presenting an optimal commercialisation vision of FBR cycle technology and a comprehensive R&D program toward that end. An interim summary of these activities will be checked and reviewed, and based on the results, the future R&D activities will be defined aiming at narrowing down the number of alternatives for the FBR cycle. The 280 MW(e) prototype fast breeder reactor MONJU remains shutdown after a sodium leakage accident in the secondary heat transport system that occurred in December 1995 during the 40% power pre-operational testing phase. Considerable effort has been put into activities aiming at regaining public understanding and acceptance. In December 2002, the Minister of Economy, Trade and Industry (METI) granted the permission for safety licensing examination related to the countermeasures against sodium leaks in MONJU. However, the Nagoya high court - Kanazawa branch rendered a negative judgment of the Administrative Suit on January 2003. METI appealed to the Supreme Court. In the experimental FR JOYO, thirty-five duty cycle operations and thirteen special tests with the MK-II core were completed by June 2000 without any fuel pin failures or serious plant trouble. The reactor is currently being upgraded to the MK-III core (increase of the neutron flux, increase of the reactor availability, upgrading of the irradiation technologies). The MK-III core will start operation in 2003 for the development of advanced fuels and materials, and minor actinide burning and transmutation technology.

In the Republic of Kazakhstan, the fast breeder reactor BN-350 was commissioned in November 1972 and finally shut down in April 1999. The General Plan for the BN-350 decommissioning was developed within the framework of a Kazakh – US project. At the end of March 2003, the Plan was presented for final review to a IAEA group of experts. The project EAGLE is under way since 2000 under a contract between the National Nuclear Centre of Kazakhstan RK and Japan Nuclear Cycle Development Institute. The project comprises the preparation and conduct of out-of-pile and in-pile experiments designed to address the key safety issues relevant to eliminating or mitigating the re-criticality potential during a postulated core-disruptive accident in future commercial sodium cooled FRs.

In the Republic of Korea, the Korea Atomic Energy Research Institute (KAERI) has been developing KALIMER (Korea Advanced LIquid MEtal Reactor), a pool-type liquid metal-cooled reactor, under a national long-term R&D program. The conceptual design of KALIMER with a rating of 150 MW(e) was completed in March 2002. The three-year 3rd phase of the FR technology development project started in April 2002 with the goal of developing basic key technologies and advanced FR design concepts. Efforts are concentrated on proliferation resistant core design, improved economics, enhanced safety, high temperature structural analysis, and safety analysis. A preliminary KALIMER-600 design concept with a rating of 600 MW(e) has been developed in 2002. Also, a I-NERI Project for studies on passive safety features of sodium cooled reactors has been initiated, and participation in the Generation IV (GIF) program is planned.

In Russia, based on its successful experience with fast reactors such as the BR-10, BOR-60 and BN-600 (April 8, 2002 marked the 22nd anniversary of the first power production with BN-600), work continues on an already licensed 800 MW(e) BN800 that can use civilian and ex-weapons plutonium. According to the revised "Programme for Nuclear Power Development in the Russian Federation for the Period 1998-2005, and for the Period Until 2010", the start-up of BN-800 at the Beloyarsk site is scheduled for 2010. Further activities in the fast reactor area in Russia include: (a) justification of a hybrid core design for BN-600 to incinerate weapons-grade plutonium; (b) justification of life extensions for BR-10, BOR-60, and BN-600; (c) review of the BN-800 reactor design to reduce construction costs; (d) development of advanced fast reactor designs with enhanced safety (large sodium cooled fast reactor with mixed oxide fuel, and BREST-300 lead cooled demonstration fast reactor with nitride fuel, and lead-bismuth cooled SVBR-75/100 reactor), including experimental support studies.

