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Workshop on
Nuclear Reaction Data and Nuclear Reactors:
Physics, Design and Safety

16 February - 12 March 2004

Nuclear Power: Current Status and New Developments

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Overview of Global Development of Advanced Nuclear Power Plants

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Abstract: Nuclear power has proven its viability as an energy source in many countries. Nuclear power technology is mature, and has achieved tremendous progress in the last decades. Like any other progressing technology, it continues to pursue improvements. The accumulated experience, which now exceeds 11,000 reactor-years of operation, is being used to develop advanced nuclear power plant designs. This development is proceeding for all reactor lines -- water-cooled reactors, gas-cooled reactors, and liquid metal-cooled reactors so that nuclear power can play an important and increasing role in global energy supply in the future. Improved economic competitiveness and a very high level of safety are common goals for advanced designs. To achieve economic competitiveness for new plants, proven means for achieving cost efficiency are being applied and new approaches are being pursued. There is also considerable potential for nuclear energy to expand beyond production of electricity to other applications such as sea-water desalination and hydrogen production.

1. Current Status of Nuclear Power

In the past 50 years, nuclear power has grown from a new scientific development to become a major part of the energy mix in many countries. As of September 2002, there were 440 nuclear power plants operating in 30 IAEA Member States with a total worldwide installed nuclear capacity of 360.4 GWe[1]. In addition, 32 units were under construction with a total capacity of 26.4 GWe. During 2002 nuclear power plants produced a total of 2574.2 billion kWh of electricity, which was 16% of the world's total electricity production [1].

The future contribution of nuclear power to meeting global energy demand is difficult to predict. Some countries have policies to phase out nuclear power while other countries see advantages in nuclear power to provide energy security. Countries planning to increase their nuclear capacity include China, India, Japan, Republic of Korea and Finland.

Based on information provided by its Member States, the IAEA's projects that over the next 25-30 years nuclear power will likely not keep pace with global growth of electricity demand. The IAEA estimates that nuclear power will provide about 15 – 16 % of the world's electricity in 2010; only 13 to 15 % of the world's electricity by 2020, and 11 to 12 % by 2030 [1] as countries invest in other energy options. Although the IAEA estimates that the percentage of the world's electricity produced by nuclear power will decrease, it estimates that the actual amount of nuclear generated electricity will

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[1] The data are available from IAEA's Power Reactor Information System (PRIS). The totals include the nuclear capacity and nuclear electricity generation in Taiwan, China.

increase. Compared to 2002's nuclear electricity production of 2574.2 billion kWh, the IAEA estimates that nuclear power will produce between 2830 and 2987 billion kWh annually by 2010, between 3085 and 3756 billion kWh annually by 2020, and between 2881 and 4369 billion kWh annually by the year 2030 [1].

Of course these estimates will change with time, and longer term estimates are even more uncertain depending on economic growth and environmental constraints. Several important factors will influence nuclear energy's future contribution, including:

- The degree of global commitment to greenhouse gas reduction
- Continued vigilance in safe operation of nuclear plants and fuel cycle facilities
- Continued vigilance in safeguards
- Technological maturity; economic competitiveness; and financing arrangements for new nuclear plants
- Implementation of nuclear waste disposal
- Public perception, information and education

Clearly the nuclear community should focus on insuring success in each of these areas.

2. Goals of nuclear power development

2.1 Economic competitiveness

Economic competitiveness with other energy sources is an obvious goal of new plant development. Many of the world's electricity markets are moving towards greater competition. Both private sector and state-owned electricity generating organizations carefully examine the costs of their operations, and focus on supply technologies that are low cost and low risk.

Capital costs for nuclear plants generally account for 45-75% of the total nuclear electricity generation costs, compared to 25-60% for coal plants and 15-40% for gas plants. This high capital cost presents a significant challenge to the addition of new nuclear power capacity. Until recently, nuclear power's advantage in having a small share of its generating costs in fuel costs could offset the disadvantage of its high capital costs. Moreover, in protected markets, investment costs could be recovered over several decades through regulated rates. Now, with increased competition in the electric power industry, short-term profitability has become a criterion for successful generation along with long-term economic viability. With deregulation, owners are not guaranteed cost recovery through regulated rates, and, with privatization, investors seek appropriately rewarded risk, which often translates into seeking small capital investments and high returns, and the minimization of their economic risks. If nuclear plants are to form a significant part of the future generating mix in competitive electricity markets, capital cost reduction through simplified designs must be an important focus. Reductions in operating, maintenance and fuel costs should also be pursued[2].

Design organizations are challenged to develop advanced nuclear power plants with lower capital costs and shorter construction times (e.g. by simplification, standardization, modularization, etc.) and

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[2]Although the economic competitiveness of fossil fuelled plants may be reduced in the future due to, for example, rising fuel costs and, in some countries, the introduction of taxes on CO_2 emissions, the nuclear power industry should not have a reduced incentive for cost reduction. Importantly, technologies for fossil fuelled plants also progress and one area of current development involves "clean" new plants with carbon capture.

sizes suitable for various grid capacities and owner investment capabilities. This includes large sizes for some markets and small and medium sizes for others.

To meet the competitiveness challenge, construction delays must be avoided, regulatory procedures and requirements must be stable, plant design must be well in hand before the start of construction, and construction and operations management personnel need to have high levels of competence. It is important to fully implement proven means of cost reduction, and to examine, develop and implement new approaches to reduce costs. To achieve the largest reductions in capital cost, both proven means and new approaches should be applied. These proven means and new approaches are discussed in more detail in Section 3.

Studies on projected costs of generating electricity provide results that depend strongly on the assumptions used. Due to the range of market conditions and generating costs in various countries, and the wide variety of assumptions used to forecast such costs, no single technology can be declared optimal in all countries. Importantly, in addition to economics, a country's national policy issues, such as diversity and security of its energy supply as well as environmental policies, may affect the decision on whether or not to construct nuclear power plants.

It is also important to note that the different generating options also have different cost sensitivities. Because of high capital costs and long construction periods, nuclear power generation costs, and, to a somewhat lesser extent, coal power generation costs, are highly sensitive to discount rates. Generating costs for coal-fired plants vary with coal prices and with the level of pollution abatement required. Generating costs for gas-fired power plants are highly sensitive to gas prices, which account for a large proportion of total costs[3].

In examinations of economic competitiveness, the external costs of various energy options should also be addressed. In idealized markets all costs associated with a technology would be internalised as part of its economic cost, and decisions based solely on economic costs would automatically properly reflect all social considerations. Nuclear energy is largely ahead of other energy technologies in internalising its external costs. The costs of waste disposal, decommissioning and meeting safety requirements are in most countries already included in the price of nuclear electricity. Progress towards a more level playing field where external costs of other energy technologies are more consistently internalised as part of their economic costs would thus result in more balanced assessments of energy options. As indicated by the results of the ExternE studies in Europe [3], external costs for fossil-fired plants operated to current standards are well above external costs of NPPs, also operated to current standards.

2.2 Achieving very high safety levels

In the course of nuclear power development in the latter part of the twentieth century, there have been significant developments in technology for reactor safety. These include:

- advances in the application of PSA;
- introduction of more rigorous quality assurance programmes for plant design, licensing, construction and operation;

[3] In this context it is important to note that liberalized markets do not necessarily favour less capital-intensive energy conversion systems and penalize capital intensive projects. Under conditions of low power prices and increasing prices for fossil fuel, the capital investment payback times for nuclear plants can be shorter than those for coal fired plants and CCGT plants [2].

- increased attention to the effect of internal and external hazards – in particular the seismic design and qualification of buildings;
- major advances in fracture mechanics and non-destructive testing and inspection;
- increased emphasis on the man-machine interface including improved control room design, and plant design for ease of maintenance;
- rapid progress in the field of control and instrumentation – in particular, the introduction of micro-processors into the reactor protection system; and
- increased emphasis on prevention and mitigation of severe accidents.

New nuclear plant designs are being developed to meet stringent safety requirements. While there are differences in safety requirements among countries developing new designs, the stringent requirements are generally reflected in the IAEA's **Safety Standards Series** [see for example 4, 5, 6], which consists of the following categories:

Safety Fundamentals present basic objectives, concepts and principles of safety and protection in the development and application of nuclear energy for peaceful purposes;

Safety Requirements establish the requirements that must be met to ensure safety. These requirements, which are expressed as 'shall' statements, are governed by the objectives and principles presented in the Safety Fundamentals; and

Safety Guides recommend actions, conditions or procedures for meeting safety requirements. Recommendations in Safety Guides are expressed as 'should' statements, with the implication that it is necessary to take the measures recommended or equivalent alternative measures to comply with the requirements.

The Agency's safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in their national regulations.

Technical aspects of safety including principles are discussed in Reference [4] for siting, design and construction, commissioning, operation and maintenance, and radioactive waste management and decommissioning.

