Nuclear Development
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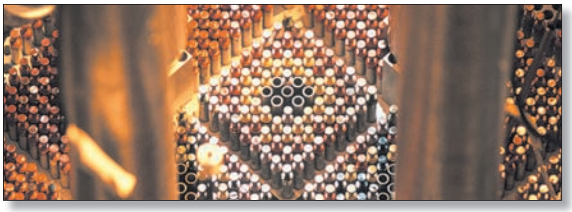
Innovation in Nuclear Energy Technology



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Nuclear Development

Innovation in Nuclear Energy Technology

NEA No. 6103

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full member. NEA membership today consists of 28 OECD member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

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FOREWORD

Innovation has characterised the successful deployment of nuclear energy in the past and remains essential today for its sustainable future. Recently, several OECD/NEA member countries have launched national and international efforts to define goals and roadmaps aimed at the development of innovative nuclear technologies. The Generation IV International Forum (GIF) and the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) are examples of such endeavours.

Innovation needs triggers and incentives. How to promote nuclear innovation is a key issue for industry and interested governments. In particular, if the target technologies are substantially different from current technologies, their development must be effectively and efficiently managed using all available tools for promoting innovation in accordance with current practices for nuclear research, development, demonstration and deployment (RDD&D).

Many studies on innovation processes in various technology sectors and national innovation systems, especially in the OECD context, have been performed. However, to date there has been no such study on innovation in nuclear technology. The NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) therefore decided to include such a study in its 2005-2006 programme of work. This report represents the output of the study.

Based on country reports and case studies from participating member countries, which have been made available in full on the NEA website, the study examines the special characteristics of nuclear innovation systems and investigates feedback from experience and performance of innovation in the nuclear sector to delineate policy recommendations for enhancing the effectiveness of nuclear innovation systems.

The study was carried out by an Expert Group (see Appendix A) comprising representatives from nuclear utilities, nuclear supplier industry and research organisations. It does not necessarily represent the views of the governments or international organisations that nominated these experts. The report is published on the responsibility of the OECD Secretary-General.

Acknowledgements

The Expert Group expresses its appreciation to Mr. Jerry Sheehan (DSTI, OECD) for having provided initial guidelines and information regarding the sectoral case studies on innovation systems, prepared under the OECD Committee for Scientific and Technological Policy (CSTP) and its Working Group on Innovation and Technology Policy (TIP), which served as a good starting point for this study.

The Group wishes to dedicate this report to Mr. Paul Govaerts, a member of the Group who regretfully passed away while the study was under way, and whose experience would surely have greatly contributed to this report**.**

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EXECUTIVE SUMMARY

Methodology

In this study, *innovation* is defined by describing its output as a new or significantly improved product (or process), bringing economic and/or social benefits by being introduced to the market (or by being used within an enterprise). *Innovation* encompasses a whole series of activities – basic research, development, demonstration, early deployment, and widespread dissemination – that result in a new or significantly improved product up to its introduction to the market and, thus, needing substantially more effort beyond R&D.

The objects of this study are *innovation systems* necessary to achieve innovation in *nuclear energy systems*. These innovation systems comprise actors of innovation (government bodies, R&D performers, system/service suppliers, energy providers) and their relationships, institutional frameworks, innovation infrastructure, management practices, nuclear legal framework, etc.

This study is based on the data and information on nuclear innovation systems of member countries, which primarily came from eleven country reports and twenty-three case studies prepared by the members of an ad hoc Expert Group. The case studies were analysed according to ten elements that can be assumed to determine innovation performance – demands; human resources; finances; physical inputs; access to science, technology and business best practices; ability and propensity to innovate; institutions and support mechanisms; networks, collaboration and clusters; effectiveness of market processes; and business environment.

Need for nuclear innovation

Considering the world energy prospects and related sustainability constraints (economic, environmental and social), nuclear energy is an option to meet the increasing global future energy needs in a "sustainable" manner. The current status of nuclear technology shows a high degree of compliance with sustainability criteria and excellent performance compared to other energy alternatives. However, there are still issues of public concern regarding a large-scale deployment of nuclear energy that can be significantly addressed by innovative approaches. This underscores the need for nuclear innovation.

Nuclear technology has considerable potential for innovation in comparison to existing nuclear power plants to maintain and strengthen the safety of nuclear installations, to implement power uprates and to achieve higher efficiency, which imply more stress on materials and components; and to optimise costs, both of operation and fuel cycle. This potential is particularly important given the upcoming challenges regarding closure of the nuclear fuel cycle, and penetration of the heat market with nuclear systems of the fourth generation.

With regard to a stronger future deployment of nuclear energy, innovative solutions are sought in such domains as resource preservation and minimisation of waste, practical elimination of catastrophic events outside the plant, maintenance of economic competitiveness, reduction of financial risks, penetration of new energy sectors, and exclusion of misuse of nuclear materials. Also R&D on and application of innovative solutions is an excellent means to attract talented young scientists and engineers and to retain them in the nuclear business.

Nuclear innovation programmes

In responding to needs with regard to existing nuclear power plants and fuel cycle facilities, there are many on-going projects with innovation elements on many topics such as materials degradation/ageing, high performance fuel and fuel reliability, non-destructive evaluation and material characterisation, equipment reliability and human performance, instrument and control (I&C) hardware and systems modernisation, nuclear asset risk management, safety risk technology and application, etc. Programmes in this category are performed usually by industry research organisations (IROs) and the corresponding demands come mainly from utilities and regulatory authorities.

Typical R&D programmes for near-term deployment (5-10 years) are those aimed at developing Generation III and III+ reactors, with improved features such as enhanced safety (by means of inherent characteristics and passive systems), standardised, simpler and more rugged design, higher availability and longer operating life by design, further reduced probability of core melt accidents, and minimal effect on the environment in case of severe accidents. More than a dozen Generation III and III+ reactors are in various stages of development; for example, evolutionary developments of the pressurised-water reactor (PWR), boiling-water reactor (BWR) and pressurised heavy-water reactor (PHWR) designs. Such reactor developments have been performed usually by system suppliers and/or utilities, with some government coordination in some countries.

Programmes for long-term deployment are focused on Generation IV nuclear systems. For instance, the Generation IV International Forum (GIF), established in January 2000 and consisting of eleven members, selected six promising systems to meet future energy challenges: sodium-cooled fast reactors (SFR), gas-cooled fast reactors (GFR), lead-cooled fast reactors (LFR), molten-salt reactors (MSR), supercritical water-cooled reactors (SCWR), and very high temperature gas reactors (VHTR). GIF has established system steering committees to implement the necessary R&D for each system by planning and integrating R&D projects contributing to their design. Currently, detailed R&D plans to close the technological gaps for each selected technology are being elaborated and reviewed.

Technically, nuclear reactors produce energy in the form of heat and can, thus, supply energy products other than electricity, including district and process heat, notably for the production of potable water, and eventually hydrogen. Since the supply of high-temperature heat is instrumental for high-efficiency nuclear hydrogen production, high-temperature reactors, like the VHTR, are receiving increased interest. Many countries with advanced nuclear power programmes, such as the United States, France, Japan, Korea and the EURATOM, have launched nuclear hydrogen programmes.

Characteristics of the nuclear sector

Nuclear energy technology has special characteristics that affect the way innovation in this domain is conducted. They can be grouped in four main fields: technology and knowledge required for nuclear energy use, nuclear energy industry market, financial and economic environment, and legal and socio-political environment.

Nuclear energy technology development requires long lead times and implies large, complex, multi-system test/experimental/fabrication installations and energy generation plants with very special quality (nuclear-grade) requirements. Research related to nuclear energy covers a broad range of disciplines, requiring generally an extensive, resource-intensive and long-term, ideally multinational, R&D effort. It must also take into account non-proliferation concerns and radiation protection considerations in its development.

The nuclear energy industry market is a relatively low-volume but high-value market, where research is triggered by suppliers, utilities, and governments. It is a market that is also subject to requirements of international agreements, especially with respect to non-proliferation and export controls.

Nuclear energy technology deployment requires high initial investment with delayed return, but on the other hand, has a long technical lifetime and high returns on the capital invested because of its low unit costs of fuel and operation. Although nuclear technology has reached a fairly mature state, it still is evolving and there remain opportunities for innovative technological development and improvement.

Nuclear energy is socially and politically sensitive because of different concerns directly related to its nature. Nevertheless, the positive impact of nuclear energy on local economic development and security of supply can play a role in social acceptance and balance to some extent public concerns on risks.

Patterns of nuclear development

In the country reports submitted, three main patterns of nuclear development have been identified: self-dependent from the onset (e.g., PWR and BWR in the United States; PHWR in Canada; gas-cooled reactor (GCR) in the United Kingdom and France), technology transfer from abroad and then self-dependent development (e.g., PWRs in France, Japan and Korea; BWRs in Japan), and essentially dependent from abroad. In all different development patterns, however, governmental drive and international collaboration have been essential for the success of the nuclear development.

Characteristics of nuclear innovation systems

Driving forces of nuclear innovation**:** The driving forces for nuclear innovation differ depending on the target technologies as well as on national and international environments. However, it is clear that there are certain fundamental driving forces for nuclear technology innovation that can be broadly grouped in three categories: market drivers, political/public drivers, and technical drivers.

Main actors**:** Nuclear innovation involves a broad range of actors, such as government and governmental bodies for policy setting and safety regulation, R&D performers (e.g., public research organisations, industrial research organisations, universities), system/service suppliers (e.g., nuclear vendors, component suppliers, fuel suppliers, engineering companies) and energy providers (e.g., utilities, heat suppliers). Their roles and the intensity of their relationships are different among the countries and have been changing in response to changing global and local circumstances.

Institutional frameworks**:** The environments where nuclear innovations take place comprise many frameworks such as national policies, national nuclear programmes, funding mechanisms, innovation incentives, public and private partnerships (PP/P), international collaboration, and nuclear education and training. These frameworks, usually set by governments and promoters of nuclear innovation, include many diverse, country dependent measures. In some countries, such frameworks are provided under the label of general science and technology without explicit mention of “nuclear”.

Human resources and infrastructure**:** A country's or company's capacity for innovation depends on the availability of qualified human resources, access to R&D facilities and knowledge, organisational culture for innovation, etc. International and inter-sectoral collaboration in these regards is gaining importance.

Programme management practices**:** Effective management of innovation programmes requires a sound visioning and planning process, and proper evaluation and oversight mechanisms, especially because of the numerous uncertainties and possible biases in the process. Exercises of visioning and planning have taken place in many countries and oversight processes are under implementation in various forms.

Nuclear legal frameworks**:** The special characteristics of nuclear technology require nuclear development to be performed within the nuclear specific legal frameworks on health and safety regulation, non-proliferation of nuclear weapons and export control. These well-established legal frameworks, either national or international, can have both positive and negative impacts on nuclear innovation.

Key factors for nuclear innovation performance

Although nuclear energy development and deployment can be regarded as a single successful innovation process, individual innovative approaches in nuclear technology have not always been successful. Many reasons for less successful developments identified in the case studies are similar to those in other technology sectors; for example, lack of competitiveness with other alternatives already in the market, lack of focus on one project, failure to respond to prevailing market requirements, no industry participation from an early stage, lack of clear decision criteria for stopping or redirecting the R&D, lack of an oversight process for the use of public funding, radical changes of the political and economic environment, lack of transferability of results from R&D to industrial scale. Other causes are specific to the nuclear sector, for example, reduced competitiveness due to increased requirements for safety features, politically driven decisions, too long lead times, concerns of neighbouring countries including their anti-nuclear groups.

Challenges and recommendations

Policy aspects**:** Governments interested to ensure that nuclear power has an ongoing and enhanced role in their energy supply mix should provide long-term policies, within an adequate framework of national policies and international rules, and funding support for the development of innovative nuclear energy systems. In particular, governments need to trigger innovation when it is uncertain who will initiate it or when no entity seems prepared to pursue apparent market opportunities. The multi-disciplinary nature of nuclear energy development requires strong governmental coordination. Also, special attention should be given to national innovation systems as a whole, which should incorporate all areas of science and technology and provide a context for the nuclear innovation system. Governments, regulators and industry need to ensure that policies and programmes are in-place for short-, medium- and long-term nuclear R&D. International organisations could provide platforms for the coordination of such national policies and programmes.

Visioning and planning**:** The realisation of innovative ideas in a controversial environment needs strong leadership and direction in a top-down approach: for current systems, leadership should stem primarily from the industry; for long-term developments, direction from governments or public institutions is required; and for near-term deployments, a coordinated steering from industry and governments seems appropriate. Visioning and planning of nuclear RD&D programmes should define in an early phase success criteria and adequate milestones, ideally before launching such programmes, the achievements of which should be reviewed independently and periodically. In such approaches, the roles of promoters and R&D performers should be clearly defined from the very beginning.

Demand analysis**:** A market evaluation for the foreseen products by the innovation promoters and the R&D performers should take place at an early stage of the short and medium term R&D projects, and efforts should be focused on products with clear market horizons. Such market analyses should be updated periodically.

R&D strategy**:** The strategy of R&D towards innovative nuclear systems should be based on a step-by-step approach including mid-term solutions as well as long-term products. It is not sufficient to focus only on promising long-term solutions without providing any intermediate results. While it is wise to start with exploring a large scope of different technological paths to be sure not to miss optimal solutions, the strategy should include a down-selection process at a time point predefined and not too far in the future. The strategy should also include appropriate measures to strengthen the cooperation with the non-nuclear R&D sector; this would create opportunities for accessing novel technological possibilities developed in other sectors and for non-nuclear spin-offs of nuclear R&D.

Funding**:** Public funding is required at the beginning of the innovation process, but should evolve towards substitution by industrial funding going through PP/Ps as an intermediate stage. In any case, funding of innovation oriented R&D should be stable in a long-term perspective and not be questioned or revised as long as the milestones and the promised intermediate deliverables are fulfilled. The preparedness of governments to allocate funding for R&D on innovative solutions will increase if progress and success oversights similar to the ones implemented for industrial R&D are in place.

Human resources and infrastructure**:** Nuclear R&D requires specialised human and infrastructural resources. National strategies, including international approaches, should be established to develop and preserve knowledge and to build and maintain the necessary infrastructures. The availability and mobility of specialised people can be enhanced through instruments such as mutual recognition of education, training and R&D activities of different institutions in different countries, and a globally accepted common qualification system. Databases of available facilities with corresponding capacities, of ongoing R&D programmes with main milestones and deliverables and an “address book” of experts with their specialisation are appropriate tools to enhance the exchange of expertise and available knowledge, to facilitate the sharing of R&D infrastructure, and to provide systematic and up-to-date information about existing facilities, ongoing R&D activities and knowledge-holders.

Partnerships and clusters**:** PP/Ps between public research organisations and industry offer excellent opportunities to bring closer the innovative spirit of researchers with the relevant issues to be resolved. To facilitate the contacts between research institutions and industrial partners, it is desirable to establish adequate public institutions dedicated to the initiation and promotion of innovation, which encourage researchers to approach industry and reduce the risk to the industry by providing seed funding during the most uncertain phases of innovative R&D activities. They may have the duty to educate potential customers towards innovation and function as “committees of promoters”. Each sector promoting nuclear R&D should work in a coordinated way. Research centers should specialise in specific areas and the constitution of clusters both at a national and international level should be encouraged. Promoters and industry should encourage this specialisation by using specific research centers for specific areas.

Education and training**:** R&D directed towards innovative solutions for current and upcoming problems is an excellent means to attract young specialists. Parallel to providing opportunities for enabling or encouraging innovative R&D, governments need to ensure that policies and programmes are in place to support and encourage scientific and technical education and training to help provide the necessary human resources to implement nuclear innovation systems. Industry and utilities, on their side, should use the opportunity to fund or co-fund nuclear-specific education at all levels (technical and scientific) for their own benefit.

Safety regulation**:** Nuclear regulatory bodies should be timely involved in innovative development activities to become familiar with new technologies and to establish necessary methods and tools for their assessment; this would help them to avoid unnecessary delays in licensing that can discourage potential future users of such systems. Harmonisation of national regulations can enlarge the international market for innovative products and, thus, increase the attractiveness of a proposed innovative R&D activity for potential promoters or enlarge the circle of institutions interested in international collaboration. Considering the need for intensive international collaboration, regulatory bodies should put increased emphasis at national level on compliance with international codes and standards. Regulatory bodies should also aim themselves at implementing innovative regulatory approaches.

Public acceptance**:** Promoters of technological innovations should communicate clearly and timely the beneficial features of new nuclear technologies, while making especially clear where are the limits of such systems, and what will never be possible. The availability of such new technologies should not be promised overly optimistically to avoid deception of the public, loss of credibility of the promoters and premature obsolescence of currently operating systems. In doing so, innovative communication approaches should be sought to promote future nuclear energy systems, which bear the burden of a highly controversial discussion on nuclear technology in the past.

International collaboration**:** International collaboration will be instrumental to the success of innovative nuclear R&D activities in terms of sharing financial burdens, optimizing the use of existing resources, avoiding duplications, exploiting synergies and enhancing mobility of specialists and knowledge. Governments and international organisations should encourage and facilitate international collaboration on innovative nuclear systems and information exchange on a broad cross-sector range including the establishment of clear cooperation rules and coordination instruments in the framework of international bodies including representatives from both governmental and industrial entities. On an institutional level, mutual and systematic information exchange about national R&D programmes is desirable for the awareness of the international community regarding ongoing R&D and the preparedness of research institutions to join such R&D programmes.

1. INTRODUCTION

1.1 Background

It is well known that technology innovation is a primary basis for long-term economic growth and competitiveness in world markets and will provide part of the solutions to many challenges the world is or will be facing. This applies also to nuclear energy.

Innovation has been a driving force for the success of nuclear energy and remains essential today for its sustainable future. Nuclear energy is an attractive option to ensure diversity and security of energy supply as well as to lower global climate change risks. All energy systems should satisfy the needs and expectation of society, such as ecological friendliness, safety and reliability, and economic competitiveness. Today nuclear energy ranks high in all these requirements.

Recently, several OECD/NEA member governments have launched national and international efforts to define goals and roadmaps aimed at the development of innovative nuclear technologies. Especially, Generation-IV International Forum (GIF), comprising 11 members, is formulating international joint programmes for the development of Generation IV nuclear systems (see Box 1.1), which would mainly have *revolutionary* characteristics requiring substantial technological innovations.[1] Also, 26 members are participating in the International Atomic Energy Agency (IAEA) International project on innovative nuclear reactors and fuel cycles (INPRO), which has been focusing on user requirements and assessment methodology of innovative nuclear reactors and fuel cycles.[2]

How to promote nuclear innovation is a key issue for industry and interested governments. Especially if the target technologies to be developed are revolutionarily different from current technologies, then their development must be effectively and efficiently managed with current practices of nuclear research, development, demonstration, and deployment (RDD&D). In case that governments have decided to phase out nuclear power plants in their countries, nuclear innovation still would be valuable in the field of decommissioning and waste disposal.

For more innovation in the nuclear arena to be realised, more and deeper discussion on ways and means for promoting nuclear innovation is crucial and more knowledge on nuclear innovation systems is required. With this kind of knowledge, innovation performance in the nuclear sector could be significantly improved similar to that of sectors such as information and communication technology and biotechnology. It should be noted also that there have been many innovative ideas in the nuclear sector which were proposed but which have not been deployed on an industrial scale.

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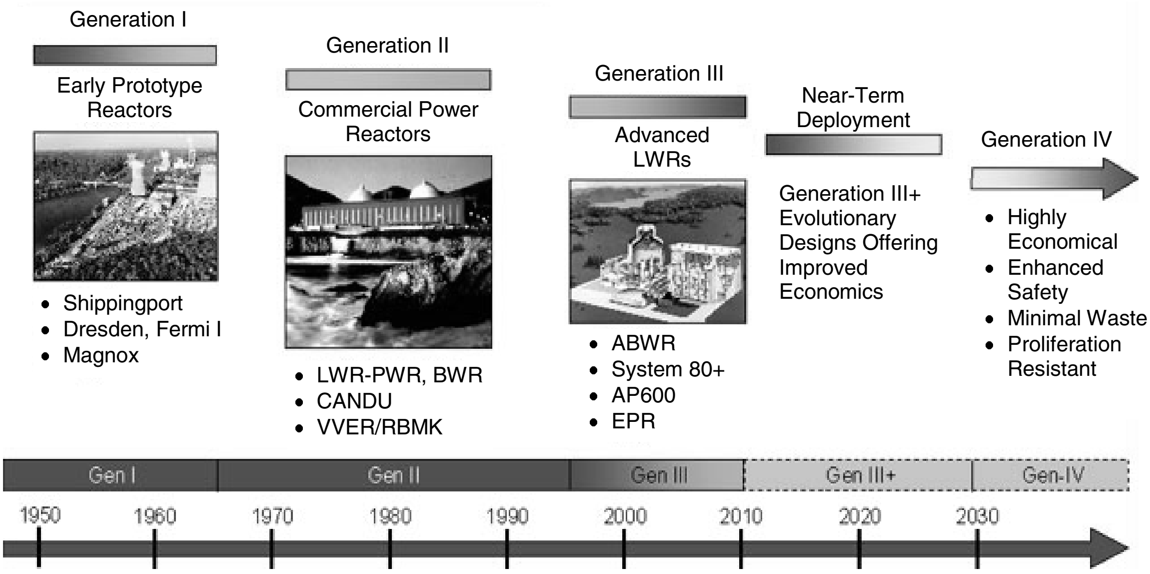
[1] For more detail on GIF, see Section 4.3.1.1 of Chapter 4.

[2] For more detail on INPRO, see Section 4.3.1.2 of Chapter 4.

Box 1.1 Evolution of nuclear reactors



Generation I: Prototype commercial reactors of the 1950s and 1960s. Relatively few are still running today.

Generation II: Commercial reactors deployed in the 1970s and 1980s and which are still in operation today. They typically use enriched uranium fuel and are mostly cooled and moderated by water. They include such light-water reactors (LWRs) as the BWR and the PWR. The fuel, ceramic uranium dioxide, is typically encased in long zirconium alloy tubes. The uranium-235 is enriched from its original 0.7% abundance to 3.5-5.0%. Also advanced gas-cooled reactors (AGRs) in the United Kingdom, the CANDU heavy-water reactors in Canada, and the VVERs and RBMKs in Russia are of the Generation II.

Generation III: *Evolutionary* reactors designed in the 1990s that offer significant advances in safety and economics. Referred to as advanced-design nuclear power plants (NPP), these reactors include the advanced boiling and pressurised water reactors. The European pressurised reactor (EPR) belongs also to this category. They are developments of Generation II technology.

Generation III+: *Evolutionary* reactors that could be deployed around 2010. They have been under development during the 1990s and are now in various stages of design and implementation. They have a simpler design and increased safety features, in particular, passive safety designs. These are technological features that may foreshadow Generation IV reactors.

Generation IV: *Revolutionary* reactors that will have innovative fuel cycle technologies and will probably be deployed by 2040. They are expected to be highly economical, incorporate enhanced safety, produce minimal waste, and be resistant to proliferation. They will tend to have closed fuel cycles and burn the long-lived actinides: they are expected to have full actinide recycle (not just recycling of plutonium and possibly uranium). Many will be fast neutron reactors.

Many studies on innovation processes and national innovation systems (NIS), especially in the OECD context, have been performed. The OECD Committee on Scientific and Technological Policy (CSTP) and its Working Group on Innovation and Technology Policy (TIP) have been performing many projects concerning NIS since 1995, including case studies in knowledge-intensive service activities, energy and pharmaceutical biotechnology. However, there has been no such study for innovation in nuclear technology.

Many OECD member governments have shown great interest in building and strengthening their NIS, which implies many policy measures to enhance technology innovation in their countries. Nuclear innovation should be a part of the considerations in building and strengthening the NIS. This requires close communications between the various sectors including the nuclear sector.

In the light of the above, the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) approved the inclusion of a study on "Innovation in Nuclear Energy Technology" in the 2005-2006 Programme of Work of the NEA.

1.2 Objectives

Providing guidance to member governments on nuclear energy policy issues is the general objective of the NDC activities. Within this framework, this study focuses on ways and means to promote nuclear innovation in support of nuclear energy systems.

The study has the following three objectives:

- To examine the special characteristics of nuclear innovation systems, including innovation actors and their relationships, innovation processes and infrastructures as well as institutional frameworks that affect performance of nuclear innovation systems.
- To investigate innovative performance and experience in the nuclear sector including good innovation practices, barriers to innovation and system imperfections in member countries. This investigation leads to the identification of key factors behind successes and failures.
- To delineate policy recommendations for enhancing the performance of nuclear innovation systems.

The recommendations of the study, if followed well by relevant organisational bodies, should lead to *innovation* of nuclear innovation systems for their better performance, better harmonisation within the nuclear sector and with other sectors, and enhanced international collaboration. Description of national and international efforts for nuclear innovative technologies is expected to bring higher public awareness of the innovation potential of nuclear energy systems that allows greater investment opportunities for nuclear energy systems. This study also opens an initiative for deeper discussions on innovation issues in the nuclear society that would broaden the visibility and transparency of nuclear RDD&D.

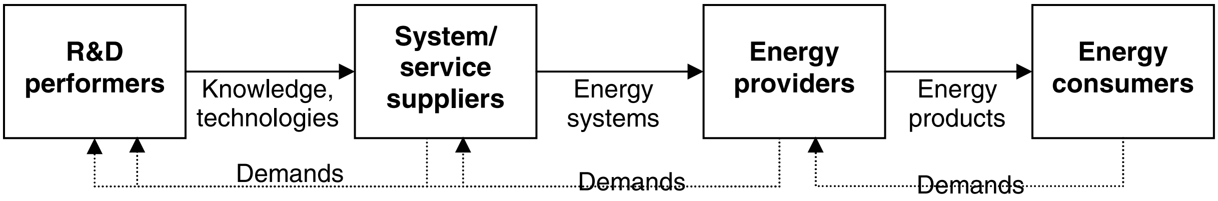
1.3 Scope

The study focuses on emerging technologies and some historical cases in energy systems including reactors and fuel cycles, nuclear safety and radioactive waste management, but does not cover radiation application areas, nuclear fusion and space propulsion.

The concept of innovation is very broad and encompasses a wide range of diverse activities. Innovation can take various types; it could be organisational as well as technological. This study considers only technological innovation as defined in Chapter 2, including product as well as process innovation.

