Advanced and Innovative Technologies

1. In response to the challenges currently facing nuclear power as outlined in Section B.1, many countries are working on advanced reactor – fuel cycle systems to improve their economics, safety and proliferation resistance. With regard to advanced NPP designs, efforts focus particularly on making plants simpler to operate, inspect, maintain and repair. Safety improvements include features to further reduce the likelihood of accidents, to allow operators more time to assess developments before acting, and to provide ever greater protection against any possible releases of radioactivity to the environment.

2. There are two basic categories of advanced designs. *Evolutionary designs* improve on existing designs through small or moderate modifications, with a strong emphasis on maintaining proven design features to minimize technological risk. Evolutionary designs incorporate improvements based largely on feedback from experience and the incorporation of new technological achievements, plus the possible introduction of some innovative features, e.g. passive safety systems. *Innovative designs* incorporate radical conceptual changes in design approaches or system configuration. They generally require substantial R&D, feasibility tests, and a prototype or demonstration plant.

3. In the near term, most new NPPs are likely to be evolutionary designs building on proven systems while incorporating technological advances and often economies of scale. For the longer term, the focus is on innovative designs, several of which are in the small-to-medium range (less then 700 MW(e)). These envision construction using factory built components, including complete modular units for fast on-site installation, creating possible economies of series production instead of economies of scale. Other advantages foreseen for smaller units are easier financing, their greater suitability for small electricity grids or remote locations, and their potential for district heating, seawater desalination and other non-electric applications. All should increase their attractiveness for developing countries.

4. The summary below of current developments categorizes designs according to reactor type: water cooled reactors (both LWRs and HWRs), gas cooled reactors and fast reactors that use liquid metal (e.g. sodium) or gas (e.g. helium) as a coolant.

A. Light water reactors (LWRs)

5. LWRs make up 80.5% of all NPPs in operation and are thus a natural focus for evolutionary design improvements. The principal large evolutionary designs are the ABWR (advanced boiling water reactor) and the ABWR-II of Hitachi and Toshiba in Japan and General Electric (GE) in the USA; the APWR (advanced pressurised water reactor) of Mitsubishi in Japan and Westinghouse of the USA and the APWR$^+$ of Mitsubishi; the BWR 90+ of Westinghouse Atom of Sweden; the EPR and the SWR-1000 of Framatome ANP from France and Germany; the ESBWR of GE; the AP-1000 of Westinghouse in the USA; the WWER-1000 of Atomenergoproject and Gidropress, Russia; the KSNP$^+$ and the APR-1400 of Korea Hydro and Nuclear Power and the Korean Nuclear Industry; and the CNP-1000 of the China National Nuclear Corporation.

6. The main small and medium-size evolutionary LWR designs are the AP-600 and the integral IRIS designs of Westinghouse; the WWER-640 of Atomenergoproject and Gidropress, the PAES-VBER of the Experimental Design Bureau for Machine Building (OKBM) and the VK-300 of RDIPE, all from Russia; the HSBWR and HABWR design concepts of Hitachi; and the NP-300 of Technicatome in France.

7. Two ABWRs are operating at TEPCO's Kashiwazaki-Kariwa site, and ten more are under construction or planned.[1] In December 2003, Teollisuuden Voima Oy (TVO) of Finland signed a turnkey contract with Framatome ANP and Siemens AG for an EPR for the Olkiluoto site. In the Republic of Korea, the first KSNP$^+$ units are planned for Shin-Kori-1 and -2 with construction to start in 2004 and 2005 respectively. Two APR-1400 units are also planned for Shin-Kori, with construction of the first to start in June 2005. For the AP-1000, Westinghouse submitted an application to the US NRC in March 2002 for Final Design Approval and Design Certification. The Final Design Approval is expected in 2004 and Design Certification is expected in 2004 or 2005. For IRIS, Westinghouse plans to submit a Design Certification application in 2005, with the objective of approval by 2008 or 2009. In 2002 the ESBWR design and technology base were submitted to the US NRC as a first step toward Design Certification. For Framatome's SWR-1000, the pre-application phase for Design Certification by the US NRC started in 2002.

8. For innovative LWR designs, SMART in the Republic of Korea and CAREM in Argentina are both integral primary system designs, and both plan verification and prototype or demonstration plants prior to commercial deployment. Examples of innovative LWRs designed particularly to achieve a high conversion ratio in converting fertile isotopes to fissile isotopes are the RMWR of the Japan Atomic Energy Research Institute (JAERI) and the RBWR of Hitachi. Thermodynamically supercritical water cooled systems (SCPR) are being developed within the framework of GIF, and will most likely require a prototype or demonstration plant.