In 2000 the Agency published the document "Safety of Nuclear Power Plants: Design" [5] which establishes nuclear plant safety design requirements applicable to safety functions and associated structures, systems and components, as well as to procedures important to nuclear plant safety. It recognizes that technology and scientific knowledge will continue to develop, and that nuclear safety is not a static entity; however, these requirements reflect the current consensus. They are expressed as 'shall' statements, and are governed by the objectives and principles in the Safety Fundamentals document. The Design Requirements document avoids statements regarding the measures that 'should' be taken to comply with the requirements. Rather, Safety Guides are published from time to time by the Agency to recommend measures for meeting the requirements, with the implication that either these measures, or equivalent alternative measures, 'should' be taken to comply with the requirements.

The new nuclear power plant designs currently under development incorporate various technical features to meet very stringent safety requirements [5]. Specifically, safety objectives for future plants include reducing the likelihood of accidents as well as mitigating their consequences in the extremely unlikely event that they occur. The objectives include the practical elimination of accident sequences that could lead to large early radioactive release, whereas severe accidents that could imply late containment failure are to be considered in the design process so that their consequences would necessitate only protective measures limited in area and in time [7], [8].

Discussions of the safety of future plants often involve different types of probabilistic safety criteria (PSC). PSC can be defined as *limits*, not to be exceeded, or as *targets*, *goals* or *objectives* (to strive for, but without the implication of unacceptability if the criteria are not met). PSC can be related to the core damage frequency (CDF), which is predicted by performing a level 1 PSA. Another type of PSC can be related to the large early release frequency (LERF) that would follow from severe core damage together with a major early failure of the containment. Use of LERF in PSC carries the implication that a late failure of the containment may be averted by accident management procedures, or mitigated by emergency response (e.g. evacuation of the public in the vicinity of the plant).

Discussions of PSC *targets* for CDF and large off-site-release have been provided for more than a decade in INSAG documents [9, 10, 11, 12]. In 1988, INSAG-3 stated "The target for existing nuclear power plants is a likelihood of occurrence of severe core damage that is below about 10^{-4} events per plant operating year. Implementation of all safety principles at future plants should lead to the achievement of an improved goal of not more than about 10^{-5} such events per plant operating year. Severe accident management and mitigation measures should reduce by a factor of at least ten the probability of large off-site releases requiring short term off-site response." The more stringent safety target for future plants was confirmed by INSAG-5 in 1992 with the statement that [evolutionary] light and heavy water nuclear plants "should meet the long term target of a level of safety ten times higher than that of existing plants".

In 1996 INSAG-10 noted that prevention of accidents remains the highest priority among the safety provisions for future plants and that probabilities for severe core damage below 10^{-5} per plant year ought to be achievable. INSAG-10 noted that values that are much smaller than this would, it is generally assumed, be difficult to validate by methods and with operating experience currently available. INSAG-10, therefore, considers improved mitigation to be an essential complementary means to ensure public safety. INSAG-10 also stated the need to demonstrate that for accidents without core melt there will be no necessity for protective measures (evacuation or sheltering) for people living in the vicinity of the plant, and for severe accidents that are considered in the design, that only protective measures that are very limited in area and time would be needed (including restrictions in food consumption). In 1999, INSAG-12 (Revision 1 of INSAG-3), confirmed that the target frequency for CDF for existing nuclear power plants is below about 10^{-4} with severe accident management and mitigation measures reducing by a factor of at least 10 the probability of large off-site releases requiring short term off-site response. INSAG-12 continued by noting that for future plants, improved accident prevention (e.g. reduced common mode failures, reduced complexity, increased inspectability and maintainability, extended use of passive features, optimized human-machine interface, extended use of information technology) could lead to achievement of an improved CDF goal of not more than 10^{-5} per reactor-year. With regard to off-site release for future plants, INSAG-12 stated that an objective for future plants is "the practical elimination of accident sequences that could lead to large early radioactive releases, whereas severe accidents that could imply a late containment failure would be considered in the design process with realistic assumptions and best estimate analyses so that their consequences would necessitate only protective measures limited in area and in time".

From the IAEA's Safety Standards Series and INSAG documents, a number of safety goals for future nuclear plants can be identified:

- a reduction in core damage frequency (CDF) relative to current plants;
- consideration of selected severe accidents in the design of the plants;

- ensuring that releases to the environment in the event of a severe accident are kept as low as practicable with the aim of providing a technical basis for simplification of emergency planning;
- reduction of the operator burden during an accident by an improved man-machine interface;
- the adoption of digital instrumentation and control; and
- the introduction of passive components and systems.

Technological advances are being incorporated into advanced designs to meet the stringent safety goals and objectives. Design features both to improve prevention of severe accidents involving core damage, as well as for mitigating their consequences are being incorporated. Considerable development has been carried out worldwide on new systems for heat removal during accidents. Progress has been made in containment design and in instrumentation and control systems.

To further reduce the probability of accidents and to mitigate their consequences, designers of new plants are adopting various technical measures. Examples are:

- larger water inventories (large pressurizers, large steam generators), lower power densities, negative reactivity coefficients to increase margins and grace periods thereby reducing system challenges;
- redundant and diverse safety systems with proven high reliability with improved physical separation between systems;
- passive cooling and condensing systems; and
- stronger containments large enough to withstand the pressure and temperatures from design basis accidents without fast acting pressure reduction systems, and with support systems to assure their integrity during severe accidents (for example, to control hydrogen concentrations). In some designs there is an outer second containment that provides protection against external events, and allows for detection and filtration of activity that potentially would leak from the inner containment.

Some new designs rely on well-proven and highly reliable active safety systems to remove decay heat from the primary system and to remove heat from the containment building during accidents. Other new designs incorporate safety systems that rely on passive means using, for example, gravity, natural circulation, and compressed gas as driving forces to transfer heat from the reactor system or the containment to either evaporating water pools or to structures cooled by air convection. Considerable development and testing of passive safety systems has been and is being carried out in several countries. In other designs a coupling of active safety systems and passive safety systems is adopted. For each of the aforementioned approaches, the main requirement is that the proposed safety systems fulfill the necessary functions with appropriate reliability.

2.3 Proliferation-resistance

The potential linkage between peaceful use of nuclear energy and the proliferation of nuclear weapons has been a continuing societal concern. To ensure the absence of un-declared nuclear material and activities or diversion of nuclear material for weapons purposes, an international non-proliferation regime has been developed. This regime consists of the following components:

- An international institutional framework for non-proliferation based on the Non-Proliferation Treaty and comprehensive IAEA safeguards agreements and protocols;
- International verification measures (the IAEA Safeguards system plus regional and bilateral agreements) to provide credible assurance of the non-diversion of nuclear material and of the absence of undeclared nuclear material and activities;

- Export controls on nuclear materials, specified facilities, equipment and other materials, including dual-use technologies and materials; and
- National physical protection measures and material accounting and controls measures, as well as IAEA recommendations on physical protection.

It is desirable that IAEA safeguards have a minimal impact on plant operations while ensuring efficient acquisition of safeguards data. With these goals in mind, as designs of nuclear plants and IAEA safeguards techniques have developed, guidelines for plant design measures have been identified by the IAEA [13], which, if taken into account in the plant design phase, would help to ensure efficient acquisition of safeguards data and minimize the impact of the safeguards activities on plant operations. These guidelines[4] are based on IAEA experience in implementing safeguards, as well as on developments in safeguards technology.

Proliferation resistance is defined [14] as *that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States intent on acquiring nuclear weapons or other nuclear explosive devices*. The degree of proliferation resistance results from a combination of, *inter alia*, technical design features, operational modalities, institutional arrangements and safeguards measures. These can be classified as *intrinsic proliferation resistant features* and *extrinsic proliferation resistant features*. Specifically:

1. *Intrinsic proliferation resistant features* are those features that result from technical design of nuclear energy systems, including those that facilitate the implementation of extrinsic measures; and

2. *Extrinsic proliferation resistance measures* are those measures that result from States' decisions and undertakings related to nuclear energy systems.

Safeguards is an extrinsic measure comprising legal agreements between the party having authority over the nuclear energy system and a verification or control authority, binding obligations on both parties and verification using, inter alia, on-site inspections.

Four general types of intrinsic proliferation resistant features of nuclear energy systems (i.e. nuclear plants and fuel cycle facilities) have been identified in [14] and are, in summary:

1. Technical features that reduce the attractiveness for nuclear weapons programmes of nuclear material during production, use, transport, storage and disposal;

2. Technical features that prevent or inhibit the diversion of nuclear material;

3. Technical features that prevent or inhibit the undeclared production of direct-use material; and

4. Technical features that facilitate verification, including continuity of knowledge. These features include those described in [13].

Approaches for introducing proliferation resistant features into nuclear energy systems include, but are not limited to, the following:

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[4] These guidelines address, for example, design of the spent fuel pool area to facilitate viewing of the spent fuel assemblies; provisions that facilitate the verification of fuel transfers out of the spent fuel pool; provision of appropriate back-up for power supply outages to avoid interruption of power to safeguards equipment; provision of access to appropriate penetrations in the containment building for data transfer lines serving remote safeguards equipment; and other design measures.