For clarifying the scope of the study, a simplified market chain for nuclear energy systems is presented as in Figure 1.1.

Figure 1.1 Simplified market chain in the nuclear energy sector



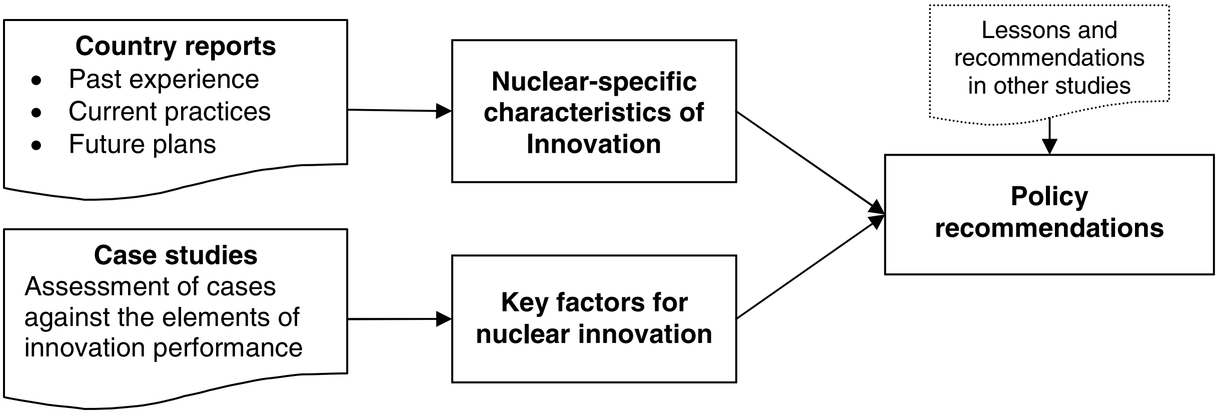
Energy consumers get goods (e.g. electricity, heat, hydrogen) they need from energy providers. Energy providers get energy production capacities they need from energy systems (e.g. nuclear power plants and adequate fuel, heat generation plant, hydrogen production plant, desalination plant) provided by system/service suppliers. Suppliers and energy providers get relevant knowledge and technologies from R&D performers. The governments can directly and indirectly interact with the above actors. Although in reality it is possible that one organisation performs multiple functions (e.g. energy provider, system/service supplier and R&D performer), for the purpose of this study each function is assumed to be performed by a different actor.

In Figure 1.1, there exist three different kinds of market: energy product market, energy system market and technology market. In the energy product market, consumers have several alternatives among which they can choose. Also in the energy system market, energy providers have several alternatives. The deployment of a nuclear energy system requires a good understanding of its market characteristics and of the actors in the market, including their relationships and related policy directives. The analysis should include not only current markets but also future markets.

1.4 Approach

To accomplish the three objectives mentioned above, this study is based mainly on two knowledge sources – country reports and case studies from member countries as illustrated in Figure 1.2.

Figure 1.2 Approach used in the study



An *ad hoc* group including experts on nuclear R&D management and innovation from ten countries (Belgium, Canada, Czech Republic, Finland, France, Japan, Korea, Spain, Switzerland, United States)[3] and EURATOM was established in October 2004 (see Appendix A). The work of the Group was followed by the IAEA. The Group had four meetings, the first in October 2004 and the last in May 2006. All participating countries submitted their country reports and case studies, which the Group and the NEA Secretariat integrated, identifying system commonalities and differences among the countries and extracting key factors for successful nuclear innovation. With these analyses, the Group made policy recommendations for decision makers for nuclear energy technology innovation.

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[3] Experts from Germany and Australia attended the first meeting, but decided not to participate in the study after the first meeting.

2. METHODOLOGY

2.1 Common understanding of *innovation* and *innovation systems*

2.1.1 Innovation

2.1.1.1 Definition

The discussion of *innovation* in nuclear energy technology first requires a clear definition of *innovation* since innovation clearly has implications beyond the development of innovative technology. Considering the definitions in Box 2.1, this study defines *innovation* first by describing its output as follows:

- it should be a new or significantly improved[1] product (or process); and
- it should bring economic and/or social benefits by being introduced to the market (or by being used within an enterprise).

The second point above implies that *innovation* is distinguished from *invention*, which could mean just the development of new ideas or technology. In this sense, *innovation* implies certain series of activities that result in a new or significantly improved product introduced on the market.[2] Most R&D programmes aim not just at *invention* but *innovation,* which needs more effort beyond R&D. There are many cases where we succeed in *invention*, but fail in *innovation*.

In this sense, when referring to the output of innovation, the term "innovative product" will be used. In the same context, terms such as "innovative idea," "innovative concept," and "innovative technology" can be used.[3] When referring to the activities regarding innovation, the term "innovation activities" will be used in the study. If an innovative product is introduced to the market, it can be said that "innovation activities" resulting in the "innovative product" were successful.[4]

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[1] The term "a new or significantly improved" applies in the context of an enterprise (or a country). The item should be new to the enterprise, not necessarily new to the market. For instance, pressurised water reactor (PWR) is not an innovative product for a country already building it by itself, but is an innovative one for a country where it is introduced for the first time.

[2] However, it does not mean that one enterprise (or a country) does all such activities by itself. Innovative products may be developed by the enterprise itself or by another enterprise under its control.

[3] For example, PWR was an innovative product in the 1960s, but not in the 1980s. European pressurised reactor (EPR) is an innovative product, which is being introduced to the market and in the process of deployment. AP1000 is an innovative product, which is expected to be introduced to the market. Generation-IV systems are "innovative concepts" and will be "innovative products" after their demonstration and commercial use.

[4] For example, innovation activities for PWR in the United States in 1960s were successful. Innovation activities for introducing PWR in France were different from those in the United States.

Box 2.1 Definitions of *innovation* in other studies

- "Conversion of new knowledge into economic and social benefits." [1]
- "Successful entry of a new science or technology-based product into a particular market." [2]
- "A new or significantly improved product (good or service) introduced to the market or the introduction within an enterprise of a new or significantly improved process." [3]
- "Commercially successful exploitation of new technologies, ideas or methods through the introduction of new products or processes, or through the improvement of existing ones." [4]
- "Renewal and enlargement of the range of products and services and the associated markets; the establishment of new methods of production, supply and distribution; the introduction of changes in management, work organisation, and the working conditions and skills of the workforce." [5]
- "Implementation of a new or significantly improved product (good or service) or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations." [6]

In 2005, OECD and EUROSTAT produced a manual on innovation, the "Oslo Manual" [6], where they further distinguished four types of innovation:

- ✓ *Product innovation*: introduction of a good or service that is new or significantly improved with respect to its characteristics or intended uses. This includes significant improvements in technical specifications, components and materials, incorporated software, user friendliness or other functional characteristics.
- ✓ *Process innovation*: implementation of a new or significantly improved production or delivery method. This includes significant changes in techniques, equipment and/or software.
- ✓ *Organisational innovation*: organisational innovation means implementation of a new organisational method in the organisation's business practices, workplace organisation or external relations.
- ✓ *Marketing innovation*: implementation of a new marketing method involving significant changes in product design or packaging, product placement, product promotion or pricing.

This study focuses on innovation activities (whether they were successful or not) for innovative products (whether they might be already introduced to the market or not).

2.1.1.2 General characteristics of innovation

To promote innovation, good understanding of innovation is crucial, primarily of those characteristics general to all sectors. The "Oslo Manual" [6] describes well the general characteristics of innovation as follows.

Innovation is associated with *uncertainty* over the input for and the output of innovation activities. It is not possible to know beforehand with certainty whether research and development will result in the successful development of a marketable innovative product or how much time and resources will be required and how successful they will be. Therefore, innovation always involves risk.

Innovation is not free of cost. It involves *investment,* which can include acquisition of fixed and intangible assets as well as other activities such as salaries, or purchase of material or services that may yield potential returns in the future. Often, lack of funding or resources are the critical barriers to innovation.

Innovation is subject to *spillovers*. The benefits of creative innovation are rarely fully given to the inventing firm. Firms that adopt "innovation" of others can benefit from knowledge spillovers or from the use of the original innovation. For some innovative items, imitation costs are substantially lower than development costs, so that an effective appropriation mechanism to provide an incentive to innovate may be required.

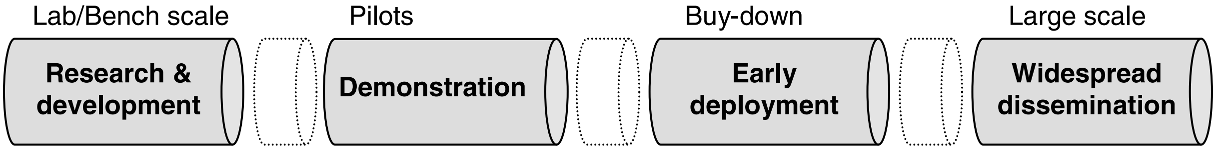
Innovation involves the *utilisation of new knowledge* or a *new use or combination of existing knowledge*. New knowledge may either be generated by the innovating firm in the course of its own innovation activities or acquired externally through various channels such as purchase of new technology. The ability to combine these different sources of knowledge rests with organisations whose role is to apply knowledge to exploit new opportunities. OECD [4] describes the processes of innovation in the perspective of knowledge management as follows:

> **Production of knowledge:** Knowledge can be produced either individually or through formal or informal networks involving organisations that may belong to different institutional sectors, science and technology fields, regions or countries. Knowledge results can be either codified or remain tacit, and can range from scientific results to technology developments. Research organisations and vendors are usually on this "supply" side by "creating" knowledge.
>
> **Diffusion of knowledge:** This encompasses flows of both scientific and technological know-how and information between (or within) institutions. Such flows can occur through informal transactions, or can be organised by market and other formal mechanisms. New knowledge can come from sources as diverse as the public science system or competitors of the innovative firms. Knowledge can circulate through numerous channels (e.g. patents, scientific publications, equipment supply, informal contacts, seminars and conferences, collaborative research, mobility of R&D personnel) which involve a variety of actors coming from different institutional sectors, industrial activities and various fields. In this regard, education and training institutions "transmit" knowledge (while creating and using it) to prepare the next generation of knowledge suppliers and users.
>
> **Exploitation of knowledge:** The fact that the knowledge created by an actor can be diffused either involuntarily or intentionally does not imply that it can be immediately absorbed and used by others. On the one hand, the ability of an institution to absorb external knowledge depends on its own skills and expertise, and on whether it can develop in-house the basic capabilities required to exploit that knowledge. On the other hand, when knowledge is protected by intellectual property rights (IPRs), others must have the right to use it in order to exploit it. Utilities and regulators are usually on the "demand" side by "using" knowledge.

2.1.1.3 Innovation activities

Primarily, innovation includes basic research (production of new knowledge), development (proof of principle or concept, prototype development), demonstration, early development, and widespread dissemination as shown in Figure 2.1.

Figure 2.1 Simplified stages of innovation



Adapted from Holdren, J.P. (1999), "Foundations of International Cooperation on Energy Innovation", Chapter 3 in *Powerful Partnerships*: *The Federal Role in International Cooperation on Energy Innovation*. Washington, DC: Executive Office of the President of the United States.

Research and development: This stage represents the world of basic research and conceptual development. Innovative ideas or concepts are born in these stages.

Demonstration: The demonstration phase typically consists of building one or more target systems of increasing scale to prove the technical and potential commercial viability of the technology. This is the point of *invention*, which then leads to the transition to *innovation*.

Early deployment: Once an innovative product has been demonstrated at a potentially commercially viable scale, there remains a long process of building a series of such systems to scale up manufacturing capacities and also to learn how to reduce costs (manufacturing, system installation, and operations and maintenance) to competitive levels. To move a new technology into the market, its higher initial costs relative to competing products must be covered. As cumulative production volume increases, costs will be reduced until some innovative technologies become fully competitive with conventional technologies. The process of paying for the difference between the cost of an innovative new technology and the cost of its competitors is known as early deployment *buy-down*. This is the point at which a business case can be validated and might begin to attract levels of capital sufficient to permit initial production and marketing.

Widespread dissemination: After an innovative product has proceeded through the R&D, demonstration, and buy-down portions of the chain in Figure 2.1, it is ready for large-scale deployment. This is the point at which investors can expect to see the beginning of returns on their investments.

Innovation activities, along the stages in Figure 2.1, involve all those scientific, technological, organisational, marketing, financial and commercial steps, including investment in new knowledge, which actually lead to, or are intended to lead to, the implementation of innovative products. Especially, the transition between the stages is difficult since the main actors in the stages and their interest are different from one another.

In addition, innovation can include the following activities: [3]

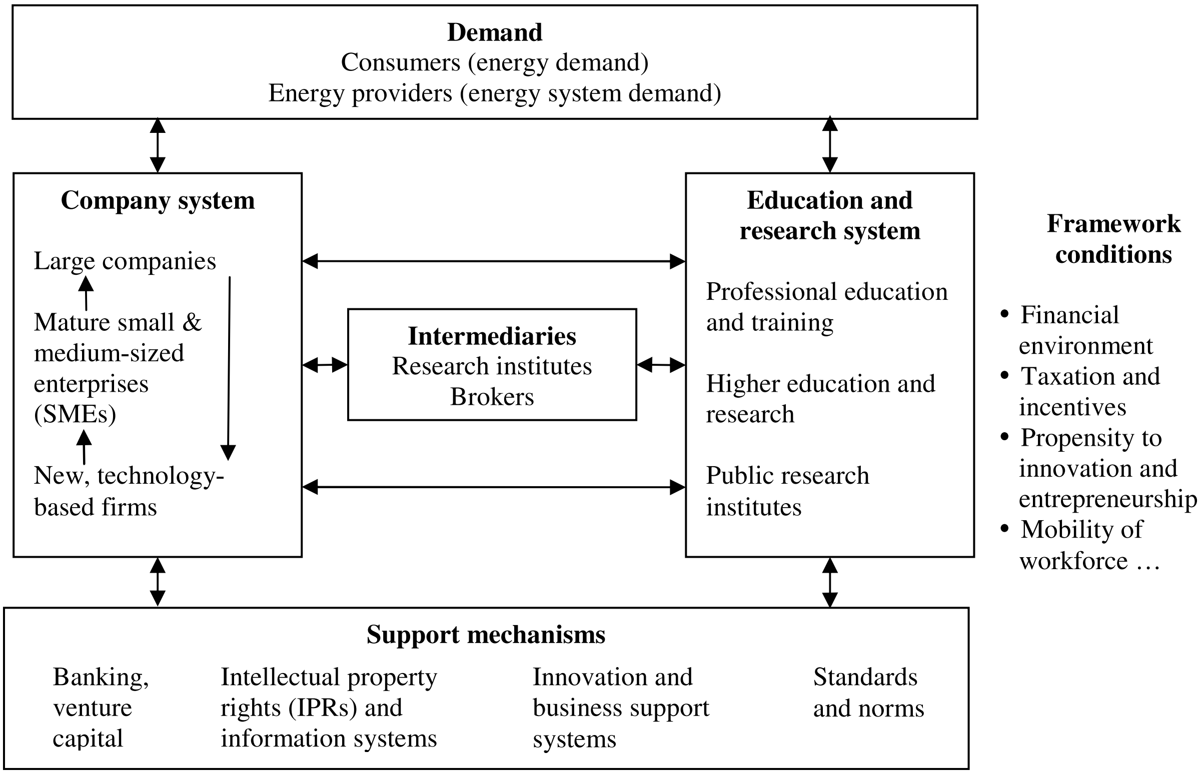
- acquisition of extramural R&D (from other enterprises, research institutes or public bodies) or by acquiring knowledge in the form of licensed goods, patents or copyrights;
- purchase of machinery and equipment that specifically leads to the introduction or implementation of innovations;
- training of the staff to equip the workforce with the necessary skills required for the development or introduction of innovative products and processes; and
- market research or advertising in relation to the market introduction of a new product.

2.1.2 Innovation system

Brilliant ideas alone cannot bring innovation. It has to go through a series of stages, including RDD&D and also involving many inter-related actors. Innovation includes a series of activities that have to take place and that must work together to implement a successful innovative product. Therefore, the combination of activities, each of which involves people who are generating and using knowledge and information, should be considered in a systems perspective – the *system of innovation*. In this sense, nuclear innovation systems may be considered to be those systems for achieving innovation in nuclear energy systems.

Considering the innovation system on a national level, OECD [8] incorporates the definition of a *national innovation system* as "the set of distinct institutions which jointly and individually contribute to the development and diffusion of new technologies and which provide the framework within which governments form and implement policies to influence the innovative process. As such, it is a system of interconnected institutions to create, store and transfer the knowledge, skills and artefacts which define new technologies". Figure 2.2 illustrates an innovation system. It should be noted that "innovation performance depends not only on how specific actors perform, but on how they interact with one another as elements of an innovation system, at local, national, and international levels". [8]

Figure 2.2 Components and linkages in the innovation system



Adapted from OECD (2002), "Case Studies in Innovation: Implementation Guidelines", DSTI/STP/TIP(2002)1.

This study considers the nuclear innovation system as a sectoral system, which is a part of the national innovation system as a whole. The national innovation system provides the nuclear innovation system with larger context such as general innovation policies, financial environment, IPRs, etc.

2.2 Integration of country reports

As shown in Figure 1.2, this study is based on the data and information on nuclear innovation systems of member countries, which primarily come from the country reports written by the members of the Group. The experiences and best practices of innovation of one country can be shared with other countries.

For effective and efficient integration of eleven country reports, their contents were agreed by the Group members: introduction of national context; national experience of nuclear energy development; current system of national nuclear innovation including main actors, related policies, infrastructure, and RD&D process; national programmes for future innovation; and conclusion and issues for improvement.[5]

Considering the different situations and contexts of the countries, the Group configured nuclear development patterns, identified similarities and differences among the current national nuclear innovation systems, and made recommendations for better nuclear innovation systems.

Each country report is available on the NEA website www.nea.fr/download/innovation.

2.3 Analysis of case studies

To identify key factors for nuclear innovation performance from past experiences, this study includes analyses on several cases of successes or failures in participating countries.

2.3.1 Conceptual framework

This study follows the methodology suggested by OECD [10], which identified ten elements that can be assumed to determine innovation performance on a national level. The ten elements can be illustrated as in Figure 2.3 and can also be applied to the cases in this study with some modifications.

A. Demands

This means the willingness and ability of potential customers (consumers, energy providers, system suppliers and/or public sector organisations) to purchase the innovative goods and services. The propensity of consumers to buy new products and services usually depends on national culture, per capita income etc., while that of firms will be much more dependent on their innovation systems; the more innovative are firms the more they will buy innovative inputs from their suppliers. However, innovation policy-makers will be particularly interested in public procurement where governments have direct influence on markets and can create demand for innovative items.

B. Human resources

This means the supply of qualified scientists and engineers, trained craftsmen and technicians, and well-educated and trained managers. Government policies related to higher education, training and university research can have a strong influence on the availability of domestically produced human resources. Polices related to immigration can influence international mobility and the inflow and outflows of workers.

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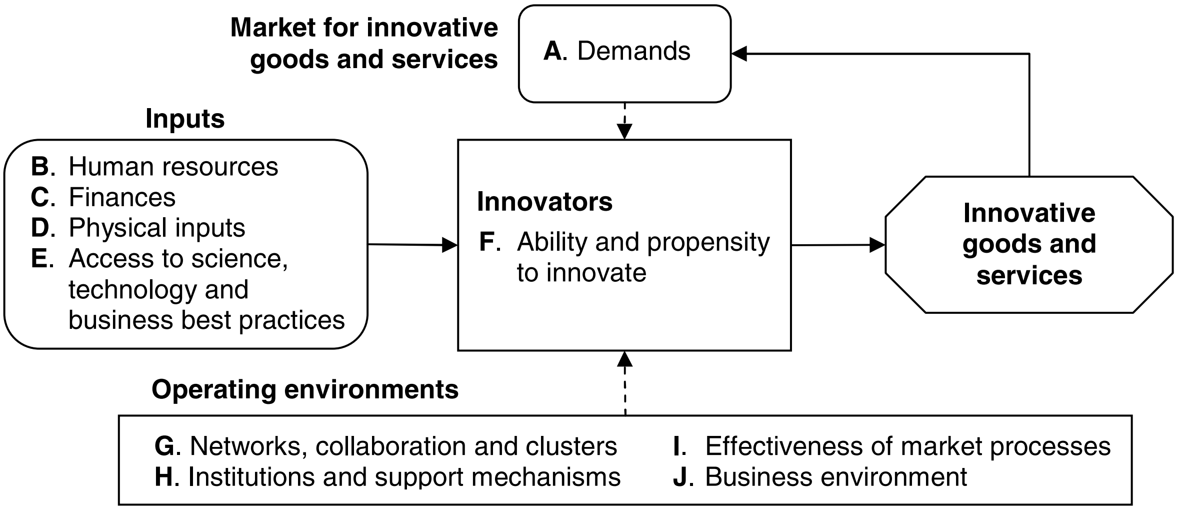
[5] The detailed table of contents is in Appendix C.

Figure 2.3 Elements determining innovation performance



Adapted from OECD (2003), "A Strategic View of Innovation Policy: A Proposed Methodology for Assessing Innovation Policy and Performance", DSTI/STP/TIP(2003)4.

C. Finances

This means the ability of firms to generate sufficient internal finance and allocate it effectively to innovation activities, and to raise external finance for innovation on appropriate terms and conditions and which meets their particular needs. Governments often provide financing for business innovation, either directly though R&D and innovation subsidies (sometimes linked to specific government needs) or indirectly through tax incentives and other means. A range of government policies can influence the availability of external financing, especially for new technology-based firms.

D. Physical inputs

This means the ease with which domestically based firms can obtain supplies of components, materials, services, capital equipment and software. Most firms will rely significantly on supplies from abroad, although in the case of some OECD countries these may be obtained within regional clusters that span international frontiers.

E. Access to science, technology and business best practice

This includes the sources of technological, scientific and technological knowledge and related knowledge of business best practice and the means by which firms can access them. Sources will include universities, R&D service companies, national/regional/local R&D support organisations, customers, suppliers, international collaborative programmes, business support organisations such as chambers of commerce, as well as a variety of government programmes. Means will include networks and clusters, supply chains, seminars, exhibitions, licensing, publications, mobility of qualified personnel, government support programmes, etc.

F. Ability and propensity to innovate

This means the ability of firms to use external resources (people, finance, technology, bought in supplies) to develop high value added products, processes and services that meet customers' needs and generate the revenues needed to finance its activities. This will include the effectiveness of internal innovation and other business processes as well as the ability of firms to develop effective organisational structures, ways of working and culture that allows and encourages managers and employees to give of their best. The ability of firms to interact effectively with their external environment, to identify and seek out the inputs that they require and to formulate appropriate strategies for survival, growth and coping with change is also crucial.

I. Institutions and support mechanisms

This covers a wide range of organisations, facilities and systems. Most important to innovation are universities, public research organisations (PROs), organisations which provide R&D support and/or links with the research base, education and training institutions, professional societies, government departments, transport and communications, a range of business support organisations, financial institutions, etc.

H. Networks, collaboration and clusters

Networks play a key role in the transmission of knowledge and information because markets are not very effective in doing this. Collaboration enables firms to share risks and costs and gives them access to complementary capabilities that they do not possess themselves. Clusters involve both market relationships and networking, typically require geographical proximity, and give firms the advantage of external economies of scale and scope including externalities.

G. Effectiveness of market processes

This is the extent to which the interaction of firms and other factors in the market place is conducive to innovation. For instance, competition provides an important stimulus to innovation while innovation is one of the most important ways in which firms compete. Similarly, while the removal of barriers to market entry is conducive to innovation, firms will try to innovate in ways that make it difficult for other firms to match them in the market place. Even if they succeed, the advantage will be only temporary or until the associated IPR expire. Radical innovation is one way in which existing entry barriers can be overcome and the competitive advantage of incumbent firms eroded. The ability of an economy to foster the creation of new firms and encourage their subsequent growth and development plays a vital role in innovation and the ability to adapt to changing economic circumstances and exploit new opportunities. These processes will be affected by competition policy, other regulatory policies particularly those affecting new firm creation, standards and the IPR regime as well as by trade policy.

J. Business environment

This covers framework conditions such as macro-economic/political/social stability, legal framework, public acceptance, etc. It should also include non-firm specific aspects of business culture, the practice and unwritten rules that govern how business is done. Corporate governance that may have significant impacts on corporate strategy and attitudes to innovation and risk is also included.

2.3.2 Description of cases

In the study, twenty-three cases were analysed within the framework of Figure 2.3. Table 2.1 shows the cases including some success cases, some failure cases, and some cases in between.

Each case study is available on the NEA website www.nea.fr/download/innovation.

Table 2.1 Description of cases

No.	Country	Target system	System type[1]	Purpose[2]	Work type[3]
1	Belgium	MOX fuel development	R	D, E	RD, D, ED, WD
2	Belgium	MYRRHA	R	D, E	RD
3	Canada	Development of advanced CANDU reactor (ACR)	E	D, E	RD
4	Canada	Development of SLOWPOKE Energy System	E	D	RD, D
5	Czech Republic	HWGCR (heavy watermoderated gas-cooled reactor) development	RC	D	ED
6	Czech Republic	Deployment of VVER-1000 nuclear power plants	E	D	D, ED
7	Finland	APROS (advanced process simulator) development	E	D	RD, D, ED
8	Finland	NURES (nuclide removal system) development	E	D	RD, D, ED
9	France	Development of fast breeder reactors (Phenix & Superphenix)	R	D	RD, D, ED
10	France	EPR (European pressurised reactor) development	E	D, E	RD, ED, WD
11	France	MOX fuel development	R	D, E	RD, D, ED, WD
12	Japan	Development of advanced thermal reactor (ATR)	R	D	RD, D, ED
13	Japan	Improvement & standardisation of light water reactor (LWR)	E	D	ED, WD
14	Korea	Development and deployment of Korea standard nuclear power plant (KSNP)	RC	D	RD, ED, WD
15	Korea	CANFLEX (CANDU Flexible) fuel development	E	D	RD, ED
16	Spain	DON (deuterium water moderated, natural uranium fuel, with organic liquid as coolant) project	R	D	RD
17	Spain	Development of mobile robotic devices for maintenance and inspection of nuclear and radioactive installations	E	D	RD, D
18	Switzerland	Development of Swiss heating reactor (SHR)	RC	D, E	RD
19	Switzerland	Development of higher burn-up fuel	E	D	RD, D, ED, WD
20	United States	Development of Clinch River breeder reactor	R	D	RD
21	United States	Advanced light-water reactor (ALWR) programme and the NP-2010 programme	E	D, E	RD, ED
22	EURATOM	Development of European fast reactor (EFR)	R	D, E	RD
23	EURATOM	Phenomena identification and ranking tables (PIRT) in the EURSAFE project	E	D	ED, WD

1. **E**: Evolutionary; **RC**: Revolutionary within the country; **R**: Revolutionary.
2. **I**: In-house use; **D**: Domestic use; **E**: Export.
3. **RD**; R&D; **D**: Demonstration; **ED**: Early deployment; **WD**: Widespread dissemination.