In the UK, there is no government sponsored Fast Reactor R&D programme, except for the UKAEA PFR decommissioning work at Dounreay. However, a small BNFL-funded Fast Reactor R&D programme involving BNFL/NNC/AEA Technology is pursued in the following fields: knowledge preservation; CAPRA-CADRA European collaboration; EU 5th Framework Programme (FWP) activities; and collaboration with Japanese research organizations. The CAPRA-CADRA collaboration with France, Germany, and Belgium covers reactor systems for plutonium and minor actinides burning sodium cooled Fast Reactors. The UK contributions involved core analyses, fuel performance analyses, including fuel performance code development and material properties, and fuel cycle scenario analyses. Recently, the emphasis of the CAPRA-CADRA activities is shifting to gas cooled Fast Reactors and to Accelarator Driven System (ADS) analyses. The UK is contributing to core design, thermal hydraulics design, and fuel design and performance of various FR and ADS concepts. As regards knowledge preservation activities, NNC is maintaining and adding to an archive database of historical FR papers. The aim of this activities is to ensure future retention/accessibility of FR historical information. As regards PFR decommissioning, both the sodium and caesium removal plants are in the commissioning phase. The demonstration of full throughput with inactive sodium was achieved in 2001.

In the U.S, the Generation IV program has seen significant progress during the year 2002. The Technology Roadmap was completed and issued in December 2002. The Roadmap identifies six systems deployable by the year 2030 or earlier that hold the potential for meeting the different Generation IV missions and the technology goals. The Roadmap also summarizes the R&D activities and the priorities for the six systems, and lays the foundation for R&D program plans. The six systems include 3, and potentially 4, concepts based on fast spectrum reactors, namely, the Gas Fast Reactor (GFR), Lead-Alloy Fast Reactor (LFR), Sodium Fast Reactor (SFR), and a version of the Supercritical Water Reactor (SCWR). The Generation IV R&D program plan is currently under development. It includes activities specifically related to the development of the individual systems, as well as crosscutting activities that support multiple systems in the areas of materials (primarily for high temperature operation), energy products (primarily for the production of hydrogen), and system evaluation (design and analysis code needs and evaluation methods for proliferation resistance and physical protection, and economics.) System specific development activities are conducted for the LFR and the GFR. Both the GFR and LFR activities are coordinated and complemented with NERI and I-NERI projects. The focus of the GFR development is in the area of fuels development and passive safety.

All the Liquid Metal Cooled Reactors activities are conducted in the framework of the Technical Working Group on Fast Reactors (TWG-FR), formerly International Working Group on Fast Reactors (IWG-FR), which is the only global forum for the review and discussion of LMFR programmes. This is of particular importance for those countries which are implementing fast reactor programmes. In several cases, these programmes also include development, design and operation of experimental fast reactors. Participation in TWG-FR activities ensures that international safety practices are taken into account during the design and operation of fast reactors, and that no country with a fast reactor programme is isolated in fast reactor technology development.

The TWG-FR has mostly focused on experimental and theoretical aspects of fast reactor technology and safety. A benchmark test with experimental data was conducted to verify and improve the codes used for the seismic analysis of reactor cores. A co-ordinated research project was conducted to apply acoustic signal processing for the detection of boiling or sodium/water reactions in LMFRs. Benchmark analyses addressed accident behaviour and design improvements of the Russian BN-800 reactor within the frame of a collaborative project between the IAEA and the European Community. In co-operation with the Department of Nuclear Safety, assistance was provided to ensure safe operation during the remaining lifetime and the development of an effective decommissioning programme for the BN-350 reactor in Kazakhstan. A co-ordinated research project is being conducted with the objective to reduce the calculational uncertainties of the LMFR reactivity effects. The first proposed benchmark model is based on the BN-600 hybrid core.

To foster the exchange of technical information and to contribute to the preservation of the base of LMFR technology knowledge, an updated LMFR database (FRDB), available on the Internet, has been developed. The FRDB contains detailed data of 35 experimental, prototype and commercial LMFRs. Each reactor plant is characterized by about 400 parameters, by design data and by relevant graphic materials.

In response to expressed needs by Member States, the Nuclear Power technology development Section has undertaken concrete steps towards the implementation of a FR data retrieval and knowledge preservation initiative. This initiative aims at providing an overall framework for the various programs being implemented in the Member States to stop data and information being destroyed, retrieve the data, assess its importance, determine what data and information should be retained, how information from different programs could be linked, how the quality of information should be assessed, and what standards should exist in software and hardware for preservation over the next 30 – 40 years. Provided adequate funding is ensured, it would support and coordinate data retrieval activities, and establish the portal for accessing the knowledge base. By addressing issues of “institutional memory" (through, e.g., retrieval and preservation of the decision making processes, including the “false trails” followed and eventually rejected) and of passing information from one generation to the next, it aims at more than collecting information on static Web-based databases.