- **a.** **Reliance on the once-through fuel cycle** would reduce fissile material diversion opportunities that might be associated with fuel reprocessing and recycling.
- **b.** **Establishment of energy parks with both nuclear power plants and fuel cycle facilities** would avoid the need to transport fissile material between sites.
- **c.** **Establishment of a closed fuel cycle with reprocessing that returns minor actinides with plutonium to the reactor for consumption**, could avoid the separation of minor actinides from fissile material so that the material is not weapons useable.
- **d.** **Operating reactors with long operating cycles (e.g., several years) without refuelling or fuel shuffling** could assure that fissile material in the core is not accessible as long as the reactor vessel is not opened. Some new design concepts include the measure that the reactor be returned to the supplier country for refuelling.
- **e.** **Incorporating features to increase the difficulty of extracting fissile material from fresh or spent fuel**.
- **f.** **Incorporating features that greatly reduce the fraction of plutonium in spent fuel** would require that a very large volume of spent fuel would need to be processed to extract sufficient plutonium for a nuclear weapon.
- **g.** **Reducing the fuel stored at a site** would reduce the amount of material that could potentially be diverted from that site.
- **h.** **Reducing the fissile material produced in the reactor** could reduce the weapons-useable material in spent fuel.

It is important to note that some approaches are mutually incompatible in the sense that one approach may not allow, or may be detrimental to, another approach.

Also, there are drawbacks associated with some of the above approaches. For example, the once-through fuel cycle does not allow nuclear energy to become a long-term sustainable source of energy. Operating reactors with long fuel cycles of several years requires higher fuel enrichment and the parasitic absorption of neutrons by fission products reduces the fuel utilization efficiency. Features that greatly increase the difficulty of extracting fissile material from spent fuel can create a cost penalty on fuel reprocessing.

2.4 Sustainable energy supply

To assure that the long term potential of nuclear energy can be fully exploited, the nuclear community must not only meet the economic challenge. It must also meet the challenges of achieving acceptance of nuclear power in international discussions on climate change as a technology compatible with sustainable energy development, and achieving improved public understanding in all areas. Clearly nuclear power can put the world's large uranium resource to productive use, can reduce harmful emissions associated with burning fossil fuels, and can expand electricity supplies. To be a truly sustainable energy supply, in addition to being economically competitive, nuclear power must implement a long-term solution to disposal of high-level radioactive waste, continue to achieve the highest level of safety for nuclear plants and for fuel cycle facilities, and assure strong vigilance in security and safeguards of nuclear material.

In the longer term, recycling the fissile content of spent fuel and breeding additional fissile material from the world's resources of U^{238} and Th^{232} can extend the energy resource available from uranium for centuries. This long-term energy strategy will be supported by fast breeder reactors. Also, thermal reactors with high conversion ratios are being developed with goals of assuring a long-term energy supply as well as reducing spent fuel accumulation.

3.0 Means for reducing costs of new plants

3.1 Proven means for reducing plant costs

There is a set of proven means for reducing costs during any construction project, including nuclear projects [15, 16, 17, 18]. These means can be generally grouped and listed as follows:

1. Capturing economies-of-scale;
2. Streamlining construction methods;
3. Shortening construction period;
4. Standardization, and construction in series;
5. Multiple unit construction;
6. Simplifying plant design, improving plant arrangement, and use of modeling;
7. Efficient procurement and contracting;
8. Cost and quality control;
9. Efficient project management; and
10. Working closely and co-operating with relevant regulatory authorities.

The larger the construction project, and the greater the financing burden, as is the case for nuclear power plants, the more important these approaches become.

The best combination of approaches depends on market conditions. In some countries, such as the Republic of Korea and Japan, **economies of scale** are being pursued for new, large[5] evolutionary LWRs.

However, for some market conditions, and especially for some developing countries, large size plants are not an appropriate match for the grid capacity, the incremental increase in demand or for the potential owner's financial investment capability. For such conditions, small and medium size reactors (SMRs) offer an alternative choice. SMRs have the potential to capture **economies of series production**, if several units are constructed.

Reducing the construction period is important because of the interest and financing charges that accrue during this period without countervailing revenue. One way to reduce the schedule is to reduce on-site and tailor-made construction and emphasize instead the manufacture of modular units or systems. Addressing licensing issues before start of construction is also a key means of achieving a short construction period. Other measures involve improved construction techniques as well as efficient management of construction and commissioning activities. Approaches that have resulted in recent good experience include extensive use of integrated design tools (known as Computer Aided Design; Computer Aided Design and Drafting; and Computer Aided Engineering). These tools facilitate the modularization process, planning and sequencing of construction activities and provide support to procurement planning.

Significant improvements can be made in plant **design** and layout, and use of computer technology and modelling. Several simplifications have been made in the last decade including computer control, process information display, and other areas. Careful planning can result in improvements in plant arrangement and system accessibility, and in design features to facilitate decommissioning.

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[5] The IAEA differentiates nuclear plants of various power levels by classifying them as:
Large-size designs: 700 MWe and larger
Medium-size designs: 300 –700 MWe
Small-size designs: below 300 MWe.

Standardization and construction in series offer significant cost savings by spreading fixed costs over several units built, and from productivity gains in equipment manufacturing, field engineering, and building construction. First-of-a-kind reactor designs or plant components require detailed safety cases and licensing procedures, resulting in major expenditures before any revenue is realized. Standardization of a series is therefore a vitally important component of capital cost reduction. Standardization and construction in series offer reduced average licensing times and costs over the series. A detailed account of the lessons from the standardized plant design and construction programme in France is provided in Ref. [19]. Experience is being established within Japan's ABWR activities and the Republic of Korea's KSNP and KSNP+ activities.

Closely related is the cost-saving practice of **multiple unit construction** at a single site. The average cost for identical units on the same site can be about 15% or more lower than the cost of a single unit, with savings coming mostly in siting and licensing costs, site labour and common facilities. A good example of multiple unit construction are the 58 PWRs that are operating in France, which have been built as multiple units at 19 sites.

Many of the benefits of technology advances would be lost without some accompanying **regulatory reform** to accommodate change. These include greater regulatory certainty, more prioritization of regulatory requirements, streamlining of regulation to match streamlined engineering and designs, and more flexibility to accommodate technological innovation.

In developing countries, **furthering self-reliance**, and **enhancing local participation** in major projects are goals pursued by governments for a variety of policy reasons. Cost savings in any of several areas - materials and construction costs, foreign exchange costs, labor costs - may result. Reducing the costs of technology transfer and relevant training are areas of emphasis for developing countries. In China, it is considered very important that favourable conditions for technology transfer and personnel training are provided with the help of industrialized countries so that a considerable portion of the work in fabricating the plant equipment and in plant construction can be done by organizations in the developing country. Because of the low cost of manpower, some materials and products can be made cheaper, with due assurance of quality. Experience in China is that the construction cost of the Qinshan-II plant (2 x 600 MWe units, the first unit achieving commercial operation in March, 2002) indicates that the cost of this plant is less than that for imported large-size plants because of localization of design and provision of a large amount of the equipment by domestic organizations.

Reference [15] provides further examples of recent and present activities to incorporate the proven means discussed above. These and other traditional proven approaches should help to achieve cost competitiveness for new nuclear power plants. However, the nuclear community must continue to move forward in identifying and implementing new approaches for further reducing the costs of new nuclear plants.

3.2 New approaches for reducing plant costs

Reference [15] discusses new approaches to reduce capital cost that should be developed and implemented in order to gain the greatest possible cost reductions. In summary, these are:

- Modularization, factory fabrication, and series production;
- Development of highly reliable components and systems, including "*smart*" (instrumented and monitored) components and methods for detecting incipient failures - to improve system reliability so that dependence on costly redundancy and diversity practices could be reduced. Development is also required to correlate signals from the "smart" components with reliability, and criteria must be developed for when to do maintenance and replacement;

- Further development of passive safety systems where the safety function can be met more cheaply than with active systems. This would include development of reliability models for passive systems.
- Development of computer based advanced technologies for design, procurement, manufacture, construction and maintenance with a focus on coordination of activities to reduce costs and schedules;
- Further development of Probabilistic Safety Analysis (PSA) methods and data bases to support plant simplification and to support examination of potential risk-informed regulatory requirements for new plants leading to more economical designs with very high safety levels. PSA assessments must (a) be capable of assessing the total risk including full power, low power, shutdown, fires and external events; (b) be capable of accounting for safety culture and human factors; (c) accurately account for ageing effects; and (d) include capability to quantify uncertainties. The challenge will be to establish PSA methods, including understanding of uncertainties in predicted results, to demonstrate that sufficient defense-in-depth, and sufficient balance among the various levels of defense-in-depth, can be achieved through simpler and cheaper technical solutions;
- Improvement of the technology base for eliminating over-design (i.e. improved understanding of thermo-hydraulic phenomena, more accurate data bases of thermo-hydraulic relationships and thermo-physical properties, better neutronic and thermo-hydraulic codes, and further code validation). The focus could be on removing the need to incorporate excessively large margins into the design simply for the purpose of allowing for limitations of calculational methodology and uncertain data.
- Reduction of number of components and materials requiring nuclear grade standards;
- Design for higher temperature (higher thermal efficiency);
- Design for multiple applications (e.g. co-generation of electricity and heat; sea-water desalination); and
- Achieving international consensus regarding commonly acceptable safety requirements that would facilitate development of standardized designs which can be built in many countries without requiring significant re-design efforts.