3. NEEDS FOR NUCLEAR TECHNOLOGY INNOVATION

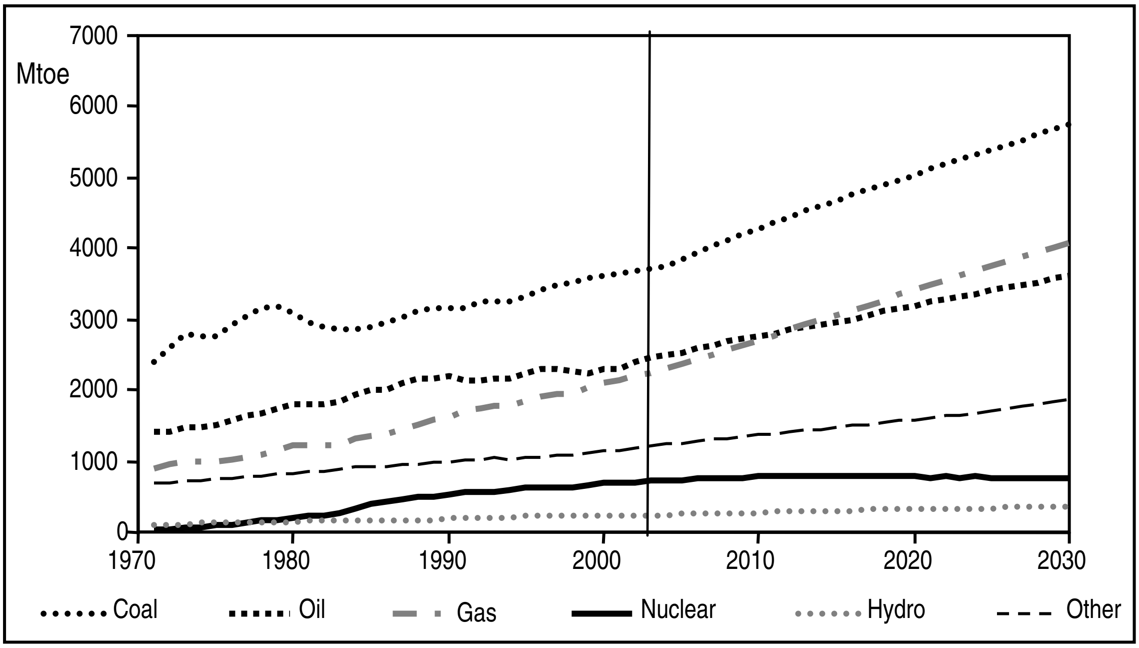
3.1 World energy prospects

3.1.1 Energy demand

In the World Energy Outlook (WEO) 2004 [11], global economic growth – the primary driver of energy demand – is assumed to average 3.2% per year over the period 2002-2030, slightly less than in the previous three decades. The rate will drop from 3.7% in 2002-2010 to 2.7% in 2020-2030, as developing countries' economies mature and population growth slows. The economies of China, India and other Asian countries are expected to continue to grow most rapidly.

The WEO 2004 paints a sobering picture of how the global energy system is likely to evolve from now to 2030. If governments stick with the policies in force as of mid-2004, the world's energy needs will be almost 60% higher in 2030 than they are now. Fossil fuels will continue to dominate the global energy mix, meeting most of the increase in overall energy use as in Figure 3.1. According to the report, the shares of nuclear power and renewable energy sources will remain limited.

Figure 3.1 World primary energy demand by fuel



Source: IEA (2004), *World Energy Outlook 2004*, OECD, Paris.

World electricity demand is expected to double between now and 2030, with most of the growth occurring in developing countries. By 2030, power generation will account for nearly half of world consumption of natural gas. It will also have absorbed over 60% of total investment in energy supply infrastructure between now and then. The global power sector will need about 4 800 GW of new capacity to meet the projected increase in electricity demand and to replace ageing infrastructure. In total, electricity investment will amount to about \$10 trillion (10^{12}), more than half of that amount for developing countries alone.

3.1.2 Energy supply and sustainable development

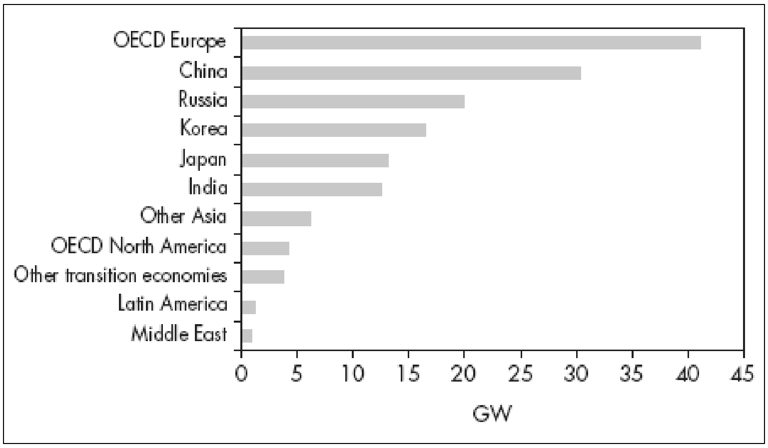
The world's vulnerability to supply disruptions will increase as more countries will depend on international trade to satisfy their domestic demand. Climate-destabilising carbon-dioxide emissions will continue to rise, calling into question the sustainability of the current energy system. Together with substantial efforts in increasing energy efficiency, huge amounts of new energy infrastructure will need to be financed. Nevertheless, many of the world's poorest people will still be deprived of modern energy services. These challenges call for urgent and decisive action by governments around the world.

It is clear from the analysis in WEO 2004 that achieving a truly sustainable energy system will call for technological breakthroughs that radically alter how energy is being produced and used. The government actions envisioned in the WEO 2004 Alternative Scenario could slowdown markedly carbon-dioxide emissions, but they could not reduce them significantly using existing technology. Carbon capture and storage technologies, which are not taken into account in either the Reference or the Alternative Scenario, hold out the tantalising prospect of using fossil fuels in a carbon-free way. Advanced nuclear-reactor designs or breakthrough renewable technologies could one day help free the world from its dependence on fossil fuels. The pace of technology development and deployment in these and other areas is the key to making the global energy system more economically, socially and environmentally sustainable in the long term. But consumers will have to be willing to pay the full cost of energy – including environmental costs – before these technologies can become competitive. Governments must decide today to accelerate this process.

3.1.3 World nuclear capacity

In IEA forecasts [11], worldwide nuclear capacity is projected to increase slightly, but the share of nuclear power in total electricity generation will decline. A substantial amount of capacity will be added (see Figure 3.2), but this will be mostly offset by reactor retirements. Three-quarters of existing nuclear capacity in OECD Europe is expected to be retired by 2030, because reactors will have reached the end of their life or because governments plan to phase out nuclear power. Nuclear power generation will increase in a number of Asian countries, notably in China, Korea, Japan and India.

Figure 3.2 Nuclear plant capacity additions by region, 2003-2030



Source: IEA (2004), *World Energy Outlook 2004*, OECD, Paris.

A similar picture can be found in the International Atomic Energy Agency (IAEA) forecasts, as shown in Figure 3.3. In the low estimates, the present barriers to nuclear power development are assumed to prevail in most countries during the coming three decades:

- low economic and electricity demand growth rates in OECD countries;
- public opposition to nuclear power, leading to policy decisions not to consider the nuclear option in spite of its competitive costs and potential contribution to reducing environmental impacts from electricity generation;
- institutional and financing issues preventing the implementation of previously planned nuclear programmes, in particular in countries in transition and in developing countries; and
- inadequate mechanisms for nuclear technology transfer and nuclear project funding in developing countries.

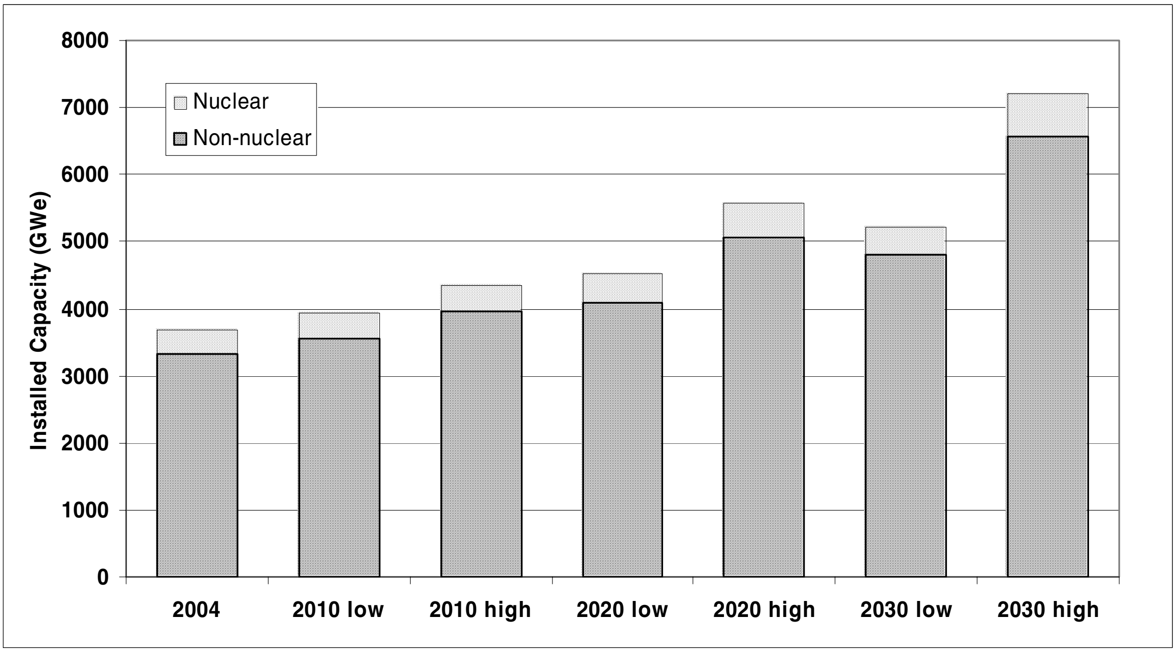
The high estimates reflect a moderate revival of nuclear power development that could result in particular from a more comprehensive comparative assessment of the different options for electricity generation, integrating economic, social, health and environmental aspects. They are based upon a review of national nuclear power programmes, assessing their technical and economic feasibility. They assume that some policy measures would be taken to facilitate the implementation of these programmes, such as strengthening of international cooperation, enhanced technology adaptation and transfer, and establishment of innovative funding mechanisms. These estimates also take into account the global concern over climate change caused by the increasing concentration of greenhouse gases in the atmosphere, and the ratification of the Kyoto Protocol.

In a study by IAEA and IIASA [13] the potential of nuclear energy is discussed based on the scenarios in the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change [14]. In the SRES, four narrative storylines (each representing a different coherent set of demographic, social, economic, technological and environmental developments) and for each storyline several different quantifications or scenarios were developed. The result is 40 scenarios for the time period up to 2100 grouped in four "families" (A1, A2, B1, and B2). In the technologically lethargic A2 and B2 Scenarios, nuclear energy's market niche remains electricity production. In the technologically aggressive A1T and B1 Scenarios, hydrogen production is a substantial contender. Between 2030 and 2050 average annual additions to the world's hydrogen production capacity in the B1 Scenario are more than twice the average capacity additions for electricity. Nuclear energy and renewable compete for this expanding market.

The IAEA/IIASA study departs from the assumption that, from the perspective of the nuclear industry, the SRES results should be viewed not as tight constraints, but as indications of opportunities and asks the question how quickly must the industry improve costs and competitiveness to capture future market shares significantly bigger than those based on the cost assumptions of SRES' authors. The study presents an "aggressive-nuclear-improvement" variation for each of the four SRES scenarios by assuming reasonable nuclear incursions in the expensive ends of the market shares of key competitors. It comes to the conclusion that, with appropriate technical and economic measures, the potential of nuclear for both electricity and heat applications can be 2 to 7 times higher than assumed by SRES, depending on the storyline.

Overall, it is clear that nuclear energy is an option to meet the world's increasing future energy needs in a "sustainable" manner. This underscores the need for nuclear innovation.

Figure 3.3 Projected electricity generation capacity and share of nuclear power



Source: IAEA (2005), *Energy, Electricity and Nuclear Power Estimates for the Period up to 2030*, Vienna.

3.2 Sustainability constraints

3.2.1 Concept of sustainable development

The concept of *sustainable development* was reborn in 1987 with the publication of the report "Our Common Future" by the World Commission on Environment and Development (the Brundtland Commission). *Sustainable development*, as defined in this report, is "the capacity to meet the needs of the present without compromising the ability of future generations to meet their own needs". In a broad sense, sustainable development incorporates equity within and across countries as well as across generations, and integrates economic growth, environmental protection and social welfare. A key challenge of sustainable development policies is to address those three dimensions in a balanced way, taking advantage of their interactions and making relevant trade-offs whenever needed.

Sustainable development was the focus of the Earth Summit held in June 1992 in Rio de Janeiro. Chapter 40 (Information for Decision Making) of Agenda 21 requested countries, international governmental and non-governmental organisations to develop the concept of indicators of sustainable development in order to identify such indicators.

3.2.2 Indicators of sustainability

The OECD three-year horizontal project on sustainable development was launched by OECD Ministers in April 1998. They called for the elaboration of the OECD's strategy in the areas of climate change, technological development, sustainability indicators and the environmental impact of subsidies. It aimed at making the sustainable development concept operational for public policies and at issuing substantive outputs for the meeting of OECD Ministers in 2001, including a series of background reports based on the work of various OECD Directorates and affiliates. The sustainable development framework referred to was intended to integrate economic, social and environmental factors in a way that will meet society's concerns at the lowest cost, and will highlight the linkages and trade-offs between these areas. Table 3.1 includes the set of environmental indicators.

Table 3.1 OECD set of key environmental indicators

Pollution issues		Natural resource and assets	
Climate change	◆ CO_2 emission intensities	Freshwater resources	◆ Intensity of use of water resources
Ozone layer depletion	◆ Indices of apparent consumption of ozone depleting substances	Forest resources	◆ Intensity of use of forest resources
Air quality	◆ SOx and NOx emission intensities	Fish resources	◆ Intensity of use of fish resources
Waste generation	◆ Municipal waste generation intensities	Energy resources	◆ Intensity of energy use
Freshwater quality	◆ Waste water treatment connection rate	Biodiversity	◆ Threatened species

Source: OECD (2001), *OECD Environmental Indicators towards Sustainable Development*, Paris.

Energy has links with all three dimensions of sustainable development. Energy services are essential for economic and social development and improved quality of life. Energy demand will continue to grow; at the same time, energy production and use activities at present are responsible for major environmental degradation at all levels – local, regional and global. There are large disparities in the level of energy consumption among different countries; one third of the world's population suffer from no access to electricity. While the depletion of the world's finite resources of energy is a long term global concern, the continued uninterrupted availability of imported energy is an immediate concern for countries short of fossil fuel resources. Thus, the provision of adequate energy at affordable costs and in a secure and environmentally congenial manner, in consonance with the social and economical developmental needs, is essential. The importance of these elements is quite obvious from the fact that both the energy sector and the energy related issues received particular emphasis in the programmes for the further implementation of Agenda 21.

The NEA has made a contribution to the OECD Project providing information on nuclear energy relevant for policy making within a sustainable development framework [16]. In this context, the specific characteristics of nuclear energy are reviewed from the economic, environmental and social viewpoints. The report provides data and analyses on the nuclear option, together with information on alternative options, to support assessments of policy makers taking into account the specific context and priorities. In this context, a number of indicators relevant for nuclear energy were identified from the framework of economic, social and environmental dimensions; examples are given in Table 3.2.

Table 3.2 Sustainable development indicators (illustrative list applicable to nuclear energy)

Economic indicators	Social indicators	Environment indicators
Capital cost ($/kWe) Marginal cost ($/kWh)	Dose to the public (Sv/kWh) Employment (man/kWh) Education (number of university courses)	Fuel use (tU/kWh) Volume of solid waste (m^3/kWh) Activity of solid waste (Bq/kWh) Activity of liquid & gaseous effluents (Bq/kWh)

Source: NEA (2000), *Nuclear Energy in a Sustainable Development Perspective*, OECD, Paris.

Furthermore, the following characteristics of nuclear energy were analysed:

- *Economic dimension* – Competition, subsidies, external costs and benefits.
- *Environmental dimension* – Natural resource management, radiological protection, safety, third party liability, radioactive waste management.
- *Social dimension* – Human capital, institutional framework, non-proliferation, public participation and political aspects, international co-operation.

The information given is descriptive and rather general in nature, rarely specific or quantitative (besides figures on generating costs and uranium resources); the potential of future technological developments has not been reflected in detail.

In summary, the national and international work on indicators of sustainable development is ongoing. The initiatives have been driven by global concerns about "the planet earth" and by demands of decision makers at countries' level being in charge of implementing the concept of sustainable development. Therefore, the indicators are of overriding importance. Although all three dimensions of sustainable development are taken into account in principle, environmental indicators, complemented with selected economic factors, are still dominating.

3.2.3 Sustainability and nuclear energy technology

The current status of nuclear technology shows a high degree of compliance with sustainability criteria and performs excellently with regard to other energy alternatives. Many studies (e.g. [17]) have examined the sustainability performance of different energy options using life cycle analysis and taking most recent technologies into account. They show that nuclear power generation is among the best alternatives, both in terms of specific indicators and in terms of aggregated indicators, e.g. total costs including externalities.

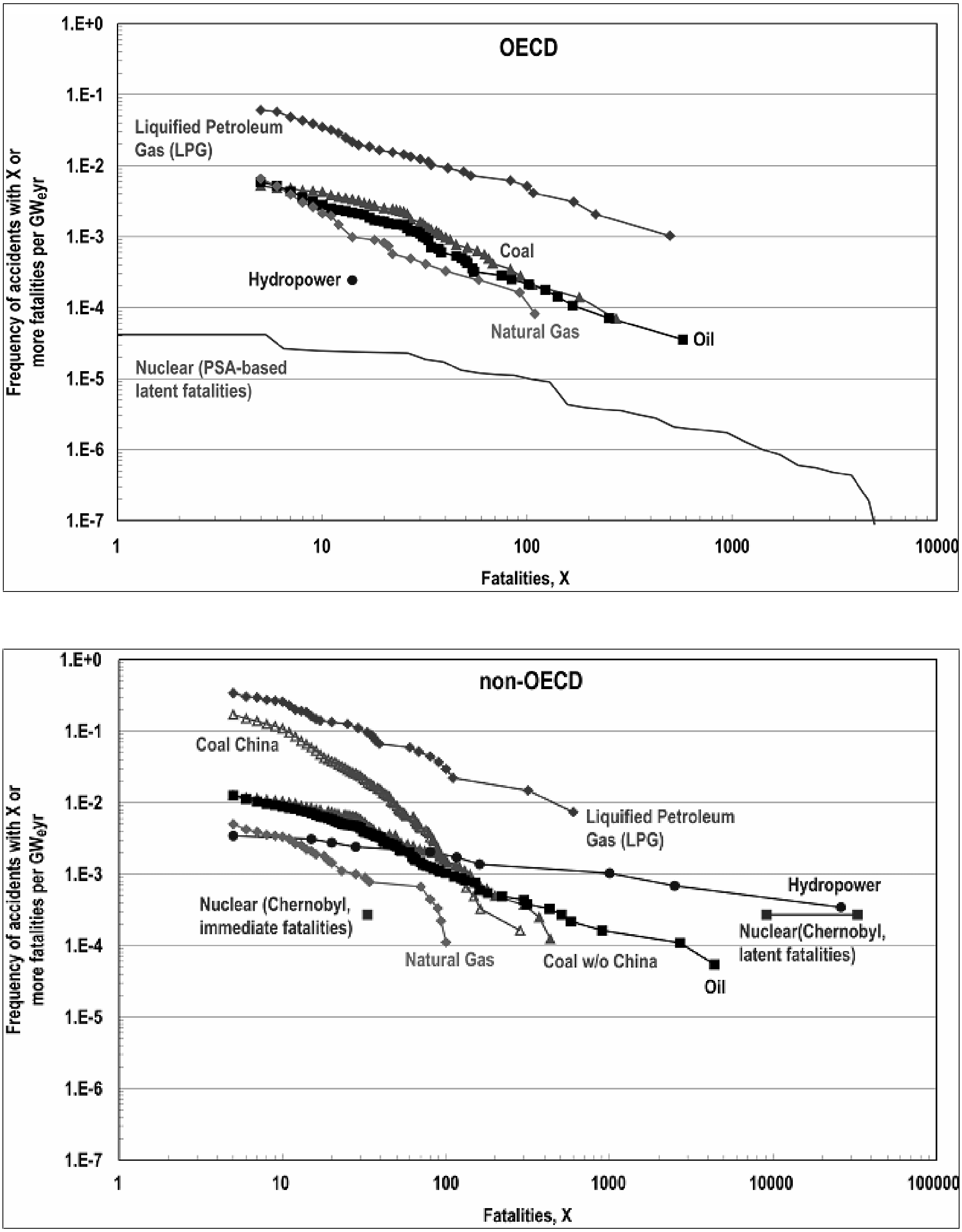
Also the safety performance of nuclear energy (measured in terms of risk for fatalities following a severe accident [18]) is excellent (see Figure 3.4).

However, this positive performance of nuclear energy is not perceived as such by some political decision-makers and by part of the public. Perceptions leading to negative statements regard:

- Safety (even the possibility of catastrophic events with a high number of latent fatalities and long-lasting land contamination) and public fears reducing acceptance.
- Convincing answers to questions regarding the management of nuclear waste (safety, irretrievability, burden for coming generations, loss of information).
- Sufficient resources (known and estimated uranium reserves for an expanding and/or sustainable nuclear capacity).
- Minimisation of the proliferation risk and of the risk of terrorist attacks.

These issues represent challenges for future nuclear systems and must be addressed both by persistent efforts of open, objective and unbiased information towards political leaders and the public and by targeted technological developments.

Figure 3.4 Severe accidents in the electricity sector in OECD and non-OECD countries 1969-96



Source: Burgherr, P., *et al* (2004), "External costs from major accidents in non-nuclear energy chains", *Report prepared by PSI for European Commission within Project NewExt,* in: Friedrich R., *et al.*, *New Elements for the Assessment of External Costs from Energy Technologies (2004).*

Sustainability in its broad form encompassing environmental, economic and societal aspects dominated naturally the goals formulated for future nuclear systems at the beginning of the Generation IV Initiative and used subsequently for the formulation of criteria and indicators for the selection of promising candidates [19]:

Sustainability-1: Generation IV nuclear energy systems including fuel cycles will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilisation for worldwide energy production.

Sustainability-2: Generation IV systems will minimise and manage their nuclear waste and notably reduce the long term stewardship burden in the future, thereby improving protection for public health and the environment.

Economics-1: Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.

Economics-2: Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.

Safety and reliability-1: Generation IV nuclear energy systems operations will excel in safety and reliability.

Safety and reliability-2: Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.

Safety and reliability-3: Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

Proliferation resistance and physical protection-1: Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

3.3 Role of nuclear technology innovation

Driving forces of technological development can be in the form of objectives of research policy (defined by the state), market maturity and market penetration (decided by the industry), operational maturity and market domination (in the responsibility of regulators and the industry), and developments with new goals for future needs (triggered by the industry and the state). This last force is closely coupled with innovation. It is characteristic that the first of the four strategic objectives of the Generation IV Initiative states that "*Technology goals for Generation IV systems must be challenging and stimulate innovation*".

3.3.1 Domains for innovative solutions

With regard to a stronger future deployment of nuclear energy, innovative solutions are sought in the following domains.

Resource preservation and minimisation of waste

Minimisation of the volume of wastes and reduction of their necessary confinement time on the one hand and improved use of the energetic content of fissile materials on the other hand imply the use of advanced fuel cycles, including advanced thermal reactors and fast neutron reactors combined with reprocessing and multiple recycling of actinides. Many such systems are discussed, in particular in the context of Generation IV activities. The role of science here will be to cover the existing technological gaps using the most advanced solutions while maintaining high levels of safety and low level of costs.

Practical elimination of catastrophic events outside the plant

Future nuclear systems must be free of the threat of catastrophic events. The consequences of even the most severe accident must be confined in the plant and not affect the environment. First concepts have been developed for thermal systems (water-cooled and gas-cooled reactors) using passive safety systems and inherently safe features. The challenge will be to maintain these characteristics also for systems of the next generation with fast neutron spectra and different safety behaviour.

Maintenance of economic competitiveness, reduction of financial burden

Future nuclear systems must maintain the current low level of operational costs and, in addition, lower the necessary investment and reduce the long lead times. Appropriate technical measures to achieve this are simplification, standardisation, pre-fabrication and modularisation. Here again, the challenge will be to combine a high level of safety, optimisation of resources and minimisation of waste with simple and low-cost concepts.

Penetration of new energy sectors

An aggressive nuclear deployment is mostly seen in the non-electricity market. The main issue here being to achieve the high process temperatures necessary for industrial applications, which requires the development of materials capable to withstand extremely high temperatures and neutron fluences and, possibly, highly corrosive coolants.

Exclusion of misuse of nuclear materials

Several technical measures, especially in the field of fuel fabrication (e.g. rock-like fuels), can substantially reduce the risk of misuse of sensitive nuclear materials. Further, new monitoring technologies making full use of advances in information technology (IT) and communication can help to improve the administrative measures already in place.