B. Heavy water reactors (HWRs)

9. HWRs account for about 8% of operating NPPs. Their special features are that they can be fueled with natural uranium due to their good neutron economy made possible by using heavy water as the moderator, and that they can be kept operating during refueling.

10. Atomic Energy of Canada Limited's (AECL's) evolutionary CANDU design, the ACR-700, retains the general reactor characteristics and power levels of the current CANDU-6 and CANDU-9, while aiming to improve the economics through plant optimization and simplification. New features in the ACR-700 are its use of slightly enriched uranium and light water coolant. It is currently undergoing a pre-application licensing review by the US NRC, after which AECL intends to seek a Design Certification in 2005. It is simultaneously undergoing a licensing review in Canada.

11. Within the framework of GIF, AECL is developing an innovative design, the CANDU-X, which would use supercritical light water coolant to achieve high thermodynamic efficiency.

12. India has made regular evolutionary improvements to its HWR designs ever since its initial units at Rajasthan-1 and -2. In 2000 construction began on two larger 490 MW(e) units at Tarapur. India is also developing the Advanced Heavy Water Reactor (AHWR), a heavy water moderated, boiling light water cooled, vertical pressure tube type reactor, that includes passive safety systems and is designed for optimal thorium use.

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[1] Two ABWRs are under construction in Taiwan, China.

C. Gas cooled reactors (GCRs)

13. Gas cooled reactors – both CO_2 cooled Magnox reactors and advanced gas cooled reactors (AGRs) – dominate nuclear electricity production in the UK. There is a long history of R&D on high temperature reactors (HTGRs) with helium as the coolant and graphite as the moderator, and prototype and demonstration plants using the Rankine steam cycle have also been built and operated. Distinctive features of HTGRs include the coated particle fuel design, which acts as a barrier against fission product release, and a low power density, high heat capacity core that increases safety.

14. There is considerable current effort devoted to gas turbine direct Brayton cycle helium cooled designs that promise high thermal efficiency and low generation costs. Eskom, South Africa’s Industrial Development Corporation, and British Nuclear Fuels (BNFL) are jointly developing a pebble bed small modular HTR (PBMR) system. Also, the Russian Ministry of Atomic Energy, OKBM, General Atomics, Framatome and Fuji Electric are jointly developing a small gas turbine modular helium reactor (GT-MHR). This is designed for electricity production using weapons grade plutonium.

15. The high temperatures made possible by the inert helium coolant and coated fuel particles are well above those possible in water cooled reactors, and have prompted research for a number of high temperature heat applications such as hydrogen production. HTGRs also have potential for low temperature heat applications such as seawater desalination by providing steam produced by the waste heat. Currently two helium cooled test reactors are in operation, the High Temperature Engineering Test Reactor (HTTR) at JAERI in Japan and the HTR-10 at the Institute of Nuclear Energy Technology (INET) in China. A helium cooled very high temperature reactor (VHTR) is being developed within the framework of GIF with a focus on hydrogen production. Similar independent efforts are ongoing in Russia with the Minatom’s OKBM taking a lead.

D. Fast reactors

16. Liquid metal cooled fast reactors (LMFRs) have been under development for many years, primarily as breeders. They have accumulated more than 200 reactor-years of operational experience based on successful designs including the small Prototype Fast Reactor in the UK, the prototype Phénix fast reactor in France, the BN-350 in Kazakhstan (which produced electricity and desalinated seawater), BN-600 in Russia, Monju in Japan, and the 1200 MW(e) Superphénix in France. In addition, there is a considerable base of experience with lead-bismuth eutectic cooled propulsion (submarine) reactors built and operated in the former USSR.

17. Fast reactors use fast neutrons for sustaining the fission process and can simultaneously convert plentiful fertile isotopes of uranium or thorium into fissile isotopes that can be used for fuel. Plutonium breeding allows fast reactors to extract 60-70 times as much energy from uranium as do thermal reactors. In addition, fast reactors could potentially help reduce plutonium stockpiles, and reduce the required isolation time for high level radioactive waste by making use of transuranic radioisotopes and transmuting some of the most cumbersome long lived fission products.