4.0 Development of advanced nuclear plant designs

New generations of nuclear power plants are being developed, building upon the background of nuclear power's success and applying lessons learned from the experience of operating plants. Various organizations are involved in this development, including governments, industries, utilities, universities, national laboratories, and research institutes. Global trends in advanced reactor designs and technology development are periodically summarized in status reports, symposia and seminar proceedings prepared by the IAEA [20, 21, 22, 23, 24, 25] to provide all interested IAEA Member States with balanced and objective information on advances in nuclear plant technology.

Advanced designs comprise two basic categories. The first category is called evolutionary designs and encompasses direct descendants from predecessors (existing plant designs) that feature improvements and modifications based on feedback of experience and adoption of new technological achievements, and possibly also introduction of some innovative features, e.g., by incorporating passive safety systems. Evolutionary designs are characterized by requiring at most engineering and confirmatory testing prior to commercial deployment. The second category consists of designs that deviate more significantly from existing designs, and that consequently need substantially more testing and verification, probably including also construction of a demonstration plant and/or prototype plant, prior to large-scale commercial deployment. These are generally called innovative designs. Often a step increase in development cost arises from the need to build a prototype reactor or a demonstration plant as part of the development programme (see Figure 1).

Advanced design

Different types of new nuclear plants are being developed today that are generally called advanced reactors. In general, an advanced plant design is a design of current interest for which improvement over its predecessors and/or existing designs is expected. Advanced designs consist of evolutionary designs and designs requiring substantial development efforts. The latter can range from moderate modifications of existing designs to entirely new design concepts. The latter differ from evolutionary designs in that a prototype or a demonstration plant is required as a part of the development programme, or that insufficient work has been done to establish whether such a plant is required.

Evolutionary design

An evolutionary design is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining proven design features to minimize technological risks. The development of an evolutionary design requires at most engineering and confirmatory testing.

Innovative design

An innovative design is an advanced design that 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.

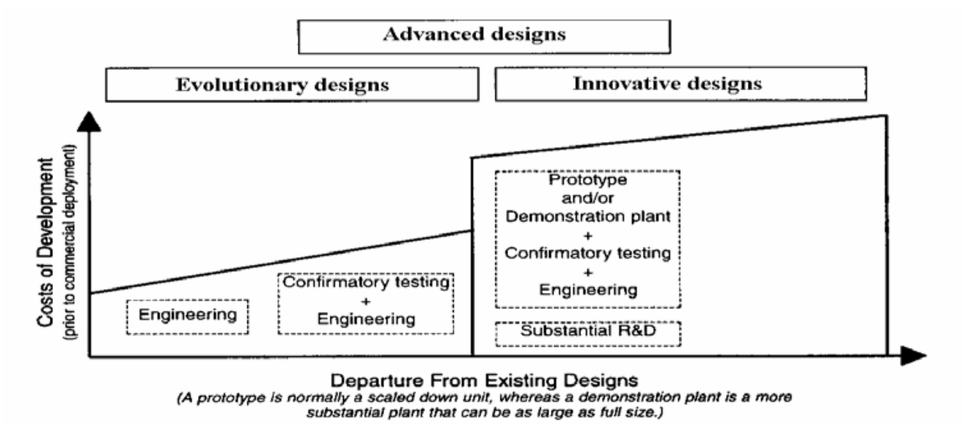

FIG. 1. Efforts and development costs for advanced designs versus departure from existing designs (Terms are excerpted from Ref. [26]).

In the near term most new nuclear plants will likely be evolutionary designs building on today's successful proven systems while incorporating technology advances and often pursuing economies of scale. In the longer term, development and demonstration of new, innovative designs, including their promised short construction and start-up times and low capital costs, could help to promote a new era of nuclear power.

Several innovative designs are 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. 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, sea-water desalination, hydrogen production, and other non-electric applications.

Advanced nuclear plant designs presently under development comprise the following basic reactor types:

- water-cooled reactors, utilizing water as coolant and moderator. These are comprised of light water reactors (LWRs), which use light water as both the coolant and the moderator, and heavy water reactors (HWRs), which use heavy water as moderator and either light or heavy water as coolant;
- gas-cooled reactors, using helium as coolant and graphite as moderator; and
- fast reactors, using liquid metal (e.g. sodium) or gas (helium) as coolant.

4.1 Light water reactors

LWRs comprise 80.5% of the total number of nuclear units in operation worldwide. This is reflected in the considerable activities which are underway to develop advanced LWR designs, as is indicated in Annex 1 which lists various advanced LWR designs together with the design organizations and the status of the development.

4.1.1 Overview of evolutionary LWR development

In France and Germany, Framatome ANP has completed the basic design for the large-size 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 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. Also, Electricite de France and the French Government are considering construction of the EPR in France[6].

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 2002 Framatome submitted the SWR-1000 for a pre-application phase for Design Certification by the U.S. NRC.

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[6] In November 2003, the French government endorsed a new nuclear programme with the publication of a White Paper on energy policy that calls for keeping the nuclear option open by building a demonstration unit based on the EPR. Following a period for public comment, the final version of the White Paper is expected to be adopted in the Council of Ministers and submitted to the French parliament in early 2004 for debate.

In Japan, benefits of standardization and construction in series are being realized with the ABWR units. The first two ABWRs in Japan, the 1360 MWe Kashiwazaki-Kariwa 6 and 7 units, have been in commercial operation since 1996 and 1997 respectively. ABWR plants are under construction at Hamaoka Unit No. 5 and Shika Unit No. 2, and deployment programmes are underway for 8 more ABWRs. Two ABWRs are under construction in Taiwan, China.

Expectations in Japan 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 costs relative to a standardized ABWR. The power level of ABWR-II has been increased relative to the ABWR, 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 advanced PWR has been completed by Mitsubishi Heavy Industries and Westinghouse for the Japan Atomic Power Company's Tsuruga-3 and –4 units, and a larger version, the APWR$^+$ is in the design stage.

In the Republic of Korea, the benefits of standardization and construction in series are being realized with the Korean Standard Nuclear Plants (KSNPs). The first two KSNPs, Ulchin 3 and 4 began commercial operation in 1998 and 1999. Yonggwang 5 and 6 began commercial operation in 2002. Two more KSNPs are under construction at Ulchin 5 and 6. The accumulated experience is now being used by KEPCO to develop the improved 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. The higher power level of the APR-1400 relative to the KSNP and the KSNP$^+$ has been selected to capture economies-of-scale. Recent development of the APR-1400 focused on improving availability and reducing costs. 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.

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. Westinghouse's mid-size AP-600 design with passive safety systems was certified in December 1999. Westinghouse is developing the AP-1000 applying the passive safety technology developed for the AP-600 with the goal of reducing the capital costs through economies-of-scale. Westinghouse, in March 2002, submitted an application to the U.S. NRC for Final Design Approval and Design Certification of the AP-1000. The Final Design Approval is expected in 2004 and Design Certification is expected in 2004/2005. An adaptation of the AP-1000, called the EP-1000, is being designed by Westinghouse and Genesi (Italy) applying the passive safety technology to meet European Utility Requirements and licensing requirements in Europe. A Westinghouse led international team is developing the modular, integral IRIS design in the small to medium-size range, with a core design capable of operating on a 4-year fuel cycle[7]. The IRIS design is in the first phase of pre-application licensing in which the NRC will provide feedback on necessary testing and an assessment of the risk-informed regulation approach. The plan is to submit an IRIS Design Certification application in 2005, with the objective of obtaining design certification in 2008/2009. General Electric is designing a large ESBWR applying

[7] IRIS is considered to be an evolutionary LWR in the context of Figure 1 in the Introduction to this TECDOC. IRIS has innovative features and the integral design represents a radical change in system configuration from existing loop reactors. However Westinghouse states that while it is innovative engineering, it relies on proven LWR technology and thus it only requires engineering and confirmatory testing. A prototype or demonstration plant is not required, but a first of a kind will be, since no other IRIS-type integral reactors have been built.

economies-of-scale together with modular passive safety systems. The design draws on technology features from General Electric's ABWR and from their earlier mid-size simplified BWR with passive systems. In mid-2002 the ESBWR design and technology base were submitted to the U.S. NRC with the objective of obtaining closure of all technology issues in 2003, as a first step toward obtaining Design Certification.

In Sweden, Westinghouse Atom has developed the large 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 under construction in China, India and the Islamic Republic of Iran. Development of a larger WWER-1500 design has been initiated.