High-level waste disposal is an element of paramount importance in the discussion of nuclear power generation sustainability. This, and the desire to reduce the quantity of long-lived waste material, have stimulated new interest in the transmutation of actinides and some long-lived fission products, and in emerging system technologies for energy production with reduced actinide generation. One such system is the combination of a particle accelerator with a sub-critical nuclear reactor; another possibility is to reduce the generation of actinides by the introduction of the thorium fuel cycle. The surmised advantages of accelerator driven systems (ADS) - apart from their intrinsic low production of long-lived radioactive waste, and transmutation capability - are also enhanced safety characteristics and better long-term resources utilization (e.g., in connection with thorium fuels). Important R&D programmes are being undertaken by various institutions in many Member States to substantiate these claims and advance the basic knowledge in this innovative area of nuclear energy development.

In Asia, ADS R&D studies are pursued with both goals in mind: energy production with reduced radioactive waste production and decreased proliferation hazard, on the one hand, and long-lived waste transmutation, on the other. The R&D efforts are concentrated in China, India, Japan and the Republic of Korea. The programmes are presently conducted at national level, with some bilateral or multilateral co-operation agreements. In China, the emphasis in the first phase (1998-2002) was on system optimisation, reactor physics and technology, accelerator physics and technology, and nuclear and material data. At the same time, considerable effort is being put into the preparation of the second phase (2000-2007) devoted to the ADS concept verification study. As regards Fusion/Fission Hybrid System, in the near-term the emphasis will be put on the experiments performed at the two large testing facilities, HL-1M and HT-7. In parallel, scope and objectives for both the medium-term and long-term development of Fusion/Fission Hybrid System will determined, and the respective R&D programs developed. In India, a detailed study of various aspects of ADS in 2001 by a Coordination Committee of BARC lead to the definition of a few short-term work modules that have their own applications and spin-offs. Currently ongoing activities are related to (a) experimental plan of a sub-critical core driven by 14-MeV neutrons from $T(d,n)^4He$ reaction for reactor physics studies, (b) development of a high-intensity 10-MeV proton linac as front-end of accelerator for ADS, (c) setting up molten lead-bismuth eutectic experimental loop, and (d) developing a fabrication and characterizing facility for bulk niobium superconducting RF cavities. In Japan, a 800 MW(th) sub-critical lead-bismuth eutectic cooled core concept is proposed. This ADS could transmute 250 kg of minor actinides per year, corresponding to the minor actinide amount produced per year in about ten 1 GW(e) LWRs. Considerable R&D work is under way and planned at JAERI in the fields of sub-critical core design, spallation target technology, accelerator development, and minor actinide fuel development. In particular, with the objective of studying and evaluating the physics and engineering feasibility aspects of the ADS, JAERI has proposed the construction of the Transmutation Experimental Facility (TEF) within the framework of the High-Intensity Proton Accelerator Project. In the Republic of Korea, KAERI has been working on the HYPER (HYbrid Power Extraction Reactor) concept since 1997. The HYPER conceptual design will be completed by 2006. KAERI's ADS R&D consists of 3 stages: a basic concept of HYPER was established in the first stage (1997 - 2000), the basic technology related to HYPER is being investigated in the second stage (2001 - 2003), and the conceptual design will be completed in the third stage (2004 - 2006). Presently, KAERI is focusing on heavy liquid metal (lead-bismuth eutectic), and on fuel studies. KAERI joined the MEGAPIE project in 2001, and is constructing a lead-bismuth corrosion loop. For the fuel studies, KAERI is discussing a possible collaboration with ANL-West, and also investigating fission product irradiation tests using its own research reactor HANARO.

In Europe, the main driving force behind ADS is long-lived waste transmutation, but the ADS capability to produce energy is also investigated. The national (Belgium, France, Germany, Italy, Spain, Sweden) programmes on ADS R&D are converging towards the demonstration of the basic aspects of the ADS concept. These R&D activities are conducted both nationally and as joint efforts within the fifth and upcoming sixth framework programme of the European Union (EU).