3.3.2 Sharing innovation with other sectors

In addressing the issues mentioned above, nuclear developments can and must keep pace with technology developments in other sectors, with exchanges in both directions. This is in particular true for materials, processes, automation and simulation, and risk management.

Materials

High-temperature materials are sought in space applications and in the development of fusion reactors. Their suitability for nuclear fission applications has to be tested under fission-specific conditions, i.e. fluence, pressure, transient loads, interaction with coolants such as helium, lead, supercritical water, etc.

Processes

Progress in the chemical industry (development of new solvents) can be used in developing high-yield separation processes for the recycling of spent nuclear fuel. New pyro-metallurgical processes are desirable for dry reprocessing routes. Production of high-purity graphite and of novel ceramic forms for proliferation resistant fuels may also benefit from new chemical processes.

Automation and numerical simulation

Advances in IT can, on the one hand, be used for new tele-fabrication and tele-manipulation techniques for fuel fabrication, fuel reprocessing and plant inspection and repair. On the other hand, high-power computers can be used for one-to-one simulations of complex phenomena (e.g. accident sequences) in real or even faster-than-real time, thus allowing for a reduction of uncertainties in designing nuclear installations.

Risk governance

Risk governance methodologies and practices in the nuclear sector can be applied in other sectors; for instance, prevention of accidents (PSA level 1), mitigation of severe accident consequences (PSA level 2), environmental risk analysis (PSA level 3), emergency management in national and international contexts, and risk communication to decision makers, opinion leaders and/or the public at large.

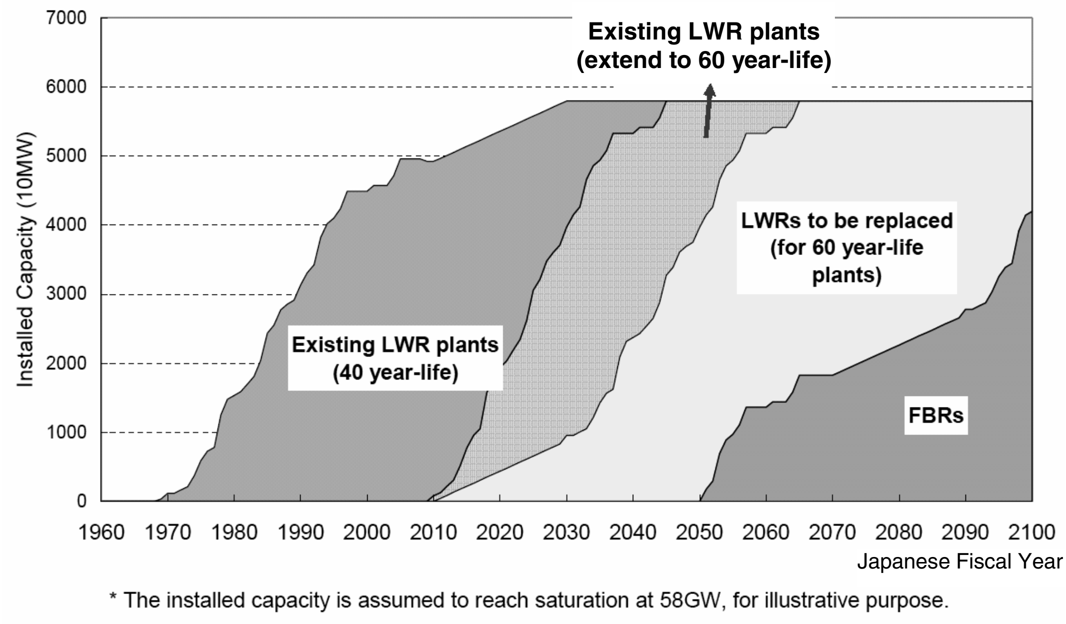
3.3.3 Knowledge preservation

Finally, R&D on and application of innovative solutions is an excellent means to create a positive climate characterised by optimism and trust in the future and, thus, to motivate staff in place, to attract talented young scientists and engineers and to retain them in the nuclear business. Ageing of the current generation of specialists and the need to ensure the next generation is a real issue for nuclear energy, and innovation in nuclear technology can help to address it.

4. NATIONAL AND INTERNATIONAL EFFORT FOR NUCLEAR INNOVATION

Many countries envisage a sustained use of nuclear energy even beyond the end of this century. Corresponding strategies for the replacement of current plants with new ones have been developed, as illustrated in Figure 4.1 from Japan.

Figure 4.1 An example of mid- and long-term projections of NPP deployment (Japan)



* The installed capacity is assumed to reach saturation at 58GW, for illustrative purpose.

Source: Country report of Japan.

As discussed in Chapter 3, there are and will be many needs for innovation in nuclear energy technology. In responding to these needs, many countries are pursuing programmes for nuclear innovation, which can be classified in four categories:

- Programmes supporting nuclear power plants and fuel cycle plants:
    - ✓ Current plants (within 5 years).
    - ✓ Near-term deployment (5-10 years from now).
    - ✓ Long-term deployment (over 10 years from now).
- Programmes outside electricity production.

Since the purpose of this chapter is to show possible areas of nuclear innovation with on-going examples, it should be noted that the programmes described here do not cover all the programmes in the participating countries, which can be found in the country reports.

4.1 Programmes supporting current nuclear power plant and fuel cycle facilities

Innovation does not necessarily mean dealing with future innovative systems. As discussed in Chapter 2, nuclear technology has considerable potential for innovations with regard to existing nuclear power plants and fuel cycle facilities.

The deregulation of electricity markets puts pressure on the NPP operators, who strive for economic competitiveness. Measures to improve the competitiveness of nuclear power, such as the exploitation of the energetic content of the nuclear fuel (high burn-up, optimised fuel assemblies), create a challenge both on the material side (extreme exposure times with deterioration of the materials) and on the fuel management side (necessity for more accurate fuel cycle calculation, optimising margins). Furthermore, public concerns regarding nuclear energy having shifted from safety issues towards waste issues and the burden for next generations, more accurate assessments of possible waste repositories are a must in the process of gaining public trust. All these requirements are driving forces for innovative technological approaches and solutions.

Programmes in this category are performed usually by industry research organisations (IROs) to meet demands from utilities. The collaborative R&D programmes and strategic technical areas of EPRI in the United States, as shown in Table 4.1, are typical examples.

Table 4.1 Strategic technical areas of EPRI in the United States

Programme area	Annual funding ($M, 2005)
Materials degradation/ageing and chemistry	30
High performance fuel/fuel reliability	12
Radioactive high-level waste and spent fuel management	4
Non-destructive evaluation (NDE) and material characterisation	8
Equipment reliability, human performance	14
I&C hardware and systems modernisation, plant information	2
Nuclear asset risk management	1
Safety risk technology and application	8
New nuclear plant deployment; environmental benefits	4
Low-level waste and radiation management	3
TOTAL	**86**

Source: Country report of the United States.

Such programmes cover a broad range of R&D areas such as operation and maintenance of current plants, plant life management, safety of nuclear installations, radioactive waste management, supporting fuel cycle facilities, etc.

4.1.1 Operation and maintenance of plants

Extensive fuel research programmes and high equipment reliability technologies have been developed for current nuclear power plants. High burnup fuels can be used today for optimising fuel cycle lengths (time the nuclear plants operate without stopping for refueling). Also, new equipment monitoring and maintenance techniques as well as sophisticated core management schemes result in longer cycles, shorter maintenance and reloading outages and thus contribute to high availabilities. The energy production associated to the nuclear plants has become very high, and so unit costs (cost/energy produced) are quite low.

Increased nuclear capacity in some countries is resulting from the uprating of existing plants. This is a highly cost-effective way of bringing on new capacity. A number of power reactors in many countries have had their generating capacity increased, typically by 5-10% with a record value of 15% in Finland.

Examples of optimisation of operational procedures include instrumentation and control (I&C) modernisation, robotics, remote handling, fuel and reloading management, fuel reliability, equipment reliability, NDE (non-destructive evaluation), risk-informed regulation, etc.

4.1.2 Plant life management

A long plant lifetime is one of the conditions necessary to make an investment profitable. There is a global trend to extend the operational life of NPPs. Most nuclear power plants originally had a nominal design lifetime of up to 40 years, but engineering assessments of many plants over the last decade has established that many can operate longer.

Especially in the United States, the NRC has introduced a standardised procedure for extension of NPP life to 60 years. In this framework, the US NRC has approved license renewals for 39 nuclear reactors since 2000, and license renewal has become a predictable, non-controversial regulatory proceeding. To date, the owners of 78 nuclear units have decided to pursue license renewal, and more are expected to follow suit. Even with high capital expenditures, analysis shows that license renewal of an existing nuclear plant is easily the least costly source of new electricity supply.

In nuclear power reactors, materials may undergo degradation due to severe irradiation conditions that limit their operation life. Hence, managing materials degradation and ageing is one of the major technical and economic challenges facing the nuclear power industry. Furthermore, for plants approaching the license renewal stage, assuring regulators of the continuing reliability and safety of in-service materials adds another dimension to this challenge. Continuous progress in the physical understanding of the phenomena involved and in computer sciences has made possible the development of multi-scale numerical tools able to simulate the effects of irradiation on mechanical and corrosion properties of materials. For instance,

- In the European Union, the PERFECT (prediction of irradiation damage effects on reactor components) project aims at developing such predictive tools for reactor pressure vessels and internal structures under irradiation conditions.
- In the United States, the EPRI R&D programme includes the "materials degradation/ageing strategic solution group" for better understanding and managing of material degradation/ ageing phenomena in major nuclear plant metallic components.

4.1.3 Safety of nuclear installations

While safety of nuclear installations has been constantly improved over the years, there is still a need to further the understanding of the complex interactions that take place under severe accident conditions. Substantial progress has been made in research on severe accident management for the nuclear industry. For instance,

- In the European Union, a total of 49 organisations are joining together in the SARNET (severe accident research network of excellence) project to pool their research capacities to resolve the most important remaining uncertainties and safety issues with regard to severe accidents.

- In France, there are several experimental and modelling programmes such as the VULCANO experiments of interaction between corium and concrete, the KROTOS experiments of interaction between corium and water, the participation in the international programme in the CABRI reactor for reactivity insertion accidents, the evaluation of the source term for fuels at high burn-up rate with the VERCORS and the VERDON programmes.

- In Finland, to fulfil the requirement of core melt accident management, a SAM (severe accident management) strategy has been developed and implemented by Fortum.

- In the OECD/NEA, several international joint projects (MASCA, MCCI, PKL, SETH, etc.) have been implemented for conducting research on severe accidents.

4.1.4 Radioactive waste management

Low-level waste (LLW) management issues, including adequate decommissioning of nuclear installations, are keys to the environmental and public acceptance success of the industry, and R&D can help in the following ways:

- helping inform and allay concerns in the public through objective data and analyses demonstrating that current LLW effluents and discharges for disposal pose a bare minimum of risk to the public;

- developing new specialised LLW processing technologies and adapting technologies developed for other industries for nuclear plant LLW processing needs;

- facilitating safe LLW disposal and transportation for sustained viability of the industry; and

- demonstrating that future ALWR plants can be capable of “near zero” discharge and on-site LLW storage for the lifetime of the plant, which would essentially remove LLW issues from new plant discussions.

Also, the development of high-level waste repositories is critical for the continued viability of nuclear energy, and is an enabling condition for new plant orders in the world. In the framework of the radioactive waste disposal research programme, many activities aim at a better understanding of the mechanisms that are relevant for the assessment of the long-term safety of a geological repository. Basic mechanisms governing the migration of radionuclides, which escape from a repository after the failure of the engineered barriers, are being identified and investigated generically. The radionuclide behaviour is then modelled, in order to determine the amount of radio-activity that reaches the biosphere.

Technological innovations in this domain are expected in the use of novel analytical techniques (e.g. synchrotron light) for the understanding of the physicochemical interactions between radionuclides and soil minerals and the subsequent establishment of atomistic models for such phenomena, as well as the setting-up of large-scale field experiments to investigate the behaviour of significant amounts of radionuclides in the soil.

4.1.5 Supporting fuel cycle facilities

Most current reprocessing plants are based on the PUREX process. In France, the growing experience in this area allows continuous improvement of the plant operations such as new effluent management, substantial reduction of waste volume, wider performance range of the vitrification process, and wider range of fuels to be reprocessed. For instance, the uranium and plutonium separation ratios reach 99.88%. This excellent performance of the extraction systems contributes to waste minimisation.

4.2 Programmes supporting power plants and fuel cycles for near-term deployment

4.2.1 Generation III and III+ reactors

The greatest departure of Generation III designs from Generation II designs is that many incorporate passive or inherent safety features, which require no active controls or operational intervention to avoid accidents in the event of malfunction and may rely on gravity, natural convection, resistance to high temperatures and other physical phenomena. Furthermore, Generation III reactors include the following improved features:

- Standardised design to expedite licensing, reduce capital cost and reduce construction time.
- Simpler and more rugged design, making them easier to operate and less vulnerable to operational upsets.
- Higher availability and longer operating life by design – typically 60 years.
- Further reduced probability of core melt accidents.
- Minimal effect on the environment in case of severe accident.

More than a dozen Generation III and III+ reactors, as shown in Table 4.2, are in various stages of development. Some are further evolutionary developments of the PWR, BWR and CANDU designs. The only designs under operation are the large evolutionary ABWRs in Japan. These reactor developments have been performed usually by system suppliers and/or utilities, with some coordination by the government in some countries.

Table 4.2 Current status of Generation III/III+ reactors

Reactor	Type	Developer	Capacity (MWe)	Current status
EPR	PWR	AREVA NP (France)	up to 1 750	• 1 unit under construction in Finland, to be completed in 2010 • 1 unit ordered in France, to be completed in 2012 • a US version is in pre-application review in the US
AP1000	PWR	Westinghouse (US)	1 000	• design certificate in the US in 2005
APR1400	PWR	KHNP (Korea)	1 400	• 2 units under construction in Korea, to be completed in 2013
ABWR	BWR	Hitachi, Toshiba (Japan), GE (US)	1 350	• 3 units in operation in Japan since 1996 • design certificate in the US in 1997
ESBWR	BWR	General Electric (US)	1 390	• under certification in the US
SWR 1000	BWR	AREVA NP (Germany)	up to 1 290	• design concept
BWR 90$^+$	BWR	Westinghouse (Sweden)	1 500	• design concept
IRIS	PWR	Westinghouse (US)	335	• plan to submit an application for design certification in 2006 for completing it in the 2008-2010 timeframe • design in pre-application review in US
PBMR	GCR	Eskom (South Africa)	165 (module)	• prototype due to start building in 2006 • some large component ordered • design in pre-application review in US
GT-MHR	GCR	General Atomics (US)	286 (module)	• design concept
ACR	HWR	AECL (Canada)	up to 1 000	• under certification in Canada
CANDU 9	HWR	AECL (Canada)	up to 1 300	• licensability approval in 1997

Note: For abbreviations, refer to Appendix B.

In the European Union, four designs are being developed to meet the European utility requirements (EUR)[1]: EPR, SWR 1000, ESBWR and BWR 90$^+$. In the United States, eight evolutionary advanced reactors are considered by the Near-term Deployment Group; 2 PWR type (AP1000/AP600, IRIS), 3 BWR type (ABWR, ESBWR, SWR1000), and 2 HTR type (PBMR, GT-MHR).

4.2.2 Advanced reprocessing technology

Current commercial reprocessing plants use the well-proven hydrometallurgical PUREX (plutonium uranium extraction) process. However, several factors give rise to a more sophisticated view of reprocessing today, and use of the term partitioning reflects this with the following reasons:

- New management methods for high- and intermediate-level nuclear waste types are under consideration, where separating out long-lived radionuclides is the prime objective.

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1. http://www.europeanutilityrequirements.org/.

- New fuel cycles, such as those for fast neutron reactors and the possible advent of accelerator-driven systems, require a new approach to reprocessing.

An advanced version of PUREX has the minor actinides (americium, neptunium, curium) being separated in a second aqueous stage and later directed to an accelerator-driven system cycling with pyroprocessing for transmutation when Generation IV systems are available. The waste stream then contains mainly fission products. The PUREX process may also be supplemented to recover iodine by volatilisation and technetium by electrolysis.

Another variation of PUREX is being developed by the US DOE for civil wastes. In this, only uranium is recovered (hence UREX or UREX+ process) initially for recycle or for disposal as low-level waste; iodine and technetium may also be recovered at the head end. The residual is treated to recover plutonium for recycling in conventional reactors, and the other actinides for transmutation in fast reactors.

In Korea, KAERI is developing the DUPIC (direct use of spent PWR fuel in CANDU reactors) fuel cycle, which is based upon dry thermal and mechanical processes to directly fabricate CANDU (Canada deuterium uranium) fuel from spent PWR fuel material without separating the fissile material and fission products. This offers several benefits to countries operating both PWR and CANDU reactors, such as additional energy extracted from the spent PWR fuel by using it in a CANDU reactor, efficient natural uranium utilisation, and a significant reduction in spent fuel arisings.

4.3 Programmes supporting power plants and fuel cycles for long-term deployment

4.3.1 Generation IV nuclear systems

To play an essential role, future nuclear energy systems will need to provide: (1) manageable nuclear waste, effective fuel utilisation, and increased environmental benefits; (2) competitive economics; (3) recognised safety performance; and (4) enhanced proliferation resistance and physical protection of nuclear energy systems and nuclear materials.

4.3.1.1 Generation IV International Forum

The Generation IV International Forum (GIF) was established in January 2000 as a group of international governmental entities with the goal of facilitating bilateral and multilateral cooperation related to the development of new nuclear energy systems. GIF is a formal, government sanctioned organisation committed to collaboratively pursue R&D on promising Generation IV systems for meeting future energy challenges. Much benefit is to be gained from seeking common ground between countries with similar interests and from sharing expertise, resources and test facilities to gain efficiencies and avoid duplication.

The current GIF members are Argentina, Brazil, Canada, China, France, Japan, South Africa, Korea, Russia, Switzerland, United Kingdom, United States and EURATOM, with the OECD/NEA conducting technical Secretariat and the IAEA as permanent observer. IAEA's participation enables in particular coordination between GIF and INPRO activities (see Section 4.3.1.2).

With international collaboration, approximately 100 system concepts were analysed and evaluated for their potential to meet the goals of the Generation IV programme. More than 100 experts from 12 countries and international organisations participated in the process. The selection of systems for cooperative development by GIF was based on the evaluations of each system's ability to fulfil targeted applications, deployment readiness, and development cost. *A Technology Roadmap for Generation IV Nuclear Energy Systems* [19], published in December of 2002, identifies the six systems selected (see Table 4.3) and describes the research and development pathways for establishing technical and commercial viability, demonstration and, potentially, commercialisation.

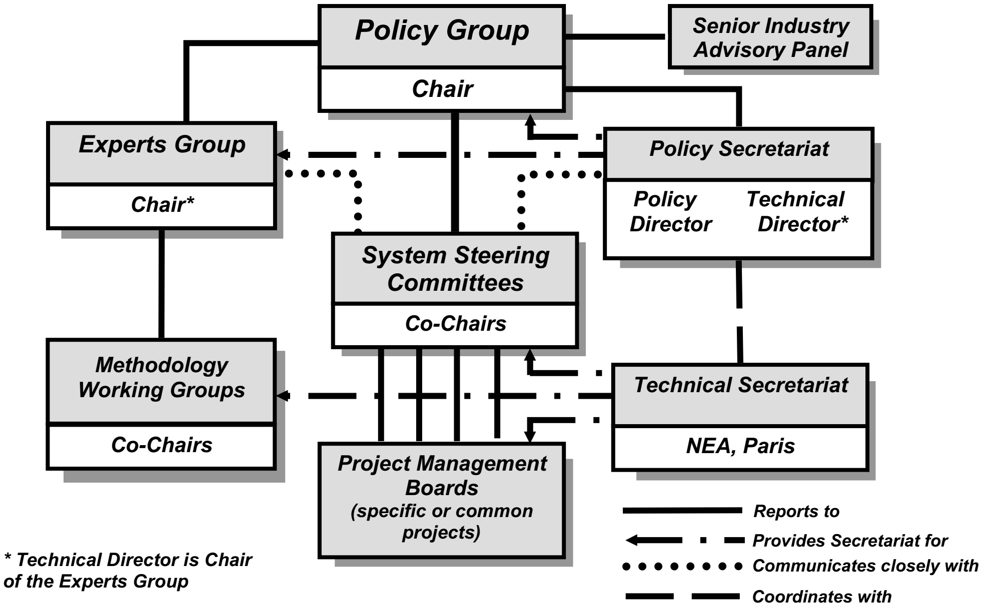
Table 4.3 Generation IV reactor concepts in the framework of GIF

	Neutron spectrum	Coolant	Temp. (°C)	Fuel	Fuel cycle	Size(s) (MWe)
Gas-cooled fast reactors (GFR)	fast	helium	850	^{238}U	closed, on site	288
Lead-cooled fast reactors (LFR)	fast	Pb-Bi	550-800	^{238}U	closed, regional	50-150 300-400 1 200
Molten salt reactors (MSR)	epithermal	fluoride salts	700-800	UF in salt	closed	1 000
Sodium-cooled fast reactors (SFR)	fast	sodium	550	^{238}U & MOX	closed	150-500 500-1 500
Supercritical water-cooled reactors (SCWR)	thermal or fast	water	510-550	UO$_2$	open (thermal) closed (fast)	1 500
Very high temperature gas reactors (VHTR)	thermal	helium	1 000	UO$_2$ prism or pebbles	open	250

Adapted from Hirschberg, S., and Dones, R. (2005), "Sustainability Aspects of Current and Future Electricity Supply Systems", *Chimia,* Volume 59, No. 12.

The GIF has established system steering committees to implement the research and development for each Generation IV reactor concept, with participation by GIF members interested in contributing to collaborative R&D. Each system steering committee is planning and integrating R&D projects contributing to the design of a system. Participants in system committees, and in projects, will sign agreements governing intellectual property rights and other matters in order to work cooperatively on the concepts. Figure 4.2 illustrates the GIF governance structure.

Figure 4.2 Governing structure of GIF



* Technical Director is Chair of the Experts Group

Currently, detailed R&D plans to close the technological gaps for each selected technology are being elaborated and reviewed. In parallel, the contractual framework for the multilateral collaboration on the selected technologies is being negotiated among the GIF members. Waiting for the formal implementation of the agreements, R&D work is already ongoing, on an informal basis and taking advantage of existing bilateral and other multilateral frameworks.

A "Framework Agreement for International Collaboration on Research and Development of Generation IV Nuclear Energy Systems" was signed in February, 2005. As of June 2006 the Parties to the Agreement are the United States, the United Kingdom, Japan, France, Canada, Switzerland, Korea and EURATOM. The United States, Japan and France signed in February, 2006 a SFR systems arrangement, which provides the framework for collaboration among these countries (including Korea which joined later) on the R&D of these advanced nuclear reactors.

Many European countries, which are not members of GIF, such as Czech Republic, Spain, Belgium and Finland, are participating in the effort through EURATOM. For instance, Finland implements the Finnish Generation IV programme (GEN4FIN) as shown in Box 4.1.

Box 4.1 Finnish Generation IV programme (GEN4FIN)

Main mission: to improve scientific and technologic expertise in the field of nuclear energy technologies and related processes through collaboration with GIF and other global forums

Long-term mission: to create new business activities for the Finnish industry through enhanced technology transfer, innovative process development, and materials engineering.

The activities in the programme will cover scientific, technological and industrial goals. Research and education, safety authority, manufacturing industry and power companies as well as ministries and other associated organisations are participating in the programme.

The implementation of the GEN4FIN programme will be carried out through R&D projects, education and training and international collaboration. This means that the programme should be scheduled for at least 5 years and all major actors in the R&D field in Finland could contribute to the programme. This would correspond to the programme of GIF basic studies in 2005-2012; the design phase will follow in 2012-2020/2030.

Source: Country report of Finland.

4.3.1.2 IAEA INPRO

In response to the invitation of its General Conference for its member countries to combine their efforts under its aegis in considering nuclear fuel cycle issues by examining innovative and proliferation-resistant nuclear technology, the IAEA initiated an International project on innovative nuclear reactors and fuel cycles (INPRO) in 2000.

The objectives of INPRO, as defined in its Terms of Reference, are:

- to help to ensure that nuclear energy is available to contribute in fulfilling, in a sustainable manner, energy needs in the 21st century;

- to bring together all interested member countries of the IAEA, 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
- 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.

Phase-IA of INPRO, initiated in May 2001 and completed in June 2003, dealt with the determination of basic principles, user requirements, criteria and a suitable methodology to assess the level of fulfillment of these demands by different future nuclear technologies [20]. The INPRO methodology, which provides guidance on how to apply these requirements in evaluating a given innovative nuclear system with the consideration of local, regional and global boundary conditions, was reported in [21]. Phase-IB was started in July 2003 and comprises the validation of the INPRO methodology through case studies as well as the examination of innovative nuclear energy technologies made available by IAEA member countries. As of May 2006, 26 members[2] are participating in the IAEA INPRO programme.

Upon successful completion of the first phase, taking into account advice from the INPRO Steering Committee, and with the approval of participating members, a second phase of INPRO may be initiated. Drawing on the results from the first phase, it would examine, in the context of available technologies, the feasibility of an international project including the identification of technologies that might appropriately be implemented by member countries within such an international project.

4.3.1.3 National efforts for Generation IV nuclear systems

In Japan, as shown in Figure 4.3, JAEA and electric utilities have been implementing a feasibility study on a commercialised FBR cycle system, aiming to present, in around 2015, an appropriate picture of commercialisation of the FBR cycle and the R&D plans leading up to the commercialisation, in co-operation with CRIEPI, nuclear industrial companies and universities, etc.

The United States initiated the advanced fuel cycle initiative (AFCI) to develop and demonstrate technologies that will enable the United States and other advanced countries to implement an improved, long-term nuclear fuel cycle that provides substantial environmental, non-proliferation, and economic advantages over the current once-through fuel cycle. In 2006, the United States proposed a new initiative, the Global nuclear energy partnership (GNEP) that encompasses the AFCI programme as well as other elements of the DOE nuclear R&D agenda. The GNEP will use a nuclear fuel cycle that enhances energy security, while promoting non-proliferation. It would achieve its goal by having nations with secure, advanced nuclear capabilities provide fuel services – fresh fuel and recovery of used fuel – to other nations who agree to employ nuclear energy for power generation purposes only. The closed fuel cycle model envisioned by this partnership requires development and deployment of technologies that enable recycling and consumption of long-lived radioactive waste.