In China, the China National Nuclear Corporation (CNNC) has developed the AC-600 design, and is currently developing the CNP-1000 for electricity production. CNNC is also developing the QS-600 e/w, which is based on the design of the Qinshan Phase II, for electricity production and sea-water desalination. China is pursuing self-reliance both in designing the plant to meet Chinese safety requirements, and in fostering local equipment manufacture with the objective of reducing construction and operation costs. Experience gained and lessons learned from the design, construction and operation of the Qinshan and Daya Bay NPPs are being incorporated.

4.1.2 Overview of innovative LWR development

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 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. The Argentinian CAREM reactor (prototype design 27 MWe) is cooled by natural circulation, and has passive safety systems. Designers of CAREM are planning a prototype (27 MWe) plant prior to commercial deployment. The 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 1/5th scale, 65 MWth, SMART pilot plant. The Japan Atomic Energy Research Institute is developing the small passively safe integral PSRD-100 system for electricity and/or heat supply and sea-water desalination, and Mitsubishi together with other organizations is developing the IMR design for electricity production.

In Russia, development is on-going at OKBM for both the VBER-300 integral design with the steam generator system inside the reactor pressure vessel and for the KLT-40, a floating small NPP design for electricity and heat; at RDIPE for the VK-300 BWR design for electricity and district heating; and at Atomenergoproject / Gidropress on a mid-size WWER-640 with passive safety systems.

In Japan the Toshiba Corporation and the Tokyo Institute of Technology are developing a long operating cycle, natural circulation simplified LSBWR with passive safety systems. The LSBWR's power level is in the small size range with a target 15-year core life. Hitachi Ltd. is also developing the mid-size Hitachi Simplified BWR (HSBWR), the mid-size Advanced BWR (HABWR), and the small-size SSBWR with passive safety systems and a 20-year core life.

Also in Japan, with the goals of ensuring sustainable energy supplies by achieving a high conversion (conversion ratio equal to or beyond 1.0) of fertile isotopes to fissile isotopes and reducing spent fuel accumulation, Hitachi Ltd. is also developing the large-size, reduced moderation RBWR and JAERI is developing the large-size RMWR.

A prototype or a demonstration plant will most likely be required for thermodynamically supercritical water-cooled systems, which have been selected for development by the Generation-IV International Forum (see the summary discussion of the Generation-IV International Forum (GIF) in Section 5). In a supercritical system the reactor operates above the critical point of water (22.4 MPa and 374 °C) resulting in higher thermal efficiency than current LWRs. Thermal efficiencies of 40-45% are projected with simplified plant designs. Core design options include both thermal neutron spectrum cores and fast neutron spectrum cores for high conversion. The large-size SCPR concept being developed by Toshiba Hitachi and the University of Tokyo is an example thermodynamically supercritical LWR. In Europe, the HP-LWR project has been funded by the European Commission to assess the merit and economic feasibility of an LWR operating thermodynamically in the supercritical regime. Activities on super-critical water-cooled system concepts are also on-going at universities and research centers in the USA and in Russia.

4.2 Heavy water reactors

HWRs account for about 8% of the nuclear power reactors that are currently operating. Two types of commercial pressurized heavy water cooled reactors have been developed, the pressure tube and the pressure vessel versions. HWRs with power ratings from a few hundred MWe up to approximately 900 MWe are available. The heavy water moderation yields a good neutron economy and has made it possible to utilize natural uranium as fuel. Both the pressure tube and pressure vessel designs use on-load refuelling.

In Canada, the approach taken by AECL in development of next generation CANDU plants (the ACR-700) is to essentially retain the present evolutionary CANDU reactor characteristics and power levels (e.g. the CANDU-6 and CANDU-9 with net electric power levels around 650 MWe and 900 MWe respectively) and to improve economics through plant optimization and simplification. The ACR-700 design uses slightly enriched uranium and light water coolant. It is currently undergoing a pre-application licensing review by the US Nuclear Regulatory Commission. Following that review, AECL intends to seek a Design Certification in 2005. The ACR-700 is simultaneously undergoing a licensing review in Canada, and an ACR-1000 plant is being designed.

Also, in Canada in 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.

In India, a continuing process of evolution of HWR design has been carried out since the Rajasthan 1 and 2 projects. In 2000 construction began on two 540 MWe units at Tarapur which incorporate feedback from the indigenously designed 220 MWe units[8].

India is also developing the Advanced Heavy Water Reactor (AHWR), a heavy water moderated, boiling light water cooled, vertical pressure tube type reactor, optimized for utilization of thorium for power generation, with passive safety systems.

Reference [20] provides a detailed discussion of the status and projected development of HWRs.

4.3 Gas-cooled reactors

Gas-cooled reactors have been in operation for many years. In the United Kingdom (UK), the nuclear electricity is mostly generated by CO_2-cooled Magnox and advanced gas-cooled reactors (AGRs).

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[8] The most recent plants in this series, the 220 MWe Kaiga-1 and the Rajasthan-3 and –4 units, were connected to the grid in the year 2000.

Development of high temperature reactors (HTGRs) with helium as coolant, and graphite as moderator, has also been going on for a long period of time. Prototype and demonstration plants with the Rankine steam cycle for electric power generation have been built and operated.

The inert He coolant and the coated fuel particle design enable HTGRs to operate at temperatures considerably above those in water-cooled reactors. Development is also conducted for high temperature heat applications. Currently two helium cooled test reactors are in operation. The High-Temperature Engineering Test Reactor (HTTR) at the Japan Atomic Energy Research Institute (JAERI) in Japan and the HTR-10 at the Institute of Nuclear Energy Technology (INET) in China.

Presently, a considerable effort is devoted to the gas-turbine direct cycle, pebble bed small-size modular HTR (PBMR) that promises high thermal efficiency and low power generation cost. Eskom, South Africa's Industrial Development Corporation, and BNFL (United Kingdom) are jointly developing such a system. Also, the Ministry of the Russian Federation for Atomic Energy, the Experimental Design Bureau for Machine Building (OKBM), General Atomics, Framatome and Fuji Electric are jointly developing a small gas turbine modular helium reactor (GT-MHR) for electricity production and the consumption of weapons grade plutonium.

A helium-cooled Very High Temperature Reactor (VHTR) with a focus on hydrogen production is being developed within the framework of GIF (see Section 5).

4.4 Fast reactors

Liquid metal-cooled fast reactors (LMFRs) have been under development for many years in a number of countries, primarily as breeders. The successful design, construction and operation of several sodium-cooled reactor plants, such as the small size Prototype Fast Reactor in the United Kingdom, the prototype Phénix fast reactor in France, the BN-350 in Kazakstan (part of its thermal energy was used for sea-water desalination), both the demonstration BN-600 in Russia, and the Monju in Japan, as well as the commercial size Superphénix in France, have provided an extensive experience base of more than 200 reactor-years for further improvements. In addition, this is a considerable base of experience with lead-bismuth (eutectic) cooled propulsion (submarine) reactors built and operated in the former USSR.

Fast reactors use fast neutrons for sustaining the fission process, and they can actually produce fuel, as well as consuming it. Plutonium breeding allows fast reactors to extract sixty-to-seventy times more energy from uranium than thermal reactors do. Their capability to produce more fissile material than they consume may become indispensable in the longer term if the deployment of nuclear power is increased substantially. Fast reactors may also contribute to reducing plutonium stockpiles, and to the reduction of the required isolation time for high-level radioactive waste by utilizing transuranic radioisotopes and transmuting some of the most cumbersome long-lived fission products.

Examples of current LMFR activities include: the construction in China of the small size Chinese Experimental Fast Reactor (CEFR) with first criticality scheduled for 2006; the development of the small-size KALIMER design in the Republic of Korea; the successful operation of the Indian Fast Breeder Test Reactor (FBTR) and its utilization for fast reactor R&D, especially fuel irradiation and materials research; the development of the medium size Prototype FBR (PFBR) in India for which construction has started in 2003; efforts in Japan aimed at restarting MONJU, and 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, and design studies of advanced fast reactors (sodium-cooled, lead-cooled, and lead-bismuth eutectic cooled) having improved economics and enhanced safety.

In France, the Phénix plant has restarted in 2003 with the main mission of conducting experiments on long-lived radioactive nuclide incineration and transmutation.

Development activities for a gas (helium) cooled fast reactor (GFR) with an integrated fuel cycle with full actinide recycle and for lead alloy and sodium-cooled systems are being conducted within GIF.

Co-operative international research is underway in several countries on fast neutron spectrum hybrid systems (e.g., accelerator driven systems (ADS)). 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 activities include development of the HYPER concept by the Republic of Korea; design studies in Japan on a lead-bismuth eutectic cooled concept and R&D at JAERI in the fields of sub-critical core design, spallation target technology, accelerator development and minor actinide fuel development; and research on basic physical processes in Russia and in eight countries in the European Union, and in the Advanced Accelerator Applications programme of the U.S.A. (recently merged with the Advanced Fuel Cycles initiative).

5. International initiatives for innovative plants

Many countries believe that nuclear energy must remain or become an integral part of their energy mix to meet energy supply needs. To help achieve this goal, there are two major international efforts, the Generation IV International Forum and the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO).