In Russia, there is considerable R&D effort dedicated to the development of the ADS technology. These studies are strongly coupled with advanced fuel cycle studies that aim at waste minimization and at a strong overall simplification of the nuclear fuel cycle (e.g., molten salt). Recent ADS R&D highlights in Russia include (a) the delivery of the spallation target MK-1 was to the University of Nevada, Las Vegas (UNLV), where it is currently undergoing thermohydraulic testing. This target was designed and constructed in Russia during the year 2001, for irradiation in the 800 kW proton beam of the LANL accelerator. The program for the target's start-up and duration tests under isothermal conditions was prepared; (b) analysis of a proposal to establish an international ADS demonstration project at the SSC RF IPPE site in Obninsk (Nuclear Waste Burner (NWB) project: the construction of the NWB could be completed in 7 to 8 years, and preliminary results show that a burning rate of ~10-20 kg minor actinides per year can be achieved in sub-critical core having 200 to 400 kg minor actinide inventory); and (c) the definition of RF Minatom's program of work for the sub-critical cascade molten salt reactor concept in a closed nuclear fuel cycle (RSC KI and VNIITF); and (d) activities within the framework of the ISTC Sub-critical Assembly Dubna (SAD) project (JINR).

In the U.S., the Advanced Accelerator Applications (AAA) program has evolved into the Advanced Fuel Cycle Initiative (AFCI), broadening the scope into a program for development of fuel cycles for enhanced nuclear fuel and waste management, including transmutation. The Program emphasizes activities in the areas of reactor and accelerator based transmutation, advanced fuels and separations development, and long term waste toxicity reduction. The main program goals are reduction of waste volumes and inventories of civilian plutonium, recovery of the energy value remaining in spent nuclear fuel, reduction of the radiotoxicity of waste for disposal, reduction of short and long term heat loads in the repository, elimination of the technical need for a second repository, and support of advanced (Generation IV) fuel development. The successful operation of the pyroprocess technology facilities at Argonne National Laboratory (ANL) in Idaho has continued with additional treatment of spent EBR-II fuel. Under the AFCI integration, however, the facilities maintain treatment goals for EBR-II fuel, but also play a more prominent role in supporting the technology development for advanced recycle technologies. Emphasis under the current AFCI separations plan is on technology development to increase process throughput, including demonstration of the oxide fuel reduction, transuranic recovery processes, high-throughput electrorefiners, and demonstration of the hybrid UREX-Pyro process. The characterization of the waste forms has continued, obtaining very positive results in terms of nuclide release rates measured in immersion tests. The development of transmutation fuels for fast spectrum systems has continued: fabrication of samples of metal and nitride fuel is currently taking place, for irradiation this year in the Advanced Test Reactor (ATR) in Idaho. Samples include a variety of compositions of plutonium and minor actinides. Non-fertile and low-fertile samples are being prepared for irradiation. Preparations are also ongoing for test irradiations at the Phénix reactor, in collaboration with the Commissariat a l'Energie Atomique (CEA). Activities in transmutation engineering have continued in several areas. In physics, work is ongoing with the analysis of the MUSE-4 experiments, support of the European accelerator-multiplier coupling experiment TRADE, and analysis of PROFIL irradiation experiment. Further progress has been made in cross section data and additions to the AAA materials handbook. The collaboration with MEGAPIE in the areas of spallation target technology and physics and engineering support, has continued. Support of the MYRRHA ADS demonstration project in Belgium is also planned. The DELTA loop at the Los Alamos National Laboratory (LANL) is now in operation. Conditioning tests are being performed and a 1000-hour corrosion test is planned for 2003.

The activities of the Nuclear Power Technology Development in the ADS area, which are also carried out in the frame of the TWG-FR, include preparation of status reports on advanced technology development, conduct of technical information exchange meetings and co-ordinated research projects on the use of thorium fuel in accelerator driven systems and reactors to constrain plutonium production and to reduce long-term waste toxicities. In particular, the IAEA is providing for a review and comparison of different options to achieve these aims, including review of new technical measures to achieve proliferation resistance.

To harmonize efforts, the elaboration of a database of existing and planned experimental facilities, as well as R&D programmes for accelerator driven systems and related research and development was initiated in 1997. Presently, the WWW-based version of the database is operational and data collection has started.