In France, prospective studies carried out by the CEA and industrial partners led to elaborate an R&D strategy on future nuclear energy systems for the medium and the long-term (> 2040), that aims at three complementary objectives: (1) innovations for light water reactors; (2) fast neutron systems with a closed fuel cycle for a sustainable energy supply through breeding in the long-term, and capable also to manage all actinides from LWRs; and (3) key technologies for the nuclear production of hydrogen or the supply of very high temperature heat for industry.

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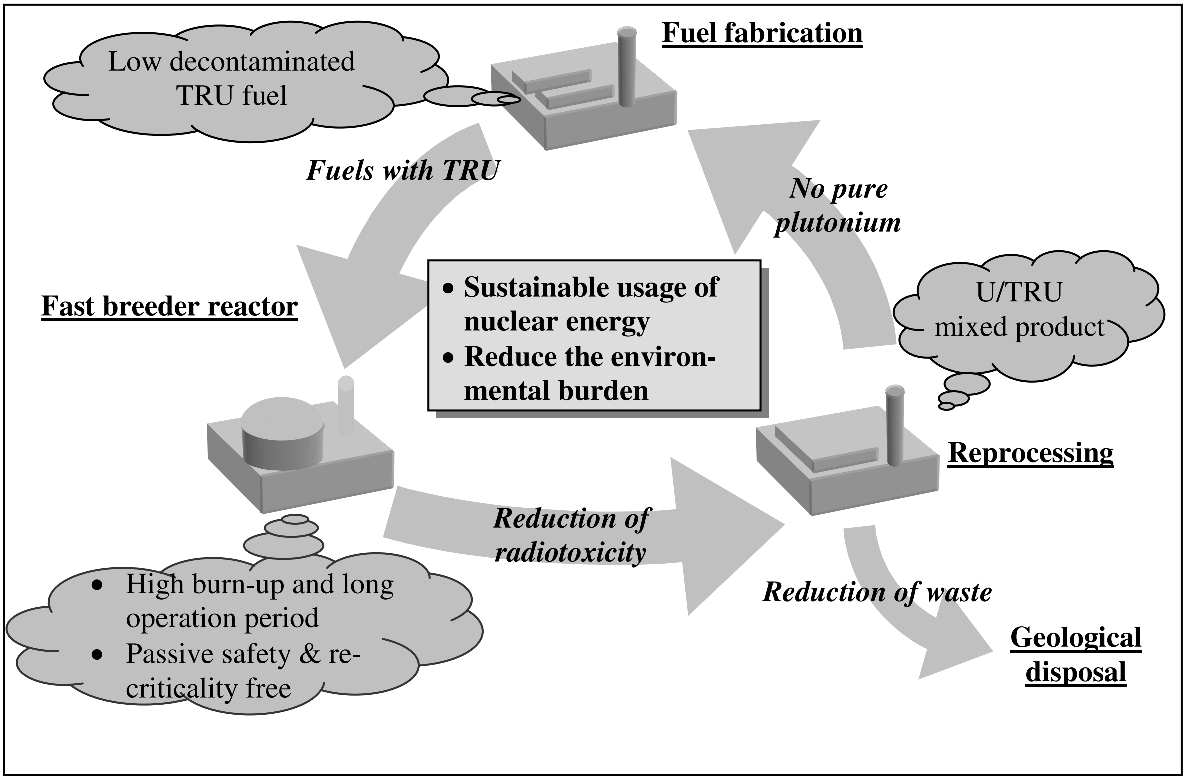
[2] Argentina, Armenia, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, France, Germany, India, Indonesia, Japan, Korea, Netherlands, Morocco, Pakistan, Russian Federation, Slovakia, South Africa, Spain, Switzerland, Turkey, Ukraine, United States, EURATOM (as of May 2006).

Figure 4.3 Concept of feasibility studies on commercialised FBR cycle system in Japan



Source: Country report of Japan.

In the European Union framework programme, there are four projects on Gen-IV systems as follows:

- VHTR (renamed as RAPHAEL[3], reactor for process heat, hydrogen and electricity generation): integrated project funded for 4 years with a total budget of € 20 M including € 9 M from EC, initiated in April 2005 and co-ordinated by AREVA NP Erlangen.
- GFR (renamed as GCFR[4], gas-cooled fast reactor): specific targeted research project funded for 4 years with a total budget of € 3.6 M including € 2 M from EC, initiated in March 2005 and co-ordinated by NNC.
- SCWR (renamed as HPLWR, high performance liquid water reactor): specific targeted research and training project funded for 3.5 years with a total budget of € 4.65 M including € 2.5 M from EC, to be initiated in October 2006 and co-ordinated by FZK.
- LFR (renamed as ELSY, European lead-cooled system): specific targeted research and training project funded for 3 years with a total budget of € 6.5 M including € 2.95 M from EC, to be initiated in October 2006 and co-ordinated by Ansaldo Nucleare.

In Korea, KAERI is developing technologies to resolve key technical issues for SFR commercialisation and a detailed conceptual design of the KALIMER (Korea advanced liquid metal reactor) by 2016, which can meet the goals of the Gen-IV nuclear energy systems.

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[3] http://www.raphael-project.org/index.html.

[4] http://www.gcfr.org.

4.3.2 Partitioning and transmutation (P&T)

In the global effort to develop sustainable energy sources, advanced fuel cycles including partitioning and transmutation (P&T) are widely investigated for the future of nuclear energy. The ongoing research shows the potential benefits of P&T contributing to simplify the management of present and future radioactive waste, including:

- large reduction of long-term radioactivity, radiotoxicity and fissile material inventories, which can contribute to improving the public acceptance of the unavoidable geological repositories; and
- minimisation of short and medium term heat sources that can allow a reduction in the volume required by the high level waste in repositories, increasing the effective capacity and reducing the required number of repositories.

Japan has carried out development of the advanced FBR nuclear fuel cycle based on P&T, of which the concept is shown in Figure 4.3. In this cycle, plutonium is co-recovered with uranium, and minor actinides, such as neptunium and americium, are also recovered from the spent fuels. Uranium and TRU elements are loaded into FBR as fuels. A symbiotic scenario to transmute minor actinides in dedicated accelerator-driven systems (ADS) is also studied, keeping in view the common technology basis with FBR development.

In France, the general objective of its P&T programme is to investigate solutions capable of reducing the quantity of long-lived radionuclides by separating them from the waste and transmuting them to non-radioactive or short-lived ones. In addition to the reference "separation-transmutation" strategy, an alternative "separation-conditioning" option is also investigated, involving R&D of new specific conditioning matrices for the separated radionuclides that are unsuitable for transmutation.

The European technical working group (ETWG) on ADS concluded in April 2001 in its report "A European roadmap for developing accelerator driven systems (ADS) for waste incineration" that the P&T in association with the ADS in combination with the geological disposal can lead to an acceptable solution from the society acceptance point of view for the nuclear waste management problems. In the European Union framework programme, there are four projects related to P&T as follows:

- EUROTRANS[5] (European research programme for the transmutation of high-level nuclear waste in an accelerator-driven system (ADS): integrated project funded for 4 years with a total budget of € 43 M including € 23 M from EC, initiated in April 2005 and co-ordinated by FZK.
- RED-IMPACT[6] (impact of partitioning, transmutation and waste reduction technologies on the final nuclear waste disposal): specific targeted research project funded for 3 years with a total budget of € 3.5 M including € 2 M from EC, initiated in March 2004 and co-ordinated by KTH.
- EUROPART[7] (European research programme for the separation of minor actinides from the highly radioactive waste coming out of the spent fuel reprocessing): integrated project funded for 4 years with a total budget of € 10.3 M including € 6 M from EC, initiated in January 2004 and co-ordinated by CEA.

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[5] http://nuklear-server.fzk.de/Eurotrans/.

[6] http://www.red-impact.proj.kth.se/.

[7] http://www.europart-project.org.

- ACTINET-6[8] (actinide sciences network): network of excellence funded for 4 years with a total budget of € 10.5 M including € 6.3 M from EC, initiated in March 2004 and co-ordinated by CEA.

4.4 Programmes outside electricity production

Technically, nuclear reactors which produce energy in the form of heat can supply energy products other than electricity, including district and process heat, potable water, and eventually hydrogen. While non-electrical applications of nuclear energy have been considered since the very beginning of nuclear energy development, they have not been deployed so far to a significant industrial scale for different reasons.

4.4.1 Nuclear hydrogen production

As an alternative path to the current fossil fuel economy, a hydrogen economy is envisaged, where hydrogen would play a major role in energy systems and serve all sectors of the economy, substituting fossil fuels. Hydrogen, as an energy carrier, can be stored in large quantities, unlike electricity, and converted into electricity in fuel cells, with only heat and water as by-products. Furthermore, hydrogen can be obtained from various primary energy sources that are domestically available in most countries. Consequently, the hydrogen economy would enhance both the security of energy supply and global environmental quality, the latter, however, only if environmental friendly technologies are used to generate hydrogen.

The adequate supply of hydrogen is a prerequisite for a successful implementation of a hydrogen economy. Although hydrogen is abundant in the universe, it should be produced from compounds containing hydrogen such as fossil fuels, biomass, or water with thermal, electrolytic or photolytic processes. Nuclear energy is also suitable for hydrogen production since nuclear reactors can produce both the heat and electricity required for it. Furthermore, it is the most commercially mature non-fossil fuel energy source capable of producing hydrogen on a large industrial scale without significant CO_2 emission. Currently, hydrogen is produced mainly by steam reforming of natural gas/methane. Nuclear-assisted steam reforming has great potential for large-scale hydrogen production in the near term. The steam reforming process, however, has CO_2 as a waste product.

Hydrogen can be obtained more efficiently by significantly raising the temperature of water. The electrolysis of steam at higher temperature (800-1 000°C) offers several advantages including lower electricity requirement and higher efficiency resulting from lowering the activation barriers at the electrolyte surfaces. With high temperature, efficient hydrogen production is also possible with the thermo-chemical water splitting process. Thousands of potential thermo-chemical cycles have been tested to assess their viability and performance for hydrogen production and the most promising for efficiency and practical applicability to nuclear heat sources have been identified, namely iodine-sulphur (IS), bromine-calcium (Ca-Br) and copper-chlorine (Cu-Cl). In addition, a thermo-chemical hybrid process can be another option, which combines both thermo-chemical and electrolytic reactions of water splitting and has the possibility of running low-temperature reactions.

Since the supply of high temperature heat is the key for nuclear hydrogen production, high temperature reactors, like VHTR, are getting more interest. Many countries with advanced nuclear power programmes have launched also nuclear hydrogen programmes such as the United States, France, Japan, Korea, etc.

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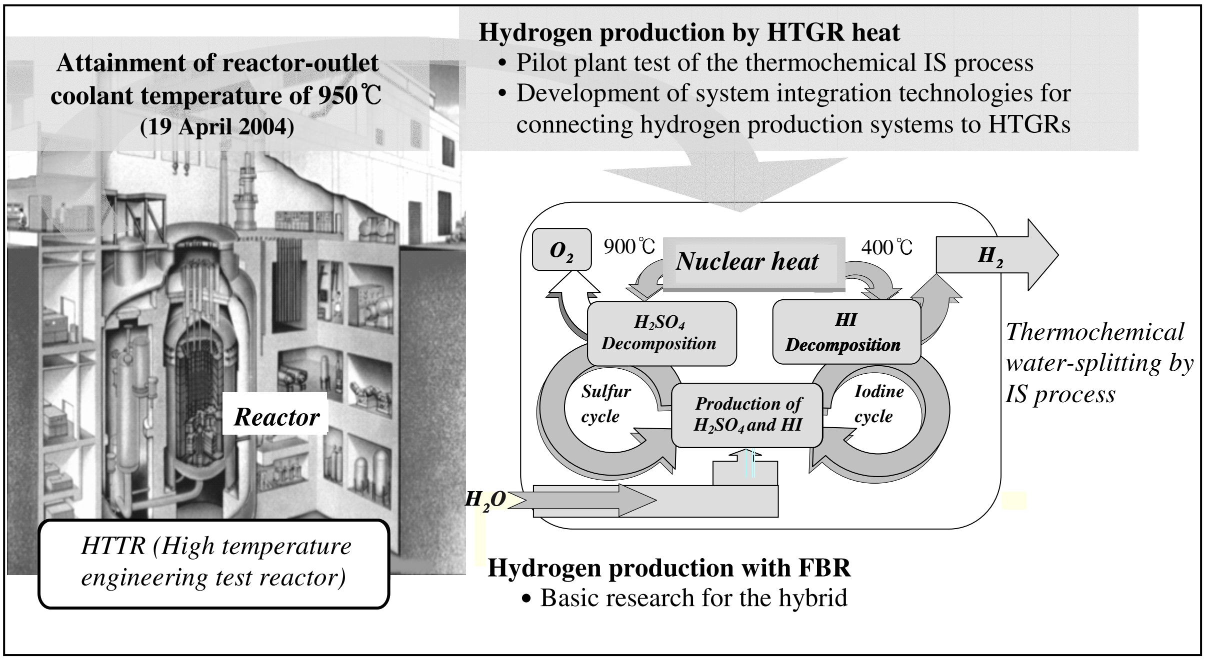
[8] http://www.actinet-network.org.

In the United States, the nuclear hydrogen initiative (NHI) is in progress as a part of DOE-NE's Hydrogen Programme. Based on the Hydrogen Posture Plan[9] and the National Hydrogen Energy Roadmap[10] of DOE, DOE-NE has developed the Nuclear Hydrogen R&D Plan, which outlines a robust demonstration strategy that provides for the assessment of alternative technologies while ensuring achievement of the programme's demonstration objective. The NHI will complete its R&D mission by developing a 50 megawatt (thermal) engineering-scale hydrogen production demonstration facility that will be connected to the next generation nuclear plant (NGNP) reactor, if this reactor is constructed. Alternatively, the mission could be accomplished by coupling the hydrogen demonstration plant to any high-temperature heat source.

In Japan, JAEA has been conducting R&D activities on HTGR cogeneration technology (electricity generation and hydrogen production) by applying the high temperature engineering test reactor (HTTR) and the thermo-chemical splitting of water through the IS process, as shown in Figure 4.4, in collaboration with international joint research frameworks such as NGNP of the United States and GIF.

Figure 4.4 Concept of nuclear hydrogen production in Japan



Source: Country report of Japan.

In Korea, KAERI embarked in 2005 on a US$ 1 billion R&D and demonstration programme aiming to produce commercial hydrogen using nuclear heat around 2020.

The EURATOM, activities in this area are related to Community research on non-nuclear energies. Hydrogen production is discussed, in particular, in the HYTHEC (hydrogen thermochemical

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[9] http://www.eere.energy.gov/hydrogenandfuelcells/posture_plan04.html.

[10] http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf.

cycles) FP-6 project under the European hydrogen and fuel cell technology platform (HFP).[11] Two important documents are prepared in view of the FP-7 (2007-2013) RTD programme that will be proposed on the basis of this technology platform bringing together public and private organisations: "strategic research agenda" covering research and development as well as demonstration, and "deployment strategy" covering market developments as well as policy & framework.

4.4.2 Nuclear desalination

Nuclear desalination refers to the production of potable water from seawater using a nuclear reactor as the source of energy (electricity and/or low-temperature heat). The reactor may be used solely for desalination or may be operated in a cogeneration mode. There have been successful experiences in nuclear desalination at several plants in Japan (12 reactors since 1977) and Kazakhstan (1 reactor since 1973 till 1999). Many countries are showing interest in or going forward in nuclear desalination projects, domestic or for exportation, including Argentina, Canada, China, Egypt, France, India, Indonesia, Korea, Morocco, Pakistan, Russia and Tunisia [22].

In Korea, the conceptual design of a nuclear desalination plant with the system-integrated modular advanced reactor (SMART) was 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 inhabitants or an industrialised complex. SMART is an advanced integral PWR with designed thermal output of 330 MWth, with major components arranged within a single pressure vessel.

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[11] For more detail on HFP, see https://www.hfpeurope.org/hfp/.

5. SPECIAL CHARACTERISTICS OF INNOVATION IN NUCLEAR ENERGY TECHNOLOGY

5.1 Specific characteristics of nuclear energy sector

Although nuclear energy is a fairly recent technology, it can be considered nowadays a mature technology. Nevertheless, it is acknowledged that there are opportunities for ongoing innovative technological development and enhancement. Moreover, nuclear energy technology has special characteristics that affect how its innovation is conducted. These characteristics can be grouped in four main perspectives as follows:

- technology and knowledge required for nuclear energy use;
- nuclear energy industry market;
- financial and economic environment; and
- legal and socio-political environment.

5.1.1 Technology and knowledge

Currently nuclear energy is used in large, complex, multi-system installations that produce electricity through a more or less conventional thermal cycle: heated fluid – turbine – electricity generator. What is really nuclear is only the primary heat source for the heated fluid, but its existence in the process influences greatly the requirements and design of the whole installation. So, nuclear innovation covers a broad scale of sciences and engineering disciplines (from nuclear physics to structural design) and is a result of the application of multiple technologies. This may be seen in the variety of technologies related to the sample cases described in Section 2.3. In all of them, however, specific characteristics, such as special quality (nuclear-grade) requirements, nuclear safety concerns, etc. are required.

Clearly, not all countries are ready to undertake nuclear energy projects by themselves, given the need to have a strong technological infrastructure from heavy industry to research support, including certain components supply, training capacity, etc., which is necessary in order to have a high national participation in building a nuclear power plant. Furthermore, to innovate in all the related technologies a very broad and active research infrastructure should also exist. This situation is difficult even for some very advanced countries, so nuclear R&D initiatives have the special characteristic of being generally multinational efforts. Reference countries usually take the lead in such projects but it is desirable that other nuclear countries join in, each with its specific specialisation. Another characteristic that makes this collaboration even more necessary is that this kind of innovation is usually extensive, cost-intensive and long-term.

There is also an important international concern that individual countries could misuse their nuclear R&D for peaceful uses to develop nuclear weapons. Very strict international agreements are in force to avoid this situation, and to guard against the diversion of civil nuclear technologies and materials to weapons applications. Nonetheless, this concern may create barriers to the globalisation of nuclear research. This also provides a security problem, as nuclear knowledge and materials have also to be guarded against possible misuse.

Nuclear research deals with radioactive substances, whose emissions of ionising radiation can cause human health and environmental damages, if not contained. This means another set of very specific precautions that, on the one hand, form another discipline of its own, known as "radiation protection", and on the other hand, make nuclear R&D more complex and resource consuming.

In summary, nuclear energy has long lead times and needs large, complex, multi-system installations with very special quality (nuclear-grade) requirements. Research related to nuclear energy covers a broad range of disciplines, being generally an extensive, resource-intensive and long-term multinational R&D effort. It must also take into account non-proliferation concerns and radiation protection considerations in its development.

5.1.2 Nuclear energy industry market

Throughout the world, 441 nuclear power plants in 31 countries produced about 16% of the electricity demand in 2005.[1] This is a relatively low number of plants, which are also concentrated in a relatively low number of countries. An important level of industrial infrastructure is needed for its implementation. The nuclear industry market is a relatively low-volume market – big utilities or consortia of utilities as customers, with a currently decreasing number of available commercial technologies or suppliers – but each installation sold usually involves a very high investment.

As research is costly and long-term, suppliers usually devote their product development efforts to maintain and update their designs; for example, Generation III or Generation III+ reactors. Generally, it is at governmental level where new approaches, e.g. Generation IV designs, have to be initiated. The evolution of the market has mixed dynamics; on one hand, it is technology-push (i.e., Generation IV) led by governments, and on the other hand, it is demand-pull (i.e., Generation III+) led by utilities.

In summary, the nuclear energy industry market is a relatively low-volume but high-value market, where research is triggered by suppliers, utilities, and governments. It is a market that is also subject to requirements of international agreements, especially with respect to non-proliferation and export controls. It is a relatively recent technology, but has reached a fairly mature state. Nonetheless, it still is evolving and there remain significant opportunities for technology improvement and innovation.

5.1.3 Financial and economic environment

Nuclear power plants require high investments, but their technical lifetime is usually much longer than the operating period needed to generate the revenue needed to reimburse these investments. This is sustained by extensive R&D that has been performed mainly around ageing of structures, equipment and components, that is, in the materials area.

However, the long technical lifetime is not the only feature of nuclear plants that makes them profitable. Low operation and fuel costs are also a characteristic of nuclear energy. This has also been

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[1] In the OECD context, at the start of 2006, 352 reactors were in operation in 17 out of 30 member countries constituting some 83% of the world's total nuclear electricity generating capacity and about 23.2% of the total electricity supply in the OECD area [22].

made possible because of extensive fuel research programmes and the highly reliable technologies that have been developed. Thus, high burnup fuels can be used today for optimising fuel cycle lengths (time the nuclear plants can operate without stopping for refueling). Also, new equipment monitoring and maintenance techniques result in high availabilities, thereby leading to high energy production and low unit costs (cost/energy produced) for nuclear plants.

This situation is also true even if other costs, like possible externalities, are included. Among the most important potential externalities of nuclear energy are costs for decommissioning and radioactive waste disposal. However, most nuclear countries already internalise these costs in their nuclear energy production costs. Other residual externalities (e.g. radioactive emissions below regulatory limits) would, if internalised, have a very small effect on the unit generating costs of nuclear plants.

In summary, nuclear energy technology is a high initial investment technology, but with a long technical lifetime and high returns on the investment made possible because of its low costs for fuel, operation and residual externalities.

5.1.4 Legal and socio-political environment

In some countries, the socio-political environment has been a serious drawback to nuclear energy and the other activities, like research, related to it. Because of several reasons related to its origin and nature, nuclear energy is a very sensitive social topic, resulting in political and social challenges to its use in some countries. The main social concerns are related to proliferation, long-lived radioactive waste and environmental impacts in case of severe accidents with release of radioactive substances to the environment. Due to these concerns, nuclear energy has one of the highest degrees of strict regulation and control, even beyond those of the aircraft and airspace industry.

Among the recognised positive effects, nuclear energy has a high local community social and economical benefit, as this kind of industry creates many primary and secondary jobs in the areas where they are implemented. Also, it gives a high security in base load electricity supply at a stable low cost.

In summary, nuclear energy is socially and politically sensitive because of different concerns directly related to its nature. Nevertheless, past and ongoing research can mitigate the potential negative effects, and the positive social aspects of nuclear energy like local economic development or security of supply can contribute to a better social acceptance of this technology.

5.2 Patterns of nuclear development

5.2.1 Various paths of development

From the country reports, three main patterns of nuclear development have been identified.

Self-dependent from the start

In the beginning of nuclear energy (early 1950s), several countries started domestic designs for energy production (electricity, heat, etc) based on nuclear energy. This initiative was promoted by the different governments that wanted to take advantage of this new energy source. Nevertheless, not all the developments ended in a commercial prototype, Case #16 in Table 2.1 – the Spanish DON reactor – being an example. Thus, only a few countries succeeded with initial commercial designs. The United

States, with both pressurised and boiling light-water reactors (PWR & BWR), Canada with its pressurised heavy-water reactor (CANDU) and the United Kingdom and France with their graphite-moderated gas-cooled reactors (GCR) are examples of country-owned technology from the start. In those examples, the initial government support created a nuclear industrial infrastructure sufficiently advanced to allow development of both the reactors and the supporting nuclear fuel cycle and components fabrication industries.

Localisation through technology transfer from abroad and then self-dependent

This is the most common model. Countries take advantage of the international character of the nuclear technology suppliers and, if they decide to promote nuclear energy, ask these suppliers of successful designs to install an initial plant in their countries. In the later plants, the country's participation in the design, component fabrication and plant construction increases, and in due time the country is able to evolve the initial design according to its own needs and, for future plants, to do all of the technological developments by itself. This is the case of the French PWR programme as well as the Japanese and Korean nuclear programmes.

Dependent from abroad

Lastly, in countries where the necessary technological infrastructure has not been fully developed, different suppliers provide the basic designs and in some case also the detailed designs (turn-key projects). Because of the high investments associated to nuclear projects, generally there is an increasing participation of the local industry in the projects. This participation can reach almost to 90% of the works and supplies, but the original design of nuclear steam supply system (NSSS) always comes from the main suppliers. This is the case of Spain, Belgium, Finland and Switzerland. Specific developments like optimised fuel or different applications of nuclear energy (delocalised heating energy systems, etc.) are developments of this kind of countries. Another case is the Czech Republic. The Czech industry reached quite a high level in both nuclear and conventional machinery technologies, and in engineering and supplies. Nevertheless, it always depended on foreign supplies of nuclear fuel and some specific systems (e.g. I&C).

5.2.2 Common features

As described in Section 5.2.1, the starting point for nuclear research infrastructure in the different kinds of countries can be different, but once they enter into nuclear energy deployment the driving forces are very similar in all of the countries, as described in Section 5.3.1.

One of the main objectives of nuclear-power countries is to master sufficient technology to be able to operate and maintain their nuclear power plants in the best possible way. As expressed in Section 5.1, this means a very broad number of sciences from nuclear physics to structure building, and research infrastructure is necessary. Nevertheless, all nuclear-power countries aim to have these capabilities, and also to participate in international collaborations with this objective. The international EPRI programme, where a high percentage is devoted to ongoing nuclear plants, is a good example of this international collaboration.