Concerns over energy resource availability, climate change, air quality, and energy security suggest an important role for nuclear power in future energy supplies. While the current Generation II (commercial power reactors) and Generation III ([currently available] advanced LWRs) nuclear power plant designs provide an economically, technically, and publicly acceptable electricity supply in many markets, further advances in nuclear energy system design can broaden the opportunities for the use of nuclear energy.

To explore these opportunities, the U.S. Department of Energy's Office of Nuclear Energy, Science and Technology has engaged governments, industry, and the research community worldwide in a wide-ranging discussion on the development of next-generation nuclear energy systems known as "Generation IV". This has resulted in the formation of the Generation-IV International Forum (GIF), a group whose member countries are interested in jointly defining the future of nuclear energy research and development. Members are Argentina, Brazil, Canada, Euratom, France, Japan, the Republic of Korea, South Africa, Switzerland, the United Kingdom and the United States. The IAEA and the OECD/NEA have permanent observer status in the GIF Policy Group, which governs the project's overall framework and policies. In short, "Generation IV" refers to the development and demonstration of one or more Generation IV nuclear energy systems that offer advantages in the areas of economics, safety and reliability, sustainability, and could be deployed commercially by 2030.

As stated in [27] the purpose of the GIF and the Vision for Generation IV 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." Following evaluations of many concepts, six systems have been selected by the GIF Policy Group for future bilateral and multilateral cooperation, and a Technology Roadmap has been prepared to guide the research and development [28]. 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
- Very high temperature gas reactor systems

The IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is based on an IAEA General Conference resolution in September 2000 inviting all interested Member States, both technology suppliers and technology users, to consider jointly international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles. Additional endorsement came in a UN General Assembly resolution in December 2001 that emphasized "the unique role that the Agency can play in developing user requirements and in addressing safeguards, safety and environmental questions for innovative reactors and their fuel cycles" and stressed "the need for international collaboration in the development of innovative nuclear technology".

The overall objectives of INPRO are (a) to help to ensure that nuclear energy is available to contribute to fulfilling energy needs in the 21st century in a sustainable manner; (b) to bring together all interested Member States, both technology holders and technology users, to consider jointly the international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles; and (c) to create a process that involves all relevant stakeholders that will have an impact on, draw from, and complement the activities of existing institutions, as well as ongoing initiatives at the national and international level. The INPRO time horizon is 50 years into the future. As of December 2003, members of INPRO include Argentina, Brazil, Bulgaria, Canada, China, Germany, India, Indonesia, the Republic of Korea, the Russian Federation, South Africa, Spain, Switzerland, the Netherlands, Turkey, and the European Commission. In its first Phase, INPRO has prepared basic principles[9] for innovative energy systems in the areas of economics, sustainability and the environment, safety of nuclear installations, waste management and proliferation resistance. These are presented in Annex 2. INPRO has published guidelines for the evaluation of innovative nuclear reactors and fuel cycles addressing economics, sustainability and environment, safety of nuclear installations, waste management, proliferation resistance as well as cross-cutting issues. [14].

6. Non-electric applications of nuclear energy

As has been discussed in the preceding sections, nuclear energy is playing an important role in electricity generation, producing about 16% of the world's electricity. However, only about one-fifth of the world's energy consumption is used for electricity generation [29]. Most of the world's energy consumption is for heat and transportation. There is currently some use of nuclear energy for providing heat, and interest in the future use of nuclear energy in the heat market is growing. Nuclear energy has considerable potential to penetrate into the energy sectors now served by fossil fuels.

For heat applications of nuclear energy, the temperature requirements vary greatly. As shown in Figure 2 from [30], for heat applications the temperatures range from around 100°C for hot water and steam for district heating and seawater desalination, to up to 1000°C for heat for the production of hydrogen by high temperature thermo-chemical processes. Although various forms of nuclear heat application are technically feasible and pursued between these temperature ranges, the major applications are directed to the lower end using water-cooled reactors [31] and to the higher end using

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[9] In the context of INPRO, a basic principle is a statement of a general rule providing guidance for the development of an innovative nuclear energy system.

high temperature gas cooled reactors [30], [32], [33]. Figure 2 also shows the temperatures produced by the various reactor types[10] and the temperatures necessary for different non-electric applications.

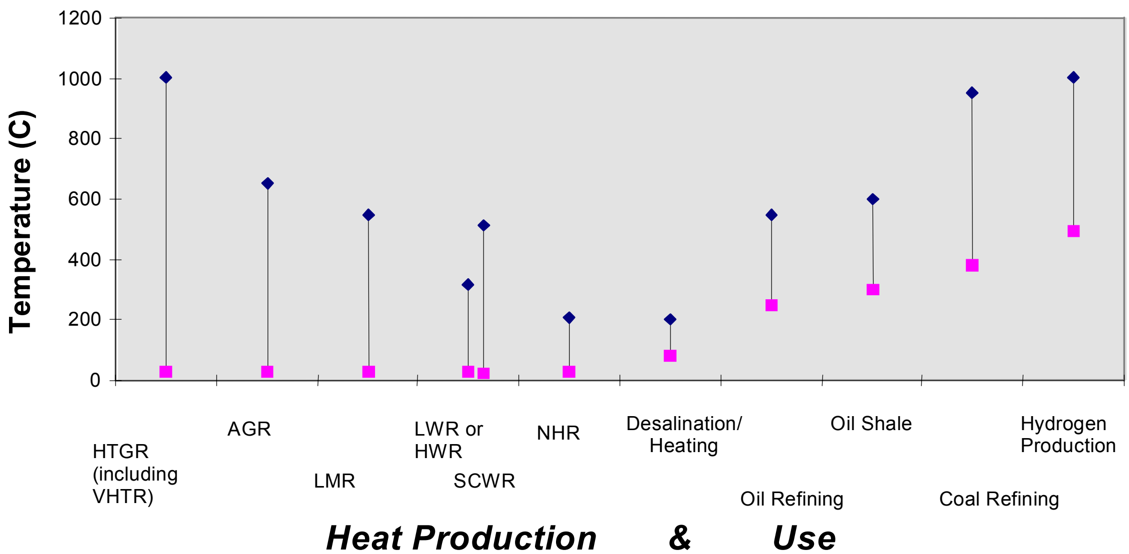

FIG. 2. Temperatures of heat produced by different reactor types and temperatures of heat used for different non-electric applications of nuclear energy. See text for an explanation of terms.

Low temperature heat applications include district heating, seawater desalination and a large variety of agricultural and industrial processes. Seawater desalination requires temperatures up to about 130 °C, district heating up to about 170 °C and low temperature industrial processes up to about 250 °C. Applications involving use of high temperature nuclear heat are not well proven and remain in the laboratory or in small-scale demonstration phase. For large-scale deployment significant research and development is still required.

6.1 Nuclear energy for hydrogen production

Hydrogen as an energy carrier is receiving increasing attention in OECD countries, notably in the U.S. and the European Union. Ref. [35] examines the wide range of activities required to realize hydrogen's potential in solving U.S. energy security, diversity, and environmental needs. Ref. [36] provides a vision outlining the research, deployment and non-technical actions that would be necessary to move from today's fossil-based energy economy to a future sustainable hydrogen-oriented economy with fuel cell energy converters.

Nuclear energy can be used for hydrogen production by using nuclear produced electricity for water electrolysis or by using nuclear heat from high or very high temperature reactors for indirect thermo-chemical water–splitting cycles. Production of hydrogen by nuclear electricity and / or high

[10] It should be noted that reactor and fuel technology development could increase the achievable temperatures. For example, super-critical water-cooled reactors would provide temperatures up to about 500 °C; a lead or lead-bismuth cooled fast reactor system possibly may achieve core outlet temperatures ranging up to 800 °C with advanced materials; and a graphite moderated, helium cooled, very high temperature reactor system would supply heat with core outlet temperature above 1000 °C [34].

temperature nuclear heat would open the application of nuclear energy for the transportation sector and reduce the reliance of the transportation sector on fossil fuel with the associated price volatility, finite supply and greenhouse gas emissions. Using electricity in electrolyzers to produce hydrogen would allow a near-term option for distributed hydrogen generation at the point of delivery to the customer, such as at a fuelling station. Although the efficiency of hydrogen production by electrolyzers is lower than with high temperature thermo-chemical processes, such distributed production could play an initiating role, because of the lower capital investment and especially until large networks for hydrogen distribution become common. In the longer term, production of hydrogen at central nuclear stations with high or very high temperature reactors connected to extensive distribution networks may become cost efficient, with distributed production continuing to meet some needs.

Some experience for high temperature applications of nuclear energy is available on the laboratory scale and from component tests for earlier development programmes for HTGR applications. Significant research and development is still required before large-scale deployment such as steam reforming of methane and thermo-chemical cycles for production of hydrogen.

Programmes are on-going in Japan and China with the goal of demonstrating the use of heat from HTGRs for high temperature applications [37] and [38]. In the USA, construction of an advanced reactor for hydrogen production is under consideration.