18. Current LMFR activities include the construction in China of the small Chinese Experimental Fast Reactor (CEFR) with first criticality scheduled for the end of 2005; the development of the small KALIMER design in the Republic of Korea; the successful operation of the Indian Fast Breeder Test Reactor (FBTR), especially for fuel irradiation and materials research; the development of the medium

size Prototype FBR (PFBR) in India for which construction started in the final quarter of 2003; Japanese initiatives to restart Monju; the Japan Nuclear Cycle Development Institute’s “Feasibility Study on a Commercialised Fast Reactor Cycle System”; efforts in Russia to complete the BN-800 reactor at Beloyarsk by 2010; the 2003 restart of Phénix in France, principally for experiments on long lived radioactive nuclide incineration and transmutation; and several design studies around the world of advanced fast reactors having improved economics and enhanced safety.

19. Development activities are underway in GIF on lead alloy and sodium liquid metal cooled fast reactor systems and on gas (helium) cooled fast reactors (GFR) with an integrated fuel cycle with full actinide recycle. Similar efforts are ongoing in Russia.

20. Research on fast neutron spectrum hybrid systems (e.g. accelerator driven systems (ADS)) is also underway in several countries. The potential advantages of ADS systems are low waste production, high transmutation capability, enhanced safety characteristics and better long term utilization of resources (e.g. with thorium fuels). ADS research activities include the development of the HYPER concept by the Republic of Korea, plus design studies and research on basic physical processes in Russia, in eight EU countries and in the US Advanced Accelerator Applications Program (recently merged with the Advanced Fuel Cycle Initiative).

E. International initiatives for innovative designs

21. Complementing the many initiatives above 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).

22. 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.

23. 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 six selected systems are:

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

24. The IAEA's 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 September 2003, members of INPRO included Argentina, Brazil, Bulgaria, Canada, China, France, Germany, India, Indonesia, the Republic of Korea, Pakistan, the Russian Federation, South Africa, Spain, Switzerland, the Netherlands, Turkey and the European Commission.

25. In its first phase, 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 "user requirements" 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 addition, INPRO has produced recommendations on cross-cutting infrastructural, institutional, legal, social and human resource issues affecting the evolution of nuclear power.

26. In July 2003, INPRO entered a new stage focussed on validating the INPRO methodology through test applications in a series of case studies. The results will be used to update and sharpen the user requirements and methodology, which will then be generally available for applications by Member States and others to evaluate proposals and guide nuclear R&D strategies.

F. Fusion

27. Nuclear fusion requires much higher temperatures than nuclear fission – on the order of 10^6 degrees Kelvin. At such high temperatures, the nuclear fuel is in a "plasma state" of free nuclei (ions) and electrons, and special techniques are needed to confine the plasma since no materials can withstand the heat. There are two major confinement concepts, magnetic (tokomak) and inertial. The International Thermonuclear Experimental Reactor (ITER), which is the focus of much of today's experimental and theoretical fusion research, uses magnetic confinement. ITER's purpose is to demonstrate plasma burning and, although ITER itself will not generate electricity, to show that electricity generation from fusion can be safe and environmentally attractive. More specifically, it is designed to generate 500 MW of fusion energy per pulse, with each pulse expected to last several minutes. The amount of energy generated is expected to be at least ten times higher than the amount of input energy needed to run the reactor.

28. Currently ITER's Engineering Design Activities stage has been completed, and the project is nearing a decision on site selection. In 2003 ITER gained three new members and lost one. The new members are the USA, which had originally left ITER back in 1999, China and the Republic of Korea. Canada withdrew from ITER in December 2003. That makes six members in total, the other three being the European Union, Japan and Russia. The two site proposals still under consideration are in France (Cadarache) and Japan (Rokkesho-muro). Following a final decision on the site, the next step is establishing the ITER International Fusion Energy Organization, anticipated for 2004, which will then carry the project forward.

29. Research also continues on other magnetic confinement approaches such as stellarators, compact tori and reversed field pinches, which also expands the basic understanding of plasma physics and fusion.

30. Inertial confinement is being developed intensively by national programmes in the USA and France. The National Ignition Facility at the University of California’s Lawrence Livermore National Laboratory, which is scheduled for completion in 2008, will be a stadium-sized facility containing a 192-beam, 1.8-Megajoule, 500-Terawatt, 351-nm laser system together with nearly 100 experimental diagnostics. Operational testing for several of the beams has already been completed.