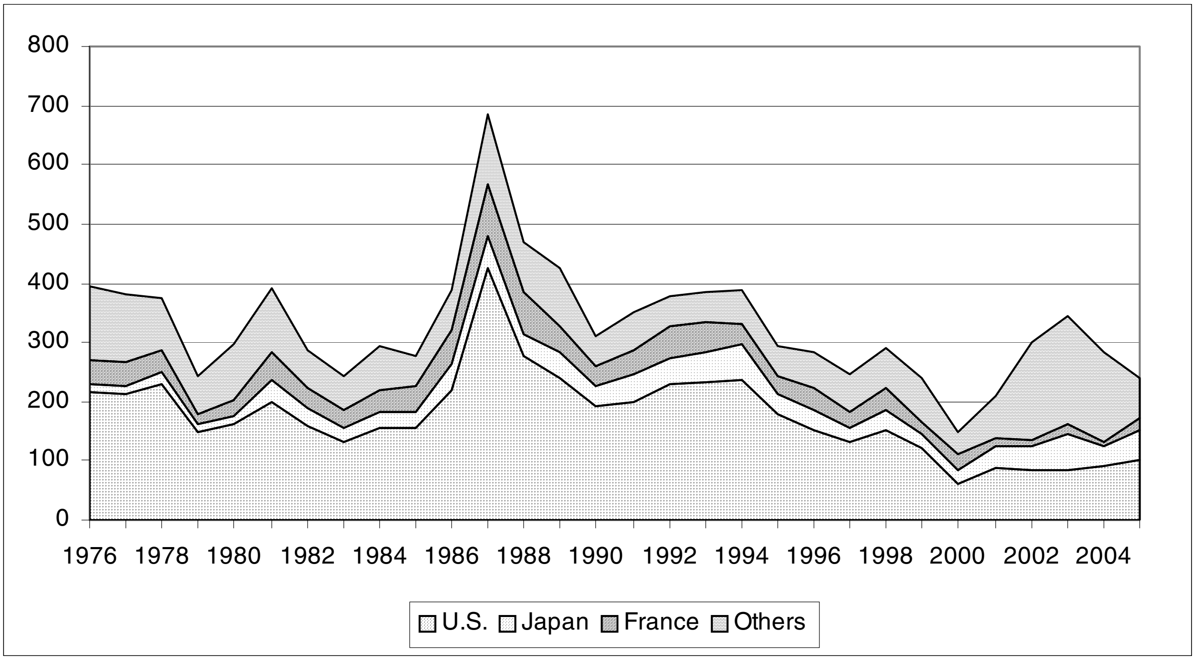
In some countries, especially those that belong to the first and second groups described in Section 5.2.1, an additional effort is made to develop more efficient designs and fuel cycles minimising radioactive waste and environmental problems. Usually suppliers, with governmental support, lead these research initiatives and very often international consortia are formed in order to share costs and technology. This is the case of Generation IV initiative, which will lead the way to future generations of nuclear power plants and nuclear systems.

There have been many actors involved in the nuclear development processes such as governments, utilities, regulators, suppliers and R&D performers. Although their roles and the intensity of their relationships might different among the countries, it should be noted that the government's drive and the close relationship among these actors were critical for the success of their nuclear development.

5.2.3 Nuclear innovation performance trend

Patents and publications are often used as a measure of innovation performance. In the nuclear sector, however, it proved difficult to gather relevant data. Nevertheless, the data on nuclear reactor technology patents in the United States country report provides an insight that could be generalised to a global trend. Figure 5.1 shows the trend of the number of US patents in Class 376 (nuclear reactor technology) from 1976 to 2005.

Figure 5.1 Trends of the number of nuclear reactor technology patents of assignee countries in USPTO



Source: Country report of the United States.

Based on the analysis of the data, as shown in Box 5.1, it can be noted that there was a downturn of patents in the 1990s and a recent marginal upturn. The analysis of the patents in Box 5.1 argues that the right environment for innovation in nuclear reactor technology is a combination of R&D investments (both public and private), regulatory stability, favourable government policies and economic incentives.

Box 5.1 Analysis of nuclear reactor technology patents in the United States

It is recognised that there is a strong correlation between Federal R&D spending for nuclear research and the number of nuclear patent applications granted to the US. Since the early 1980s federal spending on R&D has continually decreased. Only recently has there been renewed interest in federal funding of nuclear research. In 1987, there was a peak of 427 US patents in nuclear reactor technology issued to United States' assignees. In 2000, this number reached a low of 61, but has increased again to 90 in 2004. The average per year for the period 1976-2005 is 175.

However, a review of all issued US patents in this Class for the last 30 years suggests that other factors may also be important. In that time frame there were a total of 9 837 US patents issued, for an average of about 328 new issues each year. The peak and low numbers for all assignments were in the same years as the peak and low for US assignees, at 686 and 148, respectively.

For the period 1976-1981, four of the six years had above average numbers of issued patents. This period also coincides with the period prior to 1979 when US companies still ordered new nuclear power plants.

For the period 1982-1985, the number of issued patents was lower than average. The fact that no new nuclear power plants were ordered in the United States after 1978 is likely a factor in this decline.

The period 1986 through 1994 was the peak of nuclear reactor technology innovation in the US. For eight of the nine years in this period, the number of issued US patents was above average. Several factors may have played a role in this resurgence. DOE eliminated funding for the Clinch River breeder reactor in 1983, but at the same time initiated funding for the advanced light-water reactor programme. The ALWR programme made its greatest progress during the 1986-1994 timeframe. During this same period, and in the absence of new plants being built, the industry innovated to increase its productivity. Some of the innovation, and resulting patents, during this period may have been born of necessity rather than increased R&D funding. It would also be interesting to look at the number of US universities that began to file and receive US patents during this period. The Bayh-Dole act of 1980, and subsequent Executive Memoranda in the mid-80s, led to a significant increase in the number of US patents they filed. Bayh-Dole and the related Stevenson-Wydler Act allowed recipients of Federal R&D funding to retain title to, and patent, their inventions. It is possible that this change in government policy contributed to the increase in patents issued.

The period 1995 through 2001 represents the low point in patents issued. All seven years were below average. The Energy Policy Act of 1992, and subsequent deregulation of the electric utility industry, likely contributed to this decline for reasons noted earlier in this report. DOE funding for the ALWR programme ended in 1998 and may have contributed to the low patent numbers.

Although there has been a slight upturn in the number of patents issued in 2005 to the traditional nuclear countries of the United States, Japan, France, Great Britain and Canada, the greatest growth is coming from emerging countries like Korea, China and others. Some of this growth is likely due to greater regulatory stability in developed countries, but also to greater economic and political incentives in developing countries.

Source: Country report of the United States.

5.3 Characteristics of nuclear innovation systems

5.3.1 Driving forces for nuclear technology innovation

Identification of driving forces for nuclear technology innovation is useful for assessing the efficiency of the innovation and determining the relevant policies. Driving forces are different for different technology areas. Areas of emphasis for nuclear technology innovation are diverse depending on the national energy policy and the nuclear industry status of each country.

A review of the various country reports and case studies indicates a number of nuclear technology innovation driving forces or motivators. Although there are different driving forces for different technologies, as well as different priority motivators depending upon considerations such as national energy and nuclear sector policies and plans, and, to a lesser extent different nuclear sector organisational structures, it is clear that there are certain fundamental or principal driving forces for nuclear technology innovation. From the country reports and case studies, the following three principal driving forces are identified:

- **market drivers:** these include considerations such as economic enhancements, non-electricity applications, commercial risk management approaches, supply and service arrangements, siting requirements including electrical output;
- **political/public drivers:** these include public policy considerations such as environmental and nuclear safety regulatory requirements, non-proliferation and physical protection, international collaboration incentives (also bilateral collaborative policies), overall national energy policies and electrical supply strategies; and
- **technical drivers:** these include nuclear power facility operational factors such as efficiency and enhanced operability, requirements for enhanced materials and extended service, uranium utilisation, advances in instrumentation and control, construction methods, project and construction management techniques, and advanced computer simulation and modelling.

Typically, these three driving forces act in concert to motivate nuclear innovation. For example, for nuclear innovation initiatives such as the GIF, the main driving force is dominated by public policy and technical interests, followed by response to long-term perceived market needs, especially those related to sustainability and economics. In other cases, such as the US ALWR programme that was co-funded by the US DOE, and the Canadian programme to develop the advanced CANDU reactor, the principal motivators are the need for technical innovation to respond to short- to mid-term market needs. However, the fact that both of these initiatives receive government funding underscores the public policy motivation.

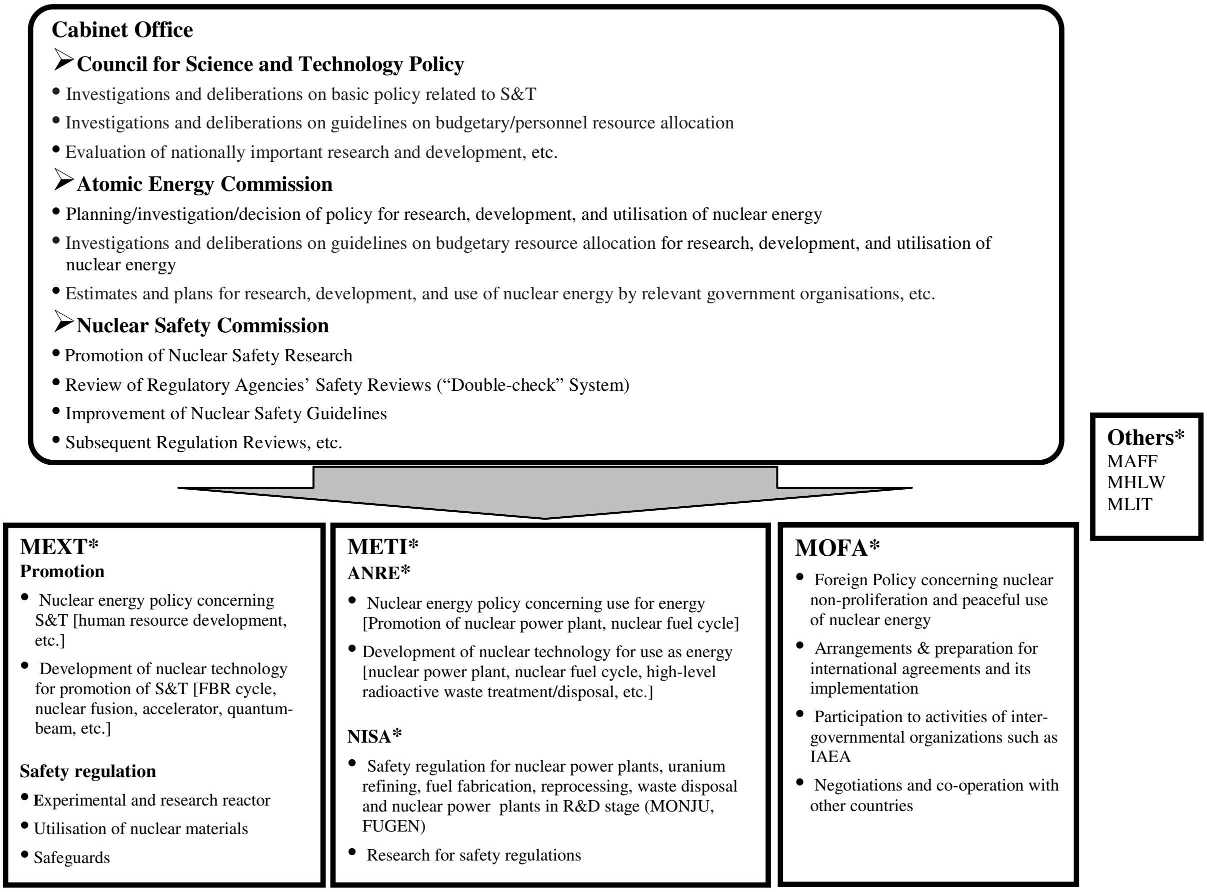
5.3.2 Main actors

5.3.2.1 Government and governmental bodies

Governments have played a key role in nuclear innovation in many perspectives. They are the first that can take the decision to use nuclear power or not in the country, and to encourage and support utilities to choose the nuclear energy option. They are also responsible for establishing the initial infrastructures for nuclear technology research, with more or less involvement depending generally on the path of development decided. Nevertheless, even in a more mature scenario, with nuclear energy ongoing, governments cannot leave everything to market forces. At the least, developments on specific topics like radioactive waste management and basic sciences like radiation effects have to be supported by governments, so they can ensure that there are no unacceptable consequences to the country from the operation of its nuclear power plants. Even more, specific nuclear programmes that demand important infrastructures have to be supported by governmental funds, in the same way as support to other industrial activities that are important to the country. Finally, but not least, governments play an important role as coordinators of the national capabilities and as interfaces in international projects related to future designs.

Generally, many governmental bodies are involved in the process in the horizontal and vertical perspectives due to the interdisciplinary and political nature of nuclear energy, which often makes innovation in the nuclear industry more difficult than in other industries. In the horizontal perspective, nuclear innovation requires a proper coordination of many policies including energy policy, science and technology development policy, environmental policy, industrial policy, safety regulatory policy, national security policy. Hence, nuclear innovation typically involves many ministries and agencies in the government, as illustrated in Box 5.2 for Japan. In the vertical perspective, nuclear innovation involves all levels in the governmental hierarchy from top executives to expert bodies, also including opinion leaders.

Box 5.2 Government and governmental bodies on nuclear energy and their roles in Japan



Cabinet Office

➢**Council for Science and Technology Policy**
- Investigations and deliberations on basic policy related to S&T
- Investigations and deliberations on guidelines on budgetary/personnel resource allocation
- Evaluation of nationally important research and development, etc.

➢**Atomic Energy Commission**
- Planning/investigation/decision of policy for research, development, and utilisation of nuclear energy
- Investigations and deliberations on guidelines on budgetary resource allocation for research, development, and utilisation of nuclear energy
- Estimates and plans for research, development, and use of nuclear energy by relevant government organisations, etc.

➢**Nuclear Safety Commission**
- Promotion of Nuclear Safety Research
- Review of Regulatory Agencies' Safety Reviews ("Double-check" System)
- Improvement of Nuclear Safety Guidelines
- Subsequent Regulation Reviews, etc.

Others*
MAFF
MHLW
MLIT

MEXT*
Promotion
- Nuclear energy policy concerning S&T [human resource development, etc.]
- Development of nuclear technology for promotion of S&T [FBR cycle, nuclear fusion, accelerator, quantum-beam, etc.]

Safety regulation
- Experimental and research reactor
- Utilisation of nuclear materials
- Safeguards

METI*
ANRE*
- Nuclear energy policy concerning use for energy [Promotion of nuclear power plant, nuclear fuel cycle]
- Development of nuclear technology for use as energy [nuclear power plant, nuclear fuel cycle, high-level radioactive waste treatment/disposal, etc.]

NISA*
- Safety regulation for nuclear power plants, uranium refining, fuel fabrication, reprocessing, waste disposal and nuclear power plants in R&D stage (MONJU, FUGEN)
- Research for safety regulations

MOFA*
- Foreign Policy concerning nuclear non-proliferation and peaceful use of nuclear energy
- Arrangements & preparation for international agreements and its implementation
- Participation to activities of inter-governmental organizations such as IAEA
- Negotiations and co-operation with other countries

* **ANRE**: Agency of Natural Resources and Energy; **MAFF**: Ministry of Agriculture, Forestry and Fisheries, **METI**: Ministry of Economy, Trade and Industry; **MEXT**: Ministry of Education, Culture, Sports, Science and Technology; **MHLW**: Ministry of Health, Labor and Welfare; **MLIT**: Ministry of Land, Infrastructure and Transport; **MOFA**: Ministry of Foreign Affairs. **NISA**: Nuclear and Industrial Safety Agency.

Source: Country report of Japan.

Table 5.1 shows the governmental bodies responsible for nuclear power policy, nuclear R&D policy, and safety regulation in the participating countries.

Table 5.1 Governmental bodies related to the nuclear energy

Country	Nuclear power	Nuclear R&D	Safety regulation
Belgium	Federal Public Service Economy, SME's, Self-employed and Energy	Federal Public Service Economy, SME's, Self-employed and Energy	• Federal Public Service Labour, • Federal Public Service Interior, • Federal Agency for Nuclear Control
Canada	Ministry of Natural Resources	Atomic Energy of Canada Limited (AECL)	Canadian Nuclear Safety Commission (CNSC)
Czech	Ministry of Industry and Trade	• Government Council for R&D • Ministry of Education and Youth	State Office on Nuclear Safety
Finland	Ministry of Trade and Industry (MTI)	MTI	STUK (Radiation and Nuclear Safety Authority) under the Ministry of Social Affairs and Health
France	Ministry of Industry	Atomic Energy Commission (CEA)	Nuclear Safety Authority (Autorité de sûreté nucléaire, ASN)
Japan	• Ministry of Economy, Trade and Industry (METI) • Ministry of Foreign Affairs (MOFA)	• Ministry of Economy, Trade and Industry (METI) • Ministry of Education, Culture, Sports, Science and Technology (MEXT) • Ministry of Foreign Affairs (MOFA)	• Nuclear and Industrial Safety Agency (NISA) under METI (for commercial plants) • MEXT (for nuclear utilisation facilities, R&D reactors)
Korea	Ministry of Commerce, Industry and Energy (MOCIE)	Ministry of Science and Technology (MOST)	MOST
Spain	Ministry of Industry, Commerce and Tourism	• Ministry of Education and Science • Ministry of Industry, Commerce and Tourism	Nuclear Safety Council under Parliament
Switzerland	Swiss Federal Office of Energy (SFOE) under the Dept. of the Environment, Transport, Energy, and Communication (DETEC)	Board of the Federal Institutes of Technology within the Swiss Science Agency under the Fed. Dept. of Home Affairs	• Federal Nuclear Safety Inspectorate (HSK) • Federal Commission for the Safety of Nuclear Installations (KSA)
United States	Department of Energy (DOE)	Department of Energy (DOE)	Nuclear Regulatory Commission (NRC)
European Commission	DG TREN (EURATOM Treaty)	DG Research, DG JRC	DG TREN (EURATOM safeguards)

Regulatory bodies and associated technical safety organisations (TSOs) can trigger nuclear innovation through their requirements. At the same time, they are also end users of the technology; not "off-the-shelf" users as are utilities, but rather as consumers of the knowledge bases to be able to judge if specific solutions adopted by utilities are adequate or not. In that way, regulatory bodies should interact with and directly promote research centres to be able to have this independent capacity.

There were significant governmental commitments and support in early days, but it has been changing and evolving especially with the commercialisation of nuclear power. In nuclear advocating countries there is largely the same or comparable commitment, although with different priorities and focus. However, in many other industrialised countries, there is either no or far less commitment. Within developing countries that are pursuing the nuclear option, in general, there remains a relatively high level of commitment and support for nuclear power, especially in those countries which have policies of enhanced and expanded nuclear power programmes.

Since many governmental bodies are involved in nuclear innovation, proper coordination inside the government is extremely important.

Inter-governmental coordination is becoming more important as witnessed by recent international collaborative R&D initiatives such as the GIF and INPRO. Also, there are increasing signs of enhanced safety and regulatory international collaboration, which is fostered by intergovernmental bodies such as the IAEA and OECD/NEA through international legal instruments such as the Nuclear Safety Convention. Moreover, within the OECD, the NEA plays an important role as one of the principal forums for information exchange and policy formulation.

5.3.2.2 R&D performers

R&D performers are the real backbone of the innovation system, as they are called upon to master the basic knowledge to provide conceptual and applied solutions to the system suppliers. Nuclear R&D performers include public research organisations (PROs), industry research organisations (IROs), universities, and industry in-house R&D. Table 5.2 shows major R&D performers in the participating countries.

Table 5.2 Major nuclear R&D performers in the participating countries

Country	PROs	IROs	Others
Belgium	SCK•CEN	Laborelec	Universities
Canada	AECL	CANDU Owner's Group	University (UNENE)
Czech	NRI Rez		UJF – Czech Academy of Science
Finland	VTT		Fortum, TVO
France	Atomic Energy Commission (CEA)		
Japan	Japan Atomic Energy Agency (JAEA)	Central Research Institute of Electric Power (CRIEPI)	• Universities • In-house R&D within Mitsubishi, Hitachi, Toshiba, etc.
Korea	Korea Atomic Energy Research Institute (KAERI)	Korea Electric Power Research Institute (KEPRI)	In-house R&D within Korea Hydro Nuclear Power Company (KHNP), Korea Nuclear Fuel Company (KNFC), Doojung
Spain	CIEMAT	UNESA, TECNATOM, IBERINCO, SOLUZIONA	Universities
Switzerland	Paul Sherrer Institute (PSI)		
United States	National Laboratories	Electric Power Research Institute (EPRI)	
European Commission	Joint Research Centre (DG JRC establishments of Karlsruhe, Petten and Ispra)	Industrial contractors of DG Research projects	Education and training contractors of DG Research

In many countries PROs have been taking a major role in nuclear development, but their roles are changing especially in the countries with nuclear phase-out policy. Due to fewer NPP orders and changes in the energy policies of some countries, many PROs are facing some identity problems leading to the extension of their scope to non-nuclear areas.

PROs were launched in the initial stage by governments and should be kept at sufficient and sustainable level by government support, so they can be ready to step forward when problems arise. They need to be very accessible and flexible to be able to respond to the problems that suppliers and utilities can pose. In small countries it is difficult and not very efficient to have many research centres devoted to a specific topic, because this produces a dispersion of resources with little possibility of creating a critical mass that can survive at all times. Thus, concepts like the Spanish Centres of Reference (see Box 5.3) could be useful for giving priority to specific research topics.

Box 5.3 Centres of Reference in Spain

Purposes: The Centres of Reference (CR) are Spanish technological institutions that have a contrasted capacity in one or more areas of knowledge related to nuclear technology, and are selected by the Spanish users of technology (Promoters) as coordinators of research in this specific area. This scheme has the objective to concentrate resources and so be able to achieve a critical mass, capable of mastering the most advanced technology in that area. Among the obligations of the CR is to develop adequate networks with other Spanish and foreign research institutions, in order to produce synergies within the Spanish research infrastructure.

Working structure: Different promoters (utilities, regulators, suppliers, etc) have different ways of working with the CR. The Spanish utilities, that participate in different international projects such as Owners Group, EPRI, etc. supply the technological information derived from this participation to the CR for its assimilation and application to the Spanish NPPs. The Regulator subsidises specific R&D proposals from these CR and other users of technology have direct contracts for specific topics.

Functions of Centres: CR have a compromise to assist users of technology in their area of knowledge and to participate in the international projects that may be of interest for the Promoters. In principle the assimilation of the technology is assumed by the CR with its own budget, and only its application in the Spanish NPP is paid by the utilities. The participation in international projects is, in principle, paid by the projects.

Number of Centres: Currently the CR nominated as such are the national laboratory CIEMAT, the technological companies TECNATOM, IBERINCO and SOLUZIONA, owned by the utilities, and the fuel supplier ENUSA. Other CR are identified and in process of nomination. The complete list can be seen in the Spanish country report.

Source: Country report of Spain.

With increasing commercialisation of nuclear power, IROs have been becoming a key player in the innovation of evolutionary nuclear technologies, especially when the governmental support for nuclear R&D was going down. However, in an increasingly deregulated market, their role is getting important in addressing specific issues and concerns as identified by industry. R&D activities are generally specific and focused on identified technical problems. Very little, if any, basic scientific research is undertaken. There is a trend for these organisations to become more international.

In some cases universities play an important role in nuclear energy technology innovation, but most commonly they play an important role in basic nuclear sciences (e.g. nuclear data) and in providing qualified human resources through education. Nuclear engineering programmes at universities are critical to the future of nuclear energy due to global problems of ageing workforce in both government and industry. In this regard, the Canadian experience with the establishment of the University Network of Excellence in Nuclear Engineering (UNENE) is noteworthy. This is an arrangement whereby participating Canadian universities provide training in nuclear fields, with financial support provided by Canadian utilities and AECL. Also, a number of funded research chairs have been established.

5.3.2.3 System, component and service suppliers

Suppliers are key actors in nuclear innovation in the perspective that they provide innovative products to their customers – energy providers. Without their efforts to introduce innovative items, it is almost impossible to have any nuclear innovation. Suppliers include nuclear vendors supplying nuclear installations such as NPPs, desalination plants, hydrogen plants, co-generation plants, and fuel cycle facilities; manufacturing companies supplying equipment; fuel suppliers; reprocessing companies; waste management companies; and service suppliers (see Table 5.3).

Suppliers should be the actors that interact with the governments to help in building the right research infrastructure needed to produce innovative solutions to the problems that arise in the operation of current nuclear plants and in the design of future plants. This group ranges from main suppliers like Westinghouse, GE or AREVA, to local suppliers of technology for a specific activity, for example "non-destructive materials testing". Suppliers also have an important role in the definition of future designs after the basic research, to transform them into applicable technology.

Suppliers have been a key actor in the development of evolutionary innovations such as Generation III/III+ reactors, advanced fuels, etc. They are targeting not only their domestic market but also the world market of new NPPs, refurbishment, decommissioning, etc.

Collaboration among suppliers is generally based on specific agreements with particular attention on important commercial aspects such as intellectual property rights. In times of high demands for nuclear power plants, collaboration among system suppliers is limited, of course, by the constraints of the competitive market. During the long years of stagnation, however, several restructuring measures and merging of nuclear suppliers has led to large scale fusioning of technological knowledge.

Table 5.3 Major suppliers in the nuclear sector in the participating countries

Country	NSSS design	Plant (turn-key)	Components	Fuel	Reprocessing	Waste management	Service
Belgium	Tractebel Engineering	–	–	Belgonucleaire	–	ONDRAF/NIRAS	Tractebel Engineering, Belgatom
Canada	AECL	AECL		Cameco/CGE	–	NWMO	–
Czech	NRI-Div. Energo- projekt, SKODA Praha	SKODA Praha	SKODA JS	–	–	NRI, SKODA JS	SKODA JS
Finland	–	–	–	–	–	Posiva	FNS, VTT, TVO Nuclear Services Oy, Francom Oy
France	AREVA NP	AREVA NP	–	AREVA NC	AREVA NC (Cogema)	ANDRA	–
Japan	Mitsubishi, Toshiba, Hitachi	Mitsubishi, Toshiba, Hitachi	Mitsubishi, Toshiba, Hitachi Ishikawajima-Harima	Mitsubishi Nuclear Fuel Co., Ltd, Global Nuclear Fuel-Japan Co. Ltd, Nuclear Fuel Industries	JNFL	NUMO (high-level wastes) JNFL (low-level wastes)	Mitsubishi, Toshiba, Hitachi
Korea	KOPEC	KHNP (Project management)	Doojung	KNFC	–	NETEC	KPS
Spain	–	–	ENSA	ENUSA	–	ENRESA	TECNATOM, IBERINCO, SOLUZIONA
Switzerland	–	–	CCI, Alstom, ABB	–	–	Nagra	Colenco
United States	Westinghouse, GE, GA, B&W	Westinghouse, GE, GA, B&W	–	–	–	–	–

Note: For the full names of the abbreviations, see Appendix B.