Members of the TWG-FR (formerly IWG-FR), established in 1967	
Belarus	Kazakhstan
Brazil	Republic of Korea
China	Russian Federation
France	Switzerland
Germany	United Kingdom
India	United States of America
Italy	European Commission
Japan	OECD/NEA

I–5. SMALL AND MEDIUM SIZED REACTORS

In operation	144
Under construction	11
Number of countries with SMRs	29
Generating capacity, GW(e)	62
Operating experience, reactor-years	5249

In the early decades, civil nuclear power essentially borrowed from the experience of reactors for nuclear submarines, which came first and were essentially small-capacity reactors. In 1970’s, the major focus for nuclear power was on the design and construction of nuclear plants of increasing size, with average size levelling out at about 1000 MW(e) with a tendency for further increase.. This was and is generally appropriate for many industrialized countries, which could add generation capability to their electrical grids in larger increments and benefit from the construction costs reduced due to scale factor. However, it is not appropriate for many developing countries that have small electric grids, limited capacity for investment or small turnover of capital in the electricity market.

Even the largest electric grids experienced problems with excess capacity in the 80’s and 90’s. In the near future some countries may face lack of sites that are appropriate for further construction of large-capacity plants. For some overpopulated developing countries new employment opportunities are created through the multiplicity of plants, which increases upon the reduction of unit power. Finally, new technologies cannot be deployed at once to a large scale. Learning from a small prototype plant may be a necessary step in reaching the final goal of wide-scale deployment of an innovative technology.

For reasons mentioned above, starting from 1980’s there has been an increasing emphasis on the development of small and medium sized reactors (SMRs)-up to about 700 MW(e). Also, it turned out that SMRs are of particular interest for advanced future non-electric applications, such as hydrogen production, coal liquefaction and other process heat applications.Some examples are listed below:

PBMR (Pty) Ltd, an international consortium from South Africa and the United Kingdom is pursuing a Pebble Bed Modular Reactor (PBMR) project to develop a gas cooled reactor (~120 MW(e)) utilizing fuel and systems developed in Germany and a closed cycle gas turbine.

In Argentina, the construction of a small 25 MW(e) prototype reactor (CAREM) with an integral steam generator that could be coupled to a desalination process was approved and site selection process is underway.

Other activities on development of LWRs of integral design are being carried out in the Republic of Korea for the 330 MW(th) SMART design, in Russia for the VK-300, VPBER-600, VBER-300, and ABV6M and in the U.S. for the IRIS modular LWR that emphasizes proliferation resistance through features to facilitate safeguards (e.g. a core life of 8 years). Conceptual and basic designs for Russian VK-300 seawater desalination/electricity co-generation plant have been completed, and there are plans to construct it at the Arkhangelsk site in 2010. In the Republic of Korea, conceptual design has been completed and basic design is underway for a 65 MW(th) prototype plant for the SMART reactorThe target for obtaining a construction permit is June 2005.

Japan operating a 30 MW(th) gas cooled high temperature test reactor (HTTR) which uses prismatic fuel. It is also studying multiple concepts and applications of evolutionary and innovative SMRs with light-water, sodium and lead-bismuth coolants..

In China, the Institute for Nuclear Energy Technology near Beijing has developed an integral PWR of 200MW(th), called the NHR-200, for desalination and district heat, as well as a 10 MW high temperature test reactor (HTR-10). The China Experimental Fast Reactor (CEFR) of 25 MW(e) is under construction.

India is developing a conceptual design of the 300 MWe AHWR co-generation plant to make efficient use of the thorium ores present in the country and later on to couple it with the Fast Reactor programme. It is also studying an option of a lead-bismuth cooled compact core reactor of 100 KWth.

The United States, Russia, France and Japan are working on the preliminary design of the 284 MW(e) Gas-Turbine Modular Helium Reactor (GT-MHR), using a prismatic block fuel design developed in the US. The concept is being designed for plutonium consumption with planned subsequent commercial application for electricity and heat production.

Russia is considering barge-mounted versions of several small sized reactors formerly used in marine reactors for electricity as well as heat generation and seawater desalination in northern parts of Siberia. Such reactors are factory fabricated and fuelled and could be eventually be returned to the supplier. Some of them are developed as modules to be serially produced for larger capacity plants.