6.2 District heating

District heating networks generally have installed capacities in the range of 600 to 1200 MW(th) in large cities, decreasing to approximately 10 to 50 MW(th) in towns and small communities. For heat applications with nuclear plants, there are basically two options: Co-generation of electricity and heat, and dedicated nuclear heating reactors. Co-generation has been widely applied and experienced. In the co-generation mode, electricity will usually constitute the main product. Large size reactors, therefore, have to be integrated into the electrical grid system and optimized for base load electricity production. For reactors in the small to medium-size range, and in particular for small and very small reactors, the share of process heat generation could be larger, and heat could even be the predominant product.

Experience with nuclear district heating has been gained in Bulgaria, China, Germany, Hungary, Russia, Slovakia, Sweden, Switzerland and the Ukraine. A listing of operating nuclear heating plants is provided in [30]. Obviously, a potential market for the application of nuclear energy for district heating appears mainly in climatic zones with relatively long and cold winters. In Western Europe, for example Finland, Sweden, and Denmark are countries where district heating is widely used.

In the district heating field, the Russian Federation is reflecting its accumulated extensive experience in the improved design concept of a local district heating source and heat supply system. Restarting of the construction work of the site of Voronez and Tomsk is expected, both using AST-500 reactors. Some other cogeneration plants for district heating are also foreseen for replacing existing plants that are approaching the end of their design lifetime.

6.3 Seawater desalination

Application of nuclear heat for seawater desalination is another field with some operational experience and good prospects. Freshwater is essential in civilization and development. Its demand is rapidly growing throughout the world and some regions are already being jeopardized with the shortage of fresh water. Seawater desalination is a process of separating dissolved saline components from seawater to obtain fresh water with low salinity, adequate for irrigation, drinking and industrial use.

Seawater desalination technologies[11] have been well established in the middle of the 20th century, with still further improvement potential. The contracted capacity of desalination plants for desalinated water now exceeds 32 million m^3/d worldwide [39].

Nuclear desalination is the production of potable water from seawater in an integrated facility in which a nuclear reactor is used as the source of energy (electrical and/or thermal) for the desalination process on the same site. The facility may be dedicated solely to the production of potable water, or may be used for the generation of electricity and the production of potable water, in which case only a portion of the total energy output of the reactor is used for water production.

The experience and future opportunities for nuclear desalination were reviewed at a Symposium on Nuclear Desalination of Seawater, [40] convened by the IAEA in May 1997. Reference [33] summarizes global experience in nuclear seawater desalination and provides a list of operating nuclear desalination plants as of mid-2000.

The technical feasibility of integrated nuclear desalination has been firmly established by successful operation at several plants. This successful operation has proved the compliance with safety requirements and the reliability of co-generation nuclear reactors. Operating experience exceeds 150 reactor-years (statistics updated [30]).

Many IAEA Member States are moving forward in preparing nuclear desalination projects [41] and [42]. Activities are currently ongoing in Argentina, Canada, China, Egypt, France, India, Indonesia, Pakistan, the Republic of Korea, Morocco, the Russian Federation, and Tunisia.

In 1996 the IAEA, in its Options Identification Programme (OIP) identified practical options [43] of technical configuration of nuclear and desalination coupling to build near term technical and economic confidence under specific conditions. They were: (1) desalination in combination with a nuclear power reactor being constructed or in an advanced design stage with construction expected in the near term; (2) desalination, as above, in combination with a currently operating reactor with some minor design modifications as required to the periphery of the existing nuclear system; and (3) desalination in combination with a small (heating) reactor.

In the Republic of Korea, the design of a nuclear desalination plant with the SMART reactor is developed to supply 40,000 m^3/day of fresh water and 90 MW of electricity to an area with an approximate population of 100,000 or an industrialized complex. A detailed design and construction project of a one-fifth scale SMART Pilot plant for demonstration of the relevant technologies, is currently underway and will be completed by 2008. This is an example of option 1 identified in the OIP. Also in Russia, efforts continue on a floating power unit based on a KLT-40 reactor for

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[11] These technologies can be classified as:

Multi-Stage Flash (MSF): MSF is a distillation process by which feed saline water (usually seawater) is allowed to flash along the lower sections of flash chambers (or stages), after the feed water has been heated in a primary vessel called the brine heater to temperatures in the range of 90-110^{o}C. Water vapor produced in the consecutive flashing stages is condensed in the upper sections on condensing tubes and collected on collection trays of the different stages as product distilled water. The concentrate brine reject is typically discharged to the sea.

Multi-Effect Distillation (MED): MED, similarly to MSF, takes place in a series of vessels (effects), where principles of condensation/evaporation and gradually reduced ambient pressure in down-stream effects permit the seawater feed to undergo boiling without the need to supply additional heat after the first effect.

Reverse Osmosis (RO): RO is a membrane process in which the water from pressurized saline water feed is separated from the solutes (the salts) while passing through a semi-permeable membrane. No heating or phase change is necessary in this process since most of the energy required is for pressurizing the feed saline water.

multipurpose use including desalination. A nuclear desalination project is foreseen in the Russian Arctic Sea coast area (Severodvinsk or Pevec) using an RO and/or MED process.

For option 2, three examples can be mentioned. A small RO facility set up at the KANUPP HWR unit in Pakistan has been in service since early 2000 producing 450 m^3/day of fresh water, and work is progressing on a Desalination Demonstration Plant, to be commissioned in 2005 at KANUPP. A 6300 m^3/day Multi-Stage Flash-Reverse Osmosis hybrid desalination plant is in commissioning in India at the Kalpakkam nuclear power plant. The product water is both for process water for the nuclear power plant and for drinking water in the neighbouring community. The Reverse Osmosis plant segment at Kalpakkam has been operating since 2002.

In Europe, the European Commission's project EURODESAL, coordinated by the French CEA, with partners in Europe and Canada, has conducted feasibility studies for both option (1) and option (2) above.

In addition to these activities, preheat Reverse Osmosis desalination experimental facilities are being set up in Egypt and Canada. Other countries are assessing a possibility of nuclear desalination plant under different time frame. For example,

- Egypt is continuing its feasibility study for an electricity and desalination plant at El-Dabaa.
- Tunisia is about to collaborate with France on a feasibility study of nuclear desalination for a site (la Skhira) in the southern part of the country along the Mediterranean coast.
- Indonesia is starting a joint feasibility study with Republic of Korea of a nuclear desalination plant in its Madura Island.
- In China, a nuclear desalination plant, based on the 200 MW(th) nuclear heating reactor with a capacity of 150,000 m^3/d is being studied for YanTai in Shandong province.

As any nuclear reactor can provide energy (low-grade heat and/or electricity), as required by desalination processes, in principle, a broad option of coupling configurations can be feasible for future deployment of nuclear desalination.

6.4 Heat for other industrial processes

Within the industrial sector, at temperatures higher than those needed for district heating and seawater desalination, process heat is used for a variety of applications. Heat applications at temperatures up to about 200 to 300 °C include the pulp and paper industry and the textile industry. Chemical industries, oil refining, oil shale and oil-sand processing and coal gasification are examples of industries with temperature requirements up to the 500-600 °C level. Refinement of coal and lignite, and hydrogen production by water splitting, are among applications that require temperatures of 600-1000 °C and above. Unlike district heating, the load factors of industrial users of heat do not depend on climatic conditions. The demands of large industrial users usually have base load characteristics.

Experience with provision of process steam for industrial purposes with nuclear energy has been gained in Canada, Germany, Norway and Switzerland. In Canada, steam from the Bruce Nuclear Power Development (BNPD) was supplied until the mid-to-late 1990s to heavy water production plants and to an adjacent industrial park at the Bruce Energy Center.

In Germany, since December 1983, the Stade PWR, has supplied steam for a salt refinery that is located at a distance of 1.5 km. In Norway, the Halden Reactor has supplied steam to a nearby factory for many years. In Switzerland, since 1979, the Gösgen PWR has provided process steam for a nearby cardboard factory.

7. Conclusions

Clearly, nuclear power contributes significantly to the world's electricity supply and has great potential to contribute to emerging needs such as sea-water desalination and hydrogen production. In the near term, nuclear power will expand, especially in Asia. Considerable development is on-going for new, advanced nuclear plant designs for all reactor lines with competitive economics and very high safety levels as common goals.

At the same time, nuclear power faces significant challenges, including: continuing to achieve a high level of safety at current plants; implementing high level waste disposal; achieving further advances in technology to assure economic competitiveness and very high levels of safety. Success in all of these areas will establish a sound basis for establishing nuclear power as a sustainable energy source.