5.3.2.4 Energy providers

Energy providers are key customers of energy systems, which are the targets of nuclear innovation, and include utilities (see Table 5.4), heat suppliers such as district heating companies, hydrogen suppliers in future, and suppliers of potable water.

Table 5.4 Major nuclear utilities in the participating countries

Country	**Utilities**[1]	**Electricity market**[2]	**Nuclear installed capacity** (Net, GWe)[3]	**Nuclear generation** (Net, TWh, 2005)	**Nuclear share** (%, 2005)
Belgium	ELECTRABEL	PD	5.8	45.3	55.0
Canada	OPG, *Bruce Power*, HQ, NB Power	R	12.5	86.0	14.4
Czech Republic	CEZ	R	3.5	23.3	30.6
Finland	FPH, TVO	D	2.7	22.3	32.9
France	EDF	R	63.4	430.0	78.3
Japan	• BWR group: *Tokyo, Tohoku, Chubu, Hokuriku, Chugoku* • PWR group: *Kansai, Hokkaido, Sikoku, Kyusyu* • Both type: *JAPC*	PD	47.4	291.9	31.7
Korea	KHNP	R	16.8	138.7	40.1
Spain	Endesa, Iberdrola, Unión Fenosa, Hidrocantabrico (association UNESA)	D	7.5	55.4	19.8
Switzerland	BKW-FMB, AXPO, ATEL, EOS	D	3.2	22.0	37.9
United States		PD	99.8	780.0	19.3

1. Entities in *Italic* are private utilities.
2. **R**: regulated, **PD**: partially deregulated, **D**: deregulated.
3. As of the end of 2005, Source: NEA (2006), *Nuclear Energy Data*, OECD, Paris.

Utilities are the end users of innovative nuclear technologies and their developments, but it is important not to assume that because of this they are the ones that should promote the whole mechanism. It may have been so in the past, where governments sometimes made specific assignments in the electricity tariffs for R&D, but in a liberalised market it is more often that utilities buy “off-the-shelf” solutions that suppliers offer for their problems. For some specific topics, however, utilities need to have first-hand research results to make right decisions without technology market distortion. As these topics are generally of an international character – material ageing, increasing reliability, etc. – what is usually done is to establish partnership with other utilities to address these first-hand issues.

Utilities also worked together to establish commonly accepted requirements; e.g., utility requirements document (URD)[2] in the United States and European utility requirements (EUR) in Europe.

Utilities have been going through many consolidations, especially in the United States. The resulting large companies have the capability to make large investments and the management strength, financial resources and scale necessary to achieve higher efficiencies. The benefits of the consolidation are apparent from the performance data, which show that the plants that form part of a larger fleet achieve higher capacity factors and lower costs than single-unit nuclear operators would achieve.

Other energy providers such as heat suppliers seem to play a minimum role in nuclear technology innovation. However, hydrogen providers, for example, have great potential as future customers of nuclear energy systems.

5.3.2.5 Other supporting organisations

There are many other organisations supporting R&D performers, system suppliers and energy providers in the process of innovation. For example, in the United States, the Nuclear Energy Institute (NEI) and the Institute of Nuclear Power Operations (INPO) have extensive programmes in support of the nuclear industry. Although neither organisation conducts technology research, both evaluate technical, regulatory, and operational issues and experience, publish reports, and maintain important links to government agencies, media, and various international organisations. Other examples are Japan Atomic Industry Forum (JAIF) and Korea Atomic Industry Forum (KAIF).

5.3.3 Institutional frameworks

5.3.3.1 National policies

National energy policies greatly affect the motivation for and the direction of nuclear innovation. There is a need for long-term energy policies, with an adequate framework of national policies and international principles and rules. Since nuclear innovation usually takes a long time and requires a large amount of investment, the predictability of national energy policies is crucial. In this sense, changes of energy policies with changes of administrations can be a hurdle for nuclear innovation.

Countries maintain different national energy policies. Countries with little domestic resources such as France, Japan and Korea maintain energy policies advocating nuclear power. Some other countries maintain a policy of nuclear power phase-out or no nuclear power introduction.

National innovation policies as a whole provide the framework of nuclear innovation. Many countries have been showing greater interest for national innovation systems. For instance, the government of the Czech Republic established the National Innovation Policy in March 2004 as shown in Box 5.4, giving it the highest national priority; the National Innovation Policy is closely linked with the National Policy of Research and Development.

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2. Utility requirements document (URD) is to be a utility consensus document. The US utilities jointly started the ALWR URD in 1985 and completed it in 1990; it covers the entire plant up to the grid interface, forming the basis for an integrated plant design, i.e., nuclear steam supply system and balance of plant. For more detail, see the country report of the United States.

Box 5.4 National innovation policy of 2004 in Czech Republic

Objectives: to contribute to the creation of an economically highly competitive society with the maintenance of the social cohesion.

Thematic areas of high priority: safe, reliable and ecological energy for the future; society of information and knowledge; quality and safety of life; new materials and technologies; needs of the Czech Republic in the social and economic area.

Crosscutting areas: human resources; evaluation of research; international co-operation in R&D; utilisation of R&D results in practice; regional aspects of R&D.

Involved organisations: Government Council for Research; Ministry of Education, Youth and Sports; Ministry of Industry and Trade; Ministry of Environment; Ministry of Health; Ministry of Local Economy; Ministry of Finance; State Office on Nuclear Safety; Czech Academy of Science; association of research organisations; grant agency; innovation centres; regional agencies; universities; research institutes, etc.

Source: Country report of the Czech Republic.

5.3.3.2 National nuclear programmes

In some countries the existence of a specific national nuclear programme goes hand in hand with the government's commitment on nuclear innovation.

- In Japan, the Atomic Energy Commission (AEC) has been formulating "Long-term programmes for research, development, and utilisation of nuclear science and engineering" approximately every five years since 1956. The last Long-term Nuclear Plan (9th) was formulated in November 2000. In October 2005, AEC replaced "Long-term Nuclear Plan" with "Framework for Nuclear Energy Policy", targeting the period over the next ten years. It specifies basic concepts of nuclear energy policy or measures to be taken by the government concerning R&D and utilisation of nuclear science and engineering and guidelines for planning and promoting such measures at the administrative level. It also highlights expectations for local governments and business entities that are closely related to nuclear energy administration as well as for the people at every level, whose understanding is indispensable to the implementation of nuclear energy policies.
- In Korea, the "Comprehensive Nuclear Energy Promotion Plan" (CNEPP) is formulated every five years based on the Atomic Energy Act, which includes long-term nuclear policy objectives and basic directions, sector-by-sector objectives, budget and investment plan, etc. The national nuclear R&D programme, called the "National Mid- and Long-term Nuclear Energy R&D Programme," was first launched in 1992 as a 10-year (1992-2001) programme and modified into a new R&D programme to be implemented from 1997 to 2006 to assess major changes in national and international situations. The programme covers all areas of the nuclear field: future nuclear energy systems, nuclear safety, radioactive waste management, radiation protection, radioisotope production and radiation application, and technological innovation for current nuclear power plants.

In some countries such as Finland, Czech Republic, etc., public nuclear R&D is performed in the context of national science and technology.

5.3.3.3 Funding nuclear innovation

The long-term characteristic of nuclear innovation implies that funding, both public and private, should be stable in this long-term perspective, as long as the established milestones are fulfilled. For example, the EC recognises the need of long-term financial investments, bearing in mind that the nuclear industry requires an environment that is:

- objective (i.e. clear allocation of responsibilities between industry and regulators);
- consistent (i.e. same treatment for all nuclear industries across the EU-25); and
- predictable (i.e. no unexpected requirements, favourable public opinion, etc.).

Funding mechanism

Nuclear R&D budgets come from various sources such as governments, utilities and others, and can use various models. In some countries utilities pay part of the budget for public nuclear R&D.

- For instance, in Korea, the public nuclear R&D budget is funded by government appropriations and the nuclear R&D fund paid by a nuclear utility with the rate of about USD 1 per MWh of nuclear generation. In Japan, the special account budget, "Promotion of Power Resources Development Tax" from all utilities, accounts for 70% of the nuclear energy budget. In Canada, the R&D programme is jointly funded by government appropriations and from commercial revenues generated by AECL.
- In 1980, the Spanish government created a mechanism basically consisting of an assignation, by law, of 0.3% of the income of the utilities from the sale of electricity to R&D activities, being a joint decision of utilities and government to finance the projects with these funds. This regulation was done in a strongly regulated environment, where the electricity supply was considered a public service following governmental investment planning and fixed tariffs, also with governmental guarantee. This model was in force until 1997, when the liberalisation of the electric sector and so of the electricity price, made the government abolish the assignation.

Another mechanism is public-private co-funding.

- For instance, as part of their new mission statement, the EIB (European Investment Bank) is entitled to support the construction of large research facilities, especially if related to innovation.
- In Switzerland, the law allows the safety authority to charge utilities the cost of R&D related to regulatory issues in addition to regular oversight cost.
- In Finland, the financing of the two national public nuclear research programmes, i.e. nuclear reactor safety programme SAFIR (around € 5 M per year) and KYT (nuclear waste research, around € 1 M per year, with utilities being responsible for much bigger programmes themselves) has been changed by new legislation since 2004 so that nuclear utilities have the mandatory biggest share in financing. Tekes (Finnish Funding Agency for Technology and Innovation) is the main public funding organisation for R&D and innovation in Finland. Tekes funds industrial projects as well as projects in research organisations and especially promotes innovative, risk-intensive projects in all technological branches including nuclear technology.

There are also measures to support innovation inside the R&D performers. In Switzerland, although no particular incentives are provided at governmental level for innovations in nuclear technology, an interesting approach, called "Seed Actions", has been implemented as shown in Box 5.5.

Box 5.5 “Seed Actions” at PSI in Switzerland

This approach has been implemented recently at PSI’s Nuclear Energy and Safety Research Department (NES) using NES own funds in a “once-in-a-lifetime” way to finance time-limited (3 years) research in novel domains. At the end of the time limit, the Seed Actions, if successful, should transform into self-sustainable R&D activities. The objectives of the Seed Actions are:

- To identify and initiate in time new research fields that could build focal points for the Department’s research in the mid-term as replacement for current R&D activities that are expected to be terminated by that time and, thus, to strengthen NES position in the forefront of innovative research.
- To foster the intrinsic inclination of the researchers to address new questions in innovative research fields and to broaden their knowledge and expertise.
- To strengthen the corporate identity of the Department through the process of a common funding source and an open and transparent competition.

Source: Country report of Switzerland.

5.3.3.4 Incentives

There is no country, among the participating countries, that provides special incentive for nuclear R&D. For example, the United States Government provides virtually no incentives for nuclear RDD&D programmes, nor does it provide subsidies or favourable tax treatment for the emissions avoidance contributions to the environment from nuclear energy, either for current plants or for construction of new plants. For over a decade, and until very recently, the federal funding to nuclear energy R&D was substantially lower than corresponding federal funding for fossil, renewables, energy efficiency, and fusion R&D.

Even when there is no specific incentive for nuclear innovation, most governments provide incentives for technology innovation in general; for instance, Belgium provides incentives as shown in Box 5.6, which can be used in the nuclear context also.

Box 5.6 Incentives for technology developments in Belgium

The Belgian legislation foresees incentives for technical and economical development in general. Any technology, including nuclear, can benefit from this legislation.

For new technologies or products, interested companies and bodies can receive up to 80% of the development cost. This subsidy has to be reimbursed during the commercialisation of the product or technology. For its part of the MOX fuel development, Belgonucléaire has received a subsidy equal to 80% of the cost. In the meantime, it has been completely reimbursed. In exceptional cases, the subsidy could be increased even up to 100% in case no commercialisation can be foreseen in the near future. For its R&D work on fast breeder reactors, Belgonucléaire has enjoyed such a subsidy.

For the construction of new plants or the refurbishment of existing plants, under certain circumstances, the public authorities can give some support, for instance:

- tax exemption can be given on the profits of the company during the first years of operation of the investment;
- if loans are needed for the financing of the investment, the public authorities can pay a part of the interest on the loan;
- in case of loans, the public authorities can give a guarantee to reimburse the loan in case the investment would go wrong.

In the eighties, the MOX-plant of Belgonucléaire has taken advantage from this legislation to some extent. For the construction of its treatment facility for low level waste, NIRAS/ONDRAF has obtained a state guarantee for the reimbursement of the loans it contracted to finance the facility.

Source: Country report of Belgium.

5.3.3.5 Partnerships and networks

OECD [24] defines public and private partnerships (PP/P) as "any formal relationship or arrangement over a fixed term/indefinite period of time, between public and private actors, where both sides interact in the decision-making process, and co-invest scarce resources such as money, personnel, facility, and information in order to achieve specific objectives in the area of science, technology, and innovation." The need for partnerships and networks seems to be well recognised in the nuclear sector. There are many PP/Ps working in the participating countries:

- In the United States, a Secretary of Energy Advisory Board Report on Strategic Energy R&D [25] strongly advocated PP/P to spur R&D productivity, and to achieve three objectives: "to leverage government R&D spending, to introduce market relevance into R&D decision making, and to accelerate the R&D process and transfer of results into the economy and the marketplace." ALWR Programme and NP2010 are good examples of PP/P implemented in the United States. Another example is the Joint Strategic Plan (JSP), which as a "top-down" document derives its goals and objectives from two governing policy documents issued in 2001 by the Administration and the industry (see Box 5.7).

Box 5.7 US DOE/Nuclear Energy Industry Strategic Plan for LWR R&D

Objective: To provide the basis for a growing public-private partnership targeted at common goals that are shared by industry and government for the future of nuclear energy.

Participating organisations

- Developed by a joint DOE-industry team.
- Reviewed and approved by DOE management and the Chairmen of the two senior nuclear utility advisory bodies in the industry, the NEI's Nuclear Strategic Issues Advisory Committee and EPRI's Nuclear Power Council.

Bases of the Plan

- The Administration's *National Energy Policy*, which recommended "the expansion of nuclear energy in the United States as a major component of national energy policy".
- The Nuclear Energy Industry's *Vision 2020*, which called for adding 50 000 megawatts of new nuclear generating capacity to the US grid by 2020, and increasing the output from existing nuclear units by 10 000 megawatts through uprates and other efficiencies.

Contents of the Plan

Goal #1: Building new nuclear power plants

- Objective 1-1: Demonstrate Early Site Permit and Combined Operating License
- Objective 1-2: Support certification of NTD reactor designs
- Objective 1-3: Shorten lead times for new plants
- Objective 1-4: Support enhanced business environment and industry infrastructure for new plants

Goal #2: Improving current plant performance

- Objective 2-1: Support increased capacity and capacity factors
- Objective 2-2: Support long term operation
- Objective 2-3: Develop cost-effective advanced security technology
- Objective 2-4: Support implementation of high burnup fuel

Implementation

- Full implementation is awaiting adequate funding priority by DOE and Congress. Most of the elements of Goal #1 are being addressed by the NP2010 Programme. Elements of Goal #2 are included in a newly authorised programme in the Energy Policy Act of 2005.

Source: Country report of the United States.

Partnerships and networks in a broader sense than just nuclear prevail in many countries, where "nuclear" ones are embedded as a part of the general science and technology ones. For instance, the European Union operates the system of Integrated Projects in order to "strengthen the science and technology bases of the EU", which provides a context for nuclear partnerships and networks in Europe.

Box 5.8 Integrated projects in the European Union

Integrated projects (IP) aim at developing innovative knowledge, products or services in order to "strengthen the science and technology bases of the EU".

Objectives

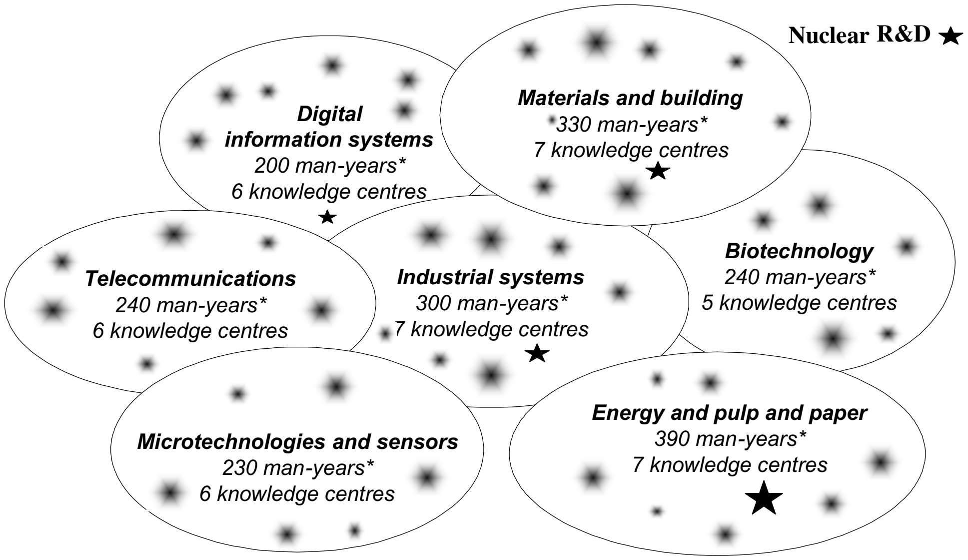
- *Vertical integration:* 1. universities; 2. research organisations; 3. system suppliers; 4. energy providers and waste agencies; 5. TSOs or regulators; 6. decision makers.
- *Horizontal integration:* 1. nuclear physics (nano-scale); 2. chemistry (meso-scale); 3. continuum mechanics (macro-scale); 4. mathematics and informatics; 5. electronics/ electricity; 6. health/environmental sciences.
- *Knowledge management:* 1. research (i.e. identification, *creation* and development of knowledge); 2. education (i.e. preservation, dissemination and *transmission* of knowledge); 3. innovation (i.e. *use* and exploitation of knowledge for research and/or industrial purposes).

Source: Report of EURATOM.

In Finland's biggest research organisation, VTT, nuclear R&D is located under the knowledge cluster of "Energy and pulp and paper" as shown in Box 5.9. The knowledge centre on nuclear R&D then has got experts from nearly all of the other six knowledge clusters like "Materials and building" or "Industrial systems". The idea of this arrangement is to provide a wide range of knowledge to a special area with a flexible organisation.

Box 5.9 Knowledge clusters and knowledge centres in VTT in Finland

7 knowledge clusters and 45 knowledge centres



* The figures describing the men-years are suggestive and describe the volume needed in research at the moment.
Source: Country report of Finland.

5.3.3.6 International collaboration

R&D can be fostered and accelerated through international collaboration. There are various forms of international collaboration such as: research collaborations between individual scientists, collaborations based on agreements between research institutions, collaborations requiring significant capital or operational funding, and collaborations designed to provide a new capital facility [26].

Bilateral collaboration

A good example of bilateral international co-operations are the ones established within the International Nuclear Energy Research Initiative (I-NERI), initiated by the US DOE in 2001 as a mechanism for coordinating international R&D on next-generation nuclear energy systems known as Generation IV. The following objectives have been established for the I-NERI Programme:

- Develop advanced concepts and scientific breakthroughs in nuclear energy and reactor technology to address and overcome the principal technical and scientific obstacles to the expanded use of nuclear energy worldwide.
- Promote collaboration with international agencies and research organisations to improve development of nuclear energy.
- Promote and maintain a nuclear science and engineering infrastructure to meet future technical challenges.

The I-NERI Programme sponsors innovative R&D in the general areas of: next-generation nuclear energy and fuel cycle technology; next-generation nuclear plant designs with higher efficiency, lower cost, and improved safety and proliferation resistance; innovative nuclear plant design, manufacturing, construction, operation, maintenance, and decommissioning technologies; advanced nuclear fuels and materials; and advanced energy products. Bilateral contracts have been signed (in chronological order) with Korea, France, OECD/NEA, European Union, Canada, Brazil and Japan.

Multilateral collaboration

An example of multilateral international collaboration aiming at innovative developments is GIF, which is discussed in detail in Section 4.3.1.1.

More recently, the Global Nuclear Energy Partnership (GNEP) was launched as a comprehensive strategy to increase US and global energy security, encourage clean development around the world, reduce the risk of nuclear proliferation, and improve the environment. GNEP will develop and demonstrate new proliferation-resistant technologies to recycle nuclear fuel and reduce waste. The United States will also work with other advanced nuclear nations to develop a fuel services programme that would provide nuclear fuel and recycling services to nations in return for their commitment to refrain from developing enrichment and recycling technologies. GNEP is designed to allow developing nations to reliably access clean nuclear energy as an electricity source for their people in a safe and cost effective manner.

The United States and its international partners will work together to develop commercial recycling technologies (e.g. the UREX+ process) that do not produce separated plutonium, thereby reducing proliferation concerns. Following initial positive results, GNEP would call for the demonstration and deployment of advanced reactors that would use state of the art technologies to produce energy from recycled nuclear fuel.

Another example of international R&D collaboration is the one conducted in the framework of the EPRI in the United States, which was organised in 1973 to conduct and sponsor research and development with respect to the production, transmission, distribution and utilisation of electric power. EPRI also provides a medium through which power producers, transmission and distribution operators and others interested in electricity can sponsor electricity research and development for the public benefit. Nuclear R&D activities include broad areas as shown in Table 4.1.

The work of EPRI is conducted by its employees, managers and officers, but also by contracted external institutions, and the results are made available to the EPRI members and to the partners contractually involved in the specific projects. Responding to growing concern over declining levels of techno-logical innovation in the electric power industry over the last decade, EPRI has established in 2005 the new Office of Innovation to streamline development of fundamentally new technologies and help reinvigorate the industry's commitment to inventiveness.

Collaboration through international organisations

Multilateral R&D is successfully conducted also in the framework of existing international organisations and bodies.

The IAEA has since 1958 concluded research contracts with laboratories and other scientific institutes in its Member States. The activities undertaken are normally implemented through coordinated research projects (CRPs) [27] that bring together research institutes in both developing and developed countries to collaborate on the research topic of interest. The IAEA may also respond to proposals from institutes for participation in the research activities by awarding individual contracts not related to a CRP. A small portion of available funds is used to finance individual projects, which deal with topics covered by the IAEA's scientific programme. The research that is supported encourages the acquisition and dissemination of new knowledge and technology generated through the use of nuclear technologies and isotopic techniques in the various fields of work covered by the IAEA's mandate.

The results are freely available to member countries and the international scientific community through dissemination in the IAEA's scientific and technical publications and in other relevant international or national journals. Where it is practical and relevant, the knowledge gained through CRPs is used to enhance the quality of projects delivered to Member States through the IAEA's technical co-operation programme.

Another example of multilateral collaboration through the IAEA is the INPRO programme, which is discussed in detail in Section 4.3.1.2.

International collaboration among the Member States of the European Union is the very essence of EU's research framework programmes (FP), and more specifically for nuclear energy, of the EURATOM FP. However, in the early stages (3rd, 4th and partially 5th FP), R&D in this framework was rather thematically orientated with narrow subjects. During the 5th FP, networks – e.g. the HTR-TN – have been implemented and represent the first examples of integrated efforts.

The new trend in recent activities confirms the principle for the integrated approach on a broadly based co-operation among industry and research institutions. The aim is the development of complete nuclear systems for intermediate and long term deployment and not only the investigation of specific aspects or subsystems. Some of the EURATOM integrated projects within the 6th FP (e.g. RAPHAEL, EUROTRANS) follow and confirm this philosophy.

Joint R&D projects conducted by the OECD/NEA under one of its technical committees are *de jure* international with broad participation but with rather narrow scope. This co-operative R&D aims either at the investigation of specific phenomena or collection of experimental data (e.g. RASPLAV, MASCA, SETH) or at the operation of a large experimental facility (e.g. HALDEN).

One particular example of international collaboration in the nuclear field is R&D on nuclear fusion and in particular the ITER[3] project. The idea for ITER originated from the Geneva superpower summit in November 1985 where Premier Gorbachov, following discussions with President Mitterand of France, proposed to President Reagan that an international project be set up to develop fusion energy for peaceful purposes. The ITER-project subsequently began as collaboration between the former Soviet Union, the United States, the European Union (via EURATOM) and Japan.

The process of selecting a location for ITER took a long time, and was finally successfully concluded in 2005.[4] On 28 June 2005 it was officially announced that ITER will be built in the European Union, at the Cadarache site in France. The decision on where to site ITER allows the project to move towards its construction phase. Agreement has been reached on the sharing between the different Parties of the costs and the in-kind contributions to the project. The way is now open for the signing of a joint implementation agreement, which will allow the international ITER organisation, based in Cadarache, to be established.

The ITER example shows that, even in the pre-competitive phase that characterises innovative R&D with international collaboration, lengthy negotiations may become necessary to accommodate national priorities and interests. On the other hand, it demonstrates the need for government involvement and commitment for the realisation of such an undertaking that exceeds the financial and technological capabilities of single countries.

Role of governments in international collaboration

The involvement of policy makers and governments in such international collaboration will vary depending on circumstances. At the simplest level no involvement is usually required. Beyond this, government is responsible for maintaining a general framework within which international collaboration can take place. For the provision of a new large-scale facility at considerable cost, government involvement is inevitable [26].

5.3.3.7 Nuclear education and training

Nuclear engineering programmes at universities are critical to the future of nuclear energy in the world. Ageing workforce problems in both government and industry are becoming apparent and will become acute within the decade. There are many national and international efforts to solve these problems.

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[3] ITER means “the way” in Latin. Formerly it was interpreted to stand for “International thermonuclear experimental reactor,” although this usage has been discontinued.

[4] Canada was the first to offer a site in Clarington, in May 2001. Soon after, Japan proposed the Rokkasho-Mura site, Spain offered a site at Vandellos near Barcelona, and France proposed the Cadarache site in the South of France. Canada withdrew from the race in 2003, and the European Union decided in November 2003 to concentrate its support on a single European site, for which the French site Cadarache was chosen. From that point onwards, the choice was between France and Japan.

In the United States, both industry and government are engaged in various activities to encourage enrolment in science and engineering programmes that will provide critical talent to replace retiring workers and meet the needs of an industry poised for major expansion. These workforce needs are not limited to nuclear engineering. They include mechanical, electrical and civil engineers, experts in the fields of materials and chemistry, radiation protection and health physics, nuclear fuel, digital control systems, geophysics (e.g., seismic design), performance monitoring and maintenance of systems, information technology, etc.