The 21st century promises the most open, competitive, globalized markets in human history, and the most rapid pace of technological change ever. If a technology is to survive and flourish in this century, continual innovation is essential. This makes no exception for nuclear power and all its components, including SMRs. On the total, particular R&D activities are on-going worldwide for more than 50 concepts of innovative SMRs.

In the USA, the DOE Nuclear Energy Research Initiative addresses innovative concepts for nuclear power. Many reactors considered in the frame of this initiative are in the SMR’s power range.

The DOE initiated Generation IV International Forum (GIF) initiative is an international project directed toward deployment of innovative reactors in the next 25-40 years. Out of the 6 nuclear energy systems selected for further R&D only 2 make no provisions for the reactors that fit into SMR range.

I–6. INTERNATIONAL PROJECTS ON INNOVATIVE REACTORS AND FUEL CYCLES

Complementing many initiatives there are two major international efforts to promote innovation, the Generation IV International Forum (GIF) and the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO).

The US Department of Energy's Office of Nuclear Energy, Science and Technology has for several years promoted development to move beyond Generation II reactors (today's commercial power stations) and Generation III reactors (the currently available advanced LWRs) to the next generation, Generation IV. The initiative led in 2000 to the establishment of GIF, an international effort to jointly define the future of nuclear energy research and development. Members of GIF are Argentina, Brazil, Canada, France, Japan, the Republic of Korea, South Africa, Switzerland, the UK the USA and Euratom. The IAEA and the OECD/NEA have permanent observer status in the GIF Policy Group, which governs the project's overall framework and policies.

The objective as stated in the GIF charter is "the development of concepts for one or more Generation IV nuclear energy systems that can be licensed, constructed, and operated in a manner that will provide a competitively priced and reliable supply of energy to the country where such systems are deployed, while satisfactorily addressing nuclear safety, waste, proliferation and public perception concerns". GIF began with an evaluation of an extensive, wide ranging collection of concepts. In 2002, the GIF Policy Group selected six of these for future bilateral and multilateral cooperation, and defined a "technology roadmap" to help prepare and guide subsequent research and development. The R&D to be conducted on a bi-lateral or multi-lateral basis may start in 2004.The six selected systems are:

- gas cooled fast reactor system,
- lead alloy liquid metal cooled reactor system,
- molten salt reactor system,
- sodium liquid metal cooled reactor system,
- supercritical water cooled reactor system, and
- very high temperature gas cooled reactor systems.

The IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) has as its main objectives, first, helping to ensure that nuclear energy is available to contribute to fulfilling energy needs in the 21st century in a sustainable manner and, second, bringing together technology holders and technology users to consider jointly the international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles. As of December 2003, members of INPRO included Argentina, Brazil, Bulgaria, Canada, China, Germany, India, Indonesia, the Republic of Korea, Pakistan, the Russian Federation, South Africa, Spain, Switzerland, the Netherlands, Turkey and the European Commission.

In its first phase, Phase-IA, INPRO outlined the prospects and potential of nuclear power and prepared guidelines for evaluating innovative concepts for both nuclear reactors and fuel cycles. These guidelines include Basic Principles, User Requirements and Criteria for innovative nuclear energy systems, covering the areas of economics, sustainability and environment, safety, waste management, and proliferation resistance. They also outline a method (the INPRO Methodology) for applying INPRO user requirements to specific designs and concepts. In additional, INPRO has produced recommendations on cross-cutting infrastructure, institutional, legal, social and human resource issues affecting the evolution of nuclear power. The results of INPRO Phase-IA are now available as IAEA-TECDOC-1362.

Phase-IB was started in July 2003 and is on-going with the validation of the INPRO Methodology through Case Studies by trial examination of particular innovative nuclear energy technologies. Case Studies are performed by Member States and selected individual experts. An interactive model for nuclear energy planning is being developed to support the INPRO Methodology.

After the validation of the INPRO methodology, interested Member States will be offered to perform an assessment of innovative technologies on the basis of the updated INPRO Methodology.

Upon successful completion of Phase-I, taking into account advise from the INPRO Steering Committee and Member States, Phase-II of INPRO may be initiated to identify innovative technologies, which might be appropriate for commencing an international project on innovative nuclear technology development.