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ANNEX 1

TABLE I. ADVANCED LIGHT WATER REACTOR DESIGNS

A) Large size advanced LWR designs (700 MWe or larger)

Name	Type	MWe Gross	MWe Net	Design Organizations	Status
ABWR	BWR	1385	1300	General Electric, USA; Hitachi Ltd. and Toshiba Corp., Japan	Operating in Japan Under construction in Japan and Taiwan, China Design certified by the U.S.NRC in USA
ABWR-II	BWR	1717	1638	Japanese utilities, General Electric, Hitachi Ltd. and Toshiba Corp.	In design phase – commercial introduction foreseen in latter half of 2010s
APWR	PWR	1538	-----	Mitsubishi, Japan/Westinghouse, USA	First units planned at the Japan Atomic Power Company's Tsuruga-3 and 4.
APWR+	PWR	1750	-----	Mitsubishi, Japan	In design phase – target for starting construction of a first unit is the end of the 2010s.
BWR 90+	BWR	----	1575	Westinghouse Atom, Sweden	Plant design is essentially complete
EPR	PWR	1650	~1550	Framatome ANP France/Germany	Detailed design completed
ESBWR	BWR	1390	1333	General Electric, USA	The Design Certification Pre-application review by the U.S.NRC was initiated in 2002
KSNP+	PWR	1050	1000	Korea Hydro and Nuclear Power Company, Republic of Korea	First units planned at KHNP's Shin-Kori-1 and 2
APR-1400	PWR	1450	1400	Korea Hydro and Nuclear Power Company etc., Republic of Korea	First units planned at KHNP's Shin-Kori-3 and 4

Name	Type	MWe Gross	MWe Net	Design Organizations	Status
AP-1000	PWR	1200	1117	Westinghouse, USA	Under review by the U.S.NRC for Design Certification
EP-1000	PWR	(see values for AP-1000)		Westinghouse, USA/Genesi, Italy	Programme now merged with AP-1000 programme. Design and analyses are being conducted to document compliance with European Utility Requirements
SWR 1000	BWR	1290	1250	Framatome ANP, Germany	In the U.S., the Design Certification Pre-application review by the U.S.NRC was initiated in 2002
WWER-1000 (V-392)	PWR	1068	1000	Atomenergoproject/Gidropress, Russia	Design is licensed for Novovoronezh Phase 2 (units 5 & 6) in Russia. The main design features were used for the two WWER units under construction at Kudankulam in India
WWER-1000 (V-466)	PWR	----[a)]	-----	Gidropress, Russia	Reactor plant design is developed for WWER-91/99, NPP92 and Balakovo-5 NPPs
WWER-1500 (V-448)	PWR	----[b)]	-----	Gidropress, Russia	Detailed design of reactor plant is under development
CNP1000	PWR	1000	-----	China National Nuclear Corporation, China	Engineering design
SCPR	SCWR	950	----	Toshiba, et al., Japan	Representative of Super-Critical Water-Cooled Reactor system selected by the Generation-IV International Forum

a) Thermal power is 3000 MW

b) Thermal power is 4250 MW

RMWR[c)]	BWR	1356	1300	JAERI, Japan	Design studies and experiments being performed. Small scale prototype possible by early 2010s; commercialization by 2020
RBWR	BWR	----	1356	Hitachi, Japan	Design studies

c) A small scale (300 MWe class) RMWR with passive safety features is also being developed by JAERI, JAPC, Hitachi and Tokyo Institute of Technology under the innovative and viable nuclear energy technology development program (IVNET) sponsored by the Ministry of Economy, Trade and Industries (METI) of Japan since FY2000

TABLE I. ADVANCED LIGHT WATER REACTOR DESIGNS

B) Medium size advanced LWR designs (300-700 MWe)

Name	**Type**	**MWe Gross**	**MWe Net**	**Design Organizations**	**Status**
AC-600	PWR	600	----	China National Nuclear Corporation, China	R&D results will be applied to development of large advanced PWR
AP-600	PWR	619	600	Westinghouse, USA	Design has been certified by the U.S. Nuclear Regulatory Commission
HSBWR	BWR	600	----	Hitachi, Japan	Conceptual design
HABWR	BWR	650	----	Hitachi, Japan	Conceptual design
WWER-640 (V-407)	PWR	640	----	Atomenergoproject, St. Petersburg / Gidropress, Russian Federation	Construction of pilot plant at Sosnovy Bor site is under consideration. This would be followed by units at the Kola nuclear power station and other sites.
VK-300	BWR	---	2x250[d)]	RDIPE, Russian Federation	Design. Testing of key systems and components underway

d) A twin unit VK-300 electrical plant would produce 2 x 250 MWe. The VK-300 may be used for co-generation of district heat and electricity (at a reduced electrical capacity rating).

IRIS	PWR	----	335	Westinghouse, USA	In Pre-application Review for Design Certification by the U.S.NRC. Westinghouse expects that IRIS will be submitted to the U.S. NRC for Design Certification in 2004/5, with Design Certification following in 2008/2009.
QS-600e/w Co-generation plant	PWR	644	610[e)]	CNNC, China	Conceptual design
PAES-600 with twin VBER-300 units	PWR	---	2x295	OKBM, Russian Federation	Conceptual design
IMR	PWR	330	----	Mitsubishi, Japan	Conceptual design
NP-300	PWR	334	314	Technicatome, France	Basic design

e) This is the net electric rating for a plant that produces only electricity with no heat for desalination. A co-generation plant used for sea-water desalination and electric power production would have a lower net electric power capacity.

TABLE I. ADVANCED LIGHT WATER REACTOR DESIGNS

C) Small size advanced LWR designs (below 300 MWe)

Name	**Type**	**MWe Gross**	**MWe Net**	**Design Organizations**	**Status**
LSBWR	BWR	306	----	Toshiba, Japan	Conceptual design
CAREM	PWR	----[f)]	27[g)]	CNEA/INVAP, Argentina	Conceptual engineering for 27 MWe prototype, which is under consideration, has been completed
SMART	PWR	90	----[h)]	KAERI, Republic of Korea	Design and construction project for a 1/5th scale pilot plant is under way with completion planned by 2008
SSBWR	BWR	150	-----	Hitachi, Japan	Conceptual design
KLT-40	PWR	----	up to 70[i)]	OKBM, Russian Federation	A first unit, an adaptation of a nuclear propulsion unit used for the ice-breaker fleet in Russia, is planned at Severodvinsk of the Arkhangelsk region in the Russian Federation.
PSRD-100	PWR	----	31[j)]	JAERI, Japan	Conceptual design

f) CAREM concepts are in the small size range, utilizing natural circulation for plants below 150 MWe, or forced flow for plants with larger ratings.

g) Rating of prototype.

h) The thermal power of the full sized unit is 330 MW, to be used in the co-generation mode for 90 MWe (gross) of electric power and for sea-water desalination to produce 40,000 m^3 of fresh water per day.

i) Depending on amount of heat used in co-generating mode.

j) The concept reported here is rated 100 MWt. A 300 MWt concept is also being developed.

ANNEX 2

INPRO Basic Principles

Economics:

1: The cost of energy from innovative nuclear energy systems, taking all costs and credits into account, must be competitive with that of alternative energy sources.

2: Innovative nuclear energy systems must represent an attractive investment compared with other major capital investments.

Sustainability and the environment:

1: Acceptability of expected adverse environmental effects - The expected (best estimate) adverse environmental effects of the innovative nuclear energy system must be well within the performance envelope of current nuclear energy systems delivering similar energy products.

2: Fitness for purpose - The innovative nuclear energy system must be capable of contributing to energy needs in the future while making efficient use of non-renewable resources.

Safety of nuclear installations:

Innovative nuclear reactors and fuel cycle installations shall:

1: Incorporate enhanced defence-in-depth as a part of their fundamental safety approach and the levels of protection in defence-in-depth shall be more independent from each other than in current installations;

2: Prevent, reduce or contain releases (in that order of priority) of radioactive and other hazardous material in construction, normal operation, decommissioning and accidents to the point that these risks are comparable to that of industrial facilities used for similar purposes;

3: Incorporate increased emphasis on inherent safety characteristics and passive safety features as a part of their fundamental safety approach;

4: Include associated RD&D work to bring the knowledge of plant characteristics and the capability of computer codes used for safety analyses to at least the same confidence level as for the existing plants;

5: Include a holistic life-cycle analysis encompassing the effect on people and on the environment of the entire integrated fuel cycle.

Radioactive Waste Management

1: Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health.

2: Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment.

3: Radioactive waste shall be managed in such a way as to assure that possible effects on human health and the environment beyond national borders will be taken into account.

4: Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.

5: Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations.

6: Radioactive waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.

7: Generation of radioactive waste shall be kept to a minimum practicable.

8: Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account.

9: The safety of facilities for radioactive waste management shall be appropriately assured during their lifetime.

Proliferation Resistance

1: Proliferation resistant features and measures should be provided in innovative nuclear energy systems to minimize the possibilities of misuse of nuclear materials for nuclear weapons.

2: Both intrinsic features and extrinsic measures are essential, and neither should be considered sufficient by itself.

3: Extrinsic proliferation resistance measures, such as control and verification measures will remain essential, whatever the level of effectiveness of intrinsic features.

4: From a proliferation resistance point of view, the development and implementation of intrinsic features should be encouraged.

5: Communication between stakeholders will be facilitated by clear, documented and transparent methodologies for comparison or evaluation/assessment of proliferation resistance.