Regional initiatives such as the European Nuclear Engineering Network (ENEN, see Box 5.10) and the Asian Network on Education and Nuclear Training (ANENT) bring together universities in different countries to provide degrees in nuclear subjects that are beyond the capability of any individual university. The World Nuclear University (WNU) is an example of government, industry and academia collaborating to support education and training. The mobility of students, teachers and experts is an integral part of such initiatives.

Box 5.10 European Nuclear Education Network

In Europe, a nuclear education and training strategy is under development, following three general principles, namely:

- Modular approach and common qualification criteria (with the aim to identify the best E&T modules and to award quality labels).
- One mutual recognition system across the EU (ECTS) (in particular, the "bologna" system, with the aim to spread excellence).
- Facilitation of mobility for teachers and students, in particular, through funding from appropriate "private and public partnerships".

In order to achieve the above objectives, a non-profit association (under French law of 1901) was formed in September 2003: this is the "*European Nuclear Education Network*" (ENEN), a spin-off of the homonymous FP-5 project, composed nowadays of 42 nuclear education and training institutions. This international association can be considered as a step towards the creation of a virtual European Nuclear University that might ultimately network education and training programmes in all areas of nuclear fission and radiation protection.

Source: Report of EURATOM.

5.3.4 Infrastructure for innovation competence

5.3.4.1 Human resources

The availability of highly motivated and qualified multidisciplinary engineers and scientists is absolutely essential to achieving nuclear technology innovation. Indeed, the availability of human resources has been recognised as a pressing issue for the nuclear power sector. The OECD/NEA has undertaken a number of studies on this important topic and has published reports, which provide recommendations to governments, regulatory bodies, R&D institutes and industry. Many of these recommendations focus on the need for governments to provide and encourage basic engineering and science-based education, especially at the post-secondary level. This is particularly relevant to enable nuclear technology innovation.

Some of particular issues related to human resources, which have been identified in the various case studies, are as follows:

- **Balance between generalists and specialists**: one of the common findings from the case studies has been recognition that there is a need to ensure an appropriate balance between personnel who are highly specialised and those who are multidisciplinary. With the necessary organisational management in place, the experience is that this mix creates a cross-fertilisation of ideas and concepts, and it tends to enhance motivation.
- **Ageing workforce and knowledge preservation**: much of the nuclear innovation described in the case studies depended on background information, the understanding of this, and know-how, which is not necessarily documented. This underscores the vital need for knowledge preservation, and the need to ensure that systems and processes are put in place to address knowledge preservation for future nuclear innovation activities. The related issue of workforce ageing applies to nuclear innovation from at least two perspectives: first, the need to have access to and involvement of senior experienced experts as part of the innovation process (many of whom provide valuable input if only as a sounding board for new ideas and concepts); and, secondly, innovation is seen by many as an incentive for involvement of new scientists and engineers, who are motivated to take up the challenge of working on and contributing to something new.
- **Balance between old and new**: one of the lessons from the case studies is the desirability of having a mix between young engineers and scientists working with older and more experienced ones, as part of an integrated innovation team. This allows and encourages open exchanges of ideas and experiences, both of which are vital to nuclear innovation.
- **Attract young talented people**: innovation is one of the keys to attracting young talented people to contribute to nuclear technology advances. Active innovation programmes in R&D, engineering, design and management are essential in demonstrating that nuclear power is alive and well and is a technology with a future. An industry that does not innovate is not alive; while those that do innovate, by providing scientific and engineering challenges, naturally attract the best and brightest young professionals.

5.3.4.2 Access to leading-edge nuclear R&D facilities and R&D information

Today, with the commercialisation of the current generation of nuclear power technologies, many of the world's premier nuclear R&D facilities, which were established by governments, are facing the challenge of reduced government funding and support. This challenge is compounded by the fact that most of these facilities are more than fifty years old, with many now in need of refurbishment. Moreover, in many OECD countries there are shortages of specialised irradiation facilities as high flux research reactors have been decommissioned and with irradiation schedules for existing reactors being booked many years in advance. In this regard, OECD/NEA is establishing a database on nuclear research facilities in OECD countries.[5]

Although expectations are that advanced computer simulations will play an ever increasingly important role as a R&D and design tool, there will continue to be a need for access to advanced and specialised R&D facilities. Models, codes and simulations will need to be verified and tested as part of

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[5] The Expert Group on "Needs of Research and Test facilities in Nuclear Science" was established in June 2004. It has been reviewing the status of research and test facilities worldwide and assessing future requirements for such facilities in the field of nuclear science and technology.

the process for certification of their use. Moreover, availability of advanced fuel irradiation and post irradiation examination facilities, as well as chemistry, thermal-hydraulic and material test loops, for example, will be essential for nuclear innovation. However, opportunities for shared facility ownership and use, under appropriate collaborative arrangements (either bilateral or multilateral) offer attractive benefits, which promote and enhance nuclear innovation. This idea is followed, for instance, in the proposal for a next generation, high performance irradiation facility in Europe such as the Jules Horowitz reactor, MYRRHA or PALLAS reactor.

5.3.4.3 Organisational culture for innovation

As nuclear installation safety has been recognised as a main driving force for innovation in the nuclear industry, there has been a natural reason to form an open culture for innovation. The discussion between academia and industry for instance in the fields of thermal hydraulics or nuclear physics has been lively and always open to new ideas. Also, the acts of national nuclear safety bodies have enhanced this behaviour by delivering important safety issues to third party investigations. This co-operation has been fruitful in many ways; it has created new challenges to be solved in order to attract talented people to the field, amplified efforts in the industry by multiplication of the expertise available, and undoubtedly increased the safety level of nuclear installations.

Openness has been the keyword in nuclear research when best design and analysing practises have been developed. The most important safety programmes analysing nuclear processes have been more or less used as open software with limited financial contributions to the programme developers. As an example of this, the International Standard Problems have been one way to agree on best practices in computational analyses.

However, nuclear research being very specialised, its outcomes have been publicised mainly through decision makers while information to the public has been very limited. Moreover, the benefits of R&D have been difficult to explain as they related mostly to safety enhancement and spin-offs outside the nuclear field were scarce. In this connection, as compared to basic research carried out by institutes such as CERN for example, nuclear research experienced more difficulties to be recognised as innovative.

5.3.4.4 Co-operation with other sectors

While being successful in creating an international research community in nuclear research, the nuclear field has become self-sufficient along the way, which might be harmful for the future development. As stated in Chapter 2 the innovations are most likely to be found between sectors when applying existing knowledge to a new field instead of mostly incremental enhancements achieved through common R&D processes. Multidisciplinary research opens new paths and is also nowadays in many cases a point to be stated when funding for research is requested from sources like EU framework programme.

The nuclear field has a lot to give to other fields, for instance in thermal hydraulics to be applied in all industrial processes. Also, probabilistic safety assessment can provide tools for other fields of industry to avoid losses. A lot of demanding research related to new materials is going on and planned with the nuclear sector as driving force, the biggest example being ITER. At the same time, the nuclear field has a lot to gain from new automation technologies, information and communication technologies, etc.

At the moment, the funding of nuclear R&D is in many cases provided from a separate source than other funding. This procedure is well founded, as there is a need to continue the successful safety research. However, this funding has declined as the industry has matured and at the same time alternative funding sources for the nuclear field have not been found. This has not been examined but there can be various reasons like common funding organisations disregarding the nuclear field because of if having direct sources of funding and maybe also reluctance among scientists to think that their know-how may have wider applicability. A closer look to these issues is advised; how to promote multidisciplinary discussion between nuclear and other fields and how to create more room for innovation are questions which remain to be answered.

5.3.5 Programme/Project management

5.3.5.1 Visioning and planning process

Innovation, by its very nature, cannot be planned precisely from the beginning to the end. There are too many uncertainties and possible biases in the process to be effectively taken into account. If one would include all possible bifurcations in the development process, the necessary resources would be tremendous. It is, thus, necessary to determine from the very beginning the final objectives and a limited number of pathways towards these objectives based on experience, intuition and sound judgement. Equally, mid-way milestones and corresponding fall-back alternatives, as well as decision points for the down-selection of pathways, belong to a sound visioning process.

Because of the inherent fuzziness of the innovation process and the essential role experience and judgement have to play, the involvement of experts from different disciplines is instrumental for a successful planning and visioning process of innovative R&D. They will contribute experience and lessons learned in their specific fields of competence, identify critical issues and ask the "simple" questions that tend often to get forgotten. Moreover, they can, at a later time point, establish the indispensable links with other disciplines, be it for technological cross-fertilisation or for the opening of additional market sectors.

The aforementioned uncertainties that characterise innovation in any technological sector may become stronger in the case of nuclear energy because of its social context and the issue of public acceptance. The perspectives for its deployment depend also on the net benefit perceived by the public, for whom the assurance of abundant and secure energy supply competes with fears about hypothetical severe accidents with catastrophic consequences.

The attitude of Governments regarding the prospects of nuclear energy in their individual countries can significantly influence the planning process for innovations in nuclear technology. While the participation of industry brings the necessary rigor and discipline into the process, the involvement of Governments sends the message of confidence in the technology and its future and, thus, fosters the enthusiasm necessary for any innovative visioning process.

An example of visioning and planning process was the launching of the Generation IV International Forum and the development of the Generation IV Technology Roadmap. Overriding objectives and specific goals were agreed upon with Government involvement and a tight schedule was established for the development of the Roadmap. More than one hundred ideas and concepts of novel nuclear systems and their fuel cycles have been evaluated by more than one hundred international experts from about 15 countries, the NEA and the IAEA. They were organised in technology specific working groups to identify those systems that optimally fulfill the goals and criteria defined at the onset of this activity.

For each of the selected nuclear systems, the experts identified technology gaps that affect either the viability of the system or its performance. The Roadmap describes the required R&D necessary to develop each of the systems, including filling the technology gaps, and the approximate time and cost to complete this development. The findings of the Roadmap then defined the basis for the development of detailed system research plans and more specific project plans for individual R&D activities within each system.

Another example of a visioning process towards nuclear innovation is the development of a European strategy for innovative nuclear technologies in the framework of MICANET (Michelangelo Network), a thematic network within the 5th European framework programme. Based largely on the work for the Generation IV Roadmap, in the elaboration of which European specialists from France, the United Kingdom and Switzerland, and from other European countries via EURATOM, were substantially involved, a strategic position paper was developed. It took into account European specific aspects (e.g. the political attitude towards nuclear energy in various European countries, the priorities of the European nuclear industry and the capabilities and competence of the European nuclear R&D community) and formulated recommendations for promising technologies that should be adequately supported by public and industrial funding in the future. The findings of this strategic paper were reflected in the prioritisation of innovative nuclear R&D for selected systems in the 6th and for the definition of so-called integrated projects and technology platforms related to these systems in the 7th European framework programme. Under FP-6, a follow-up strategic study is conducted in the projects SNF-TP (*Sustainable Nuclear Fission*, coordinator CEA) and PATEROS (*Partitioning and Transmutation European Roadmap for Sustainable Nuclear Energy*, coordinator SCK•CEN).

Another example on a national level is Korea’s Nuclear Technical Roadmap (NuTRM) exercise, as shown in Box 5.11, which started in 2003 to identify long-term strategic direction of nuclear R&D in Korea and of which the results are to be reflected in formulating the Medium- and Long-term National Nuclear R&D Programme.

Box 5.11 Nuclear Technical Roadmap (NuTRM) Exercise in Korea

Purpose: to establish the long-term vision direction, strategic development and proceeding system of nuclear R&D activities in Korea.

Mission: to compose a plan for nuclear R&D and technological innovations of the high-value-added strategic products by 2030.

The Korean Nuclear Society took the initiative role of the exercise (2003-2005) under the auspices of the KAERI and the Korea Institute of Science & Technology Evaluation and Planning (KISTEP) with the support of the MOST. A wide range of 221 nuclear and non-nuclear specialists from the government, industry, research institutes and universities participated in the exercise, thereby contributing to secure its credibility and improve its usability.

Five top-level vision committees and their fifteen subcommittees:

- predicted the future needs of nuclear power;
- set up the long-term vision of nuclear R&D and technological innovation;
- clarified the technological path to the innovation and dissemination of concrete strategic products; and
- drew up an effective plan to carry out the capacity goal of strategic technological innovation for realising the vision and the path of strategic products.

From the exercise, 27 strategic technologies were selected.

Source: Country report of Korea.

In the United States, DOE developed a top-down approach called "Strategic Plan" that identifies four strategic goals (one each for defense, energy, science and environmental aspects of its mission), plus seven general goals that support the strategic goals as follows:

DOE Mission→Strategic Goal (25 years)→General Goal (10-15 years)→Programme Goal (10-15 years)

To provide a concrete link between budget, performance and reporting, DOE developed a "GPRA[6] unit" concept. Within DOE, a GPRA unit defines a major activity or group of activities that support the core mission and aligns resources with specific goals.

5.3.5.2 Evaluation and oversight

It is well recognised that evaluation and oversight for innovation programmes is crucial for their success since they involve great uncertainties and risks. Whenever it is clear that the programmes do not satisfy their requirements, they should be stopped or redirected. Clear decision criteria for stopping or redirecting the programmes are often required.

Evaluation and oversight on nuclear innovation programmes takes various forms – periodic or ad-hoc, formal or informal, internal or external, etc. For instance, in the United States, to validate and verify the performance of its programmes, DOE-NE takes various external reviews and audits of the Congress, the General Accountability Office, and many governmental bodies[7] and provides continual management and internal oversight of its research and development programmes.

Often committees, whether standing or ad-hoc, are formed to accommodate the views of various stakeholders on the performance of the programmes. For instance, in the United States, DOE-NE obtains advice on the direction of nuclear energy R&D programmes from the independent Nuclear Energy Research Advisory Committee (NERAC). NERAC's Subcommittee on Evaluations, formed in FY 2004, conducted independent programme evaluations of DOE-NE's programmes such as Generation IV Nuclear Energy Systems Initiative, Nuclear Power 2010 programme, and the advanced fuel cycle initiative.

Some countries are using a specific tool developed for evaluation and oversight. For instance, in the United States, DOE-NE is using Programme Assessment Rating Tool (PART) developed by the OMB to provide a standardised way to assess the effectiveness of the Federal Government's portfolio of programmes.

5.3.6 Nuclear legal framework

5.3.6.1 Health and safety regulation

Most countries enforce separate laws and regulations for ensuring the safety of nuclear installations in their countries, complying with international standards and norms. Generally, construction and operation of new nuclear facilities in a country requires a license issued by its regulator. This nuclear regulatory process adds an additional regulatory level beyond that required of other electricity generation sources.

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[6] Government Performance and Results Act of 1993.

[7] These include DOE's Inspector General, the NRC, the US Environmental Protection Agency, state environmental and health agencies, the Defense Nuclear Facilities Safety Board, and the DOE's Office of Engineering and Construction Management.

In this context, the implementation of new technologies requires regulatory approval such as design certification, which often takes a long time and has large demands for data to ensure the safety. For instance, in the United States, NRC conducts exhaustive reviews of all applications of new technology in the nuclear industry. This detailed review and accompanying rulemaking proceeding takes a long time: the ABWR and System 80+ design certifications each took eight years to complete; the AP600 certification took four years. Shorter processes are hoped for in the case of AP1000 and ESBWR, given their heavy reliance on prior NRC approval of comparable features, testing and analysis, and related engineering in their predecessor designs. Certifications of designs built to non-US regulations, codes and standards will take longer to review, as will certifications of non-LWR designs for which less basis exists in US regulation.

5.3.6.2 Nuclear export control

International nuclear transfers, which can take place in diverse ways, are subject to international nuclear export control regimes. In addition, each country applies nuclear export controls within its general legal framework, focusing on the following objectives: [28]

- to ensure that transfers of nuclear material, equipment and technology take place in a secure, safe and environmentally responsible manner;
- to ensure that such transfers do not directly or indirectly assist any non-nuclear-weapon country or any unauthorised person in developing or acquiring nuclear explosive devices or using nuclear material for unauthorised purposes; and
- to provide for the fulfilment of its legal obligations under international instruments such as the Nuclear Non-Proliferation Treaty (NPT), the international nuclear export regimes (Zangger Committee, Nuclear Suppliers Group), Convention on Physical Protection of Nuclear Materials, regional non-proliferation treaties, and bilateral agreements for nuclear co-operation with other countries.

Responsible nuclear supplier countries will insist on acceptable assurances that their nuclear exports will not be diverted to non-peaceful or unsafe activities. Recipient countries that do not fully comply with and respect all relevant international treaties and all aspects of the non-proliferation regime cannot expect to receive the fullest measure of nuclear trade and co-operation and get access to innovative products.

5.4 Key factors for nuclear innovation performance

5.4.1 Overview of case studies

As explained in Chapter 2, this study identifies key factors and issues for nuclear innovation performance from the country reports and the case studies drawn from the participating countries. Table 5.5 shows the overview of case studies, describing promoters (who initiated or funded the innovation), R&D performers (who actually perform the innovation activities), potential customers (who would benefit from the innovation), results and key factors for their success or failure.

Table 5.5 Summary of case studies

#	Target system	Major actors			Result (Current status)	Key factors
		R&D performer	Promoter	Potential customer		
1	MOX Fuel	Group mixte BN-SCK•CEN	Euratom, Gov.	Utilities	Belgonucléaire produced more than 600 tHM MOX fuel for use in 23 LWR's in several countries, assisting MOX factories in other countries	• International co-operation • Partnership between research institute and vendor • Technical competence
2	MYRRHA	SCK•CEN, Euratom, GEN-IV	SCK•CEN, Euratom	SCK•CEN, utility groupings	Has been selected as the reference concept for the EUROTRANS	International research co-operation challenging scientific research & engineering development
3	ACR	AECL	AECL	Utilities	Conceptual design completed	• R&D competence (manpower, infrastructure, culture) • Government's commitment • Driven by market demand
4	SES-10	AECL	Gov.	Heat suppliers	• A demonstration reactor starting operation in '87 • No sales, programme cancelled	Failure to meet prevailing market requirements
5	HWGCR NPP	Vendors (USSR, Czech)	Gov.	Utility	1st unit commissioned in '72, shutdown in '79 due to an operator-induced accident	Availability of other competent technologies
6	VVER-1000 NPP	Vendors	Utility, Gov.	Utility	• 2 units in operation after 15 years of construction • 2 units stopped during construction	• Politically determined decisions • Chernobyl RBMK accident • Revolutionary changes of political and economic environment • Concerns of neighbouring countries, including their anti-nuclear groups
7	APS	VTT	Utility, RIs	Process industry	Multiple applications in process industry	High interest towards IT-development in Finland
8	NURES	Fortum nuclear services	Utility	Utilities	Several products	High level knowledge in utility and academia
9	FBR Phenix	CEA	Gov.	EDF	• In operation since '73 • Life extension in '03 • 52nd cycle performed in '05 with 80% availability factor	• No political doubt about its useful purpose • Dedicated research
	Super-Phenix	CEA	Gov.	EDF	• First criticality in '85 • Decree of final shutdown in '98	• Decreased usefulness of recycling • Economics and bad operating conditions
10	EPR	AREVA NP	EDF	EDF, Foreign utilities	• Detailed design finalised in '99 • 1 unit under construction in Finland and 1 unit in plan in France	• Maturity of basic product (PWR) • Search for an industrial product adapted to the market of several countries • A revival of the nuclear market
11	MOX Fuel	Cogema	Gov.	EDF, Foreign utilities	EDF loads MOX fuel in 20 units of its PWRs	• Publicly accepted usefulness of fuel reprocessing • Political will • R&D competence
12	ATR	PNC, DPDC	Gov.	Utilities	• Prototype FUGEN in operation for 24 years since '79 • Demonstration reactor project cancelled in '95	• Competence of domestic technology • PP/P (Government initiative) • Based on results of R&D facility • Economics less than LWRs • Politically determined decision

Table 5.5 Summary of case studies (cont'd)

#	Target system	Major actors			Result (Current status)	Key factors
		R&D performer	Promoter	Potential customer		
13	LWR	Utilities, vendor	Utilities, Gov.	Utilities	• Capacity factor improvement (→70%→75%→80~90%) • Construction cost 10% down-ABWR in operation in '96	• Demand of utilities • Improvement of existing LWRs by domestic technology • PP/P(Utilities initiative) • Based on operation experience • Step by step approach • Economics better than ATR
14	KSNP	KAERI, vendors, utility	Utility	Utility	6 units of KSNP in operation, 2 units under construction	• Government commitment • Technology learning strategy • Partnerships among research institute, vendors and utility
15	CANFLEX	KAERI	Gov.	Utility	• Prototype tested in CANDU in '03 • No commercialisation yet	• Technical competence • Demand from utility
16	DON	JEN	JEN	Utilities, research institutes	• Encountered unexpected technical problems • Abandoned in '68	• Availability of other competent technologies • Unresolved technical problems
17	Mobile robotic devices	Utilities, vendors, CIEMAT	OCIDE, vendors, utilities	Utilities	• Prototypes developed, one installed for testing • End without industrialisation	• No participation of vendors from the beginning • Too long lead time • Alternative product in the market
18	SHR	PSI	Vendors group	Heat suppliers	• Conceptual design and preliminary safety report in '86 • Definite suspension in '90	• Not competitive with other alternatives • Chernobyl accident • Lack of focus on one project
19	Higher burn-up fuel	PSI, WH, Studvik,…	Utility (KKL)	Utility (KKL)	Being used in the NPP	• Evolutionary strategy • Climate of trust among stakeholders
20	CRBR	National Lab	Gov., vendors	Utilities	Project cancelled during demonstration	• Lack of clear decision criteria of stopping or redirecting • Lack of oversight process • Politically driven decisions
21	ALWR/ NP2010	Vendors consortium	DOE	Utilities		• Relevant sound techniques • Adequate funding • Sound project management • Independent periodic reviews • Broad public and industry consensus
22	EFR	ERDO, EFR Associates	Euratom	EFRUG	Question/answer sheets and objective/programme sheets	To structure collaboration between RTD and engineering teams
23	PIRT	FP5 project EURSAFE	Euratom	Research community	100 key safety relevant phenomena were selected out of 1 000	To structure a complex research area

5.4.2 Assessment of the cases based on the elements for innovation performance

As mentioned in Section 2.3, twenty-three cases are assessed based on the ten criteria to determine innovation performance, which were described in Section 2.3.1.

A. Demands

Most demand-driven projects were successful. Clear requirements of PWR advancements from system suppliers and utilities were a key factor of success; for instance, the EPR development

(Case #10), the Japanese LWR improvement and standardisation (Case #13) and the US ALWR programme (Case #21). The localisation demand for PWR design and construction is on the same track; for instance, the Korean Standard Nuclear Power Plant programme (Case #14) and the deployment of VVER-1000 plants (Case #6).

While there may be a market for the innovative item, promoters or potential customers may have no interest to it since they have little knowledge or confidence in it. Their involvement from the early stage of innovation could have enhanced their interest.

- The Spanish Mobile Robotic Devices (Case #17): The problems for the commercialisation of the prototypes came from the fact that the supply of robots for nuclear installations or the provision of services with robots was not in the main business lines of the industrial partners. So the market part of the project was not properly taken care of. An attempt was made at the end of the project by including Tecnatom, which did have at least the business line of services with robots. Nevertheless, as Tecnatom had not participated in the specification of the developments, the products did not fit well with their activity, so there was no real interest to use them.

There were cases where there was no market for the innovative item. The project might start with market demand analyses based on certain assumptions that were reasonable at the time. However, the initial demand projection might be wrong or uncertainties might be too great to allow a good prediction of the likely market. In addition, there might be great changes in the market environment, such as Chernobyl accident, during the innovation process, rendering the demand analyses invalid.

- The Canadian Slowpoke Energy System (Case #4): There was a series of extensive market analyse to define both market and user requirements. From a technical point-of-view, a logical and rational case could be made for replacing fossil-fuelled boilers by nuclear heat sources. Although achieving public acceptance was acknowledged as a fundamental requirement, it turned out that political and public perceptions could not be successfully addressed. The reality was that the market would not accept such an innovative concept as nuclear heating reactors.
- The Swiss heating reactor (Case #18): Considering that district heating networks supplied with heat from NPPs were discussed at the time of the SHR project, initiated by local (communal and cantonal) authorities, one can assume that the general attitude regarding nuclear district heating was – if not positive – at least open. However, after a while, the collapse of oil prices made district heating (with its heavy investment for the transport and distribution grid) much less attractive.

There may be a market for the innovative item, but its competitiveness may be not secured. Other alternative technologies can be more competitive.

- The Japan’s ATR programme (Case #12): Since the initiation in the 1960s, there was a drastic demand change during its development. In the 1990s, the economic situation in Japan shifted to low growth periods, and the number of new nuclear reactors being built decreased due to the influence of troubles and accident such as Chernobyl. Due to electricity market deregulation utilities became hesitant make commitments to a long series of investment. As a result, they demanded more economy or more reliability for nuclear reactors. As plutonium utilisation in LWRs became more attractive, the role of ATR was viewed less fabourably.

In some cases, governments created demand through policy changes including government procurement when there is great potential but with no existing market.

- The MOX fuel development in Belgium (Case #1): Plutonium from the reprocessing of spent fuel is recognised to be best used in fast breeder reactors; however, in the late fifties, the reprocessing capacity was expected to exceed the FBR needs and development work was oriented to the use of plutonium as mixed uranium-plutonium oxide fuel for light water reactors.
- The Swiss heating reactor (Case #18): Although public procurement for innovative products was not established at that time, the Federal Government was supporting nuclear technology as one of the cornerstones of the domestic energy supply and explicitly encouraged its use beyond the traditional power generation. This message was taken over by local authorities, which fostered the aforementioned projects for nuclear district heating. Further, the Federal Government has invested (limited) public funds in the development of the three heating reactors.

B. Human resources

In most cases, competent qualified human resources were available. Usually a dedicated team of scientists and engineers, both in-house experts and external advisors, was established; for instance, the Canadian ACR (Case #3) and Slowpoke Energy System (Case #4).

However, there were also some cases lacking experience in conducting large projects such as designing and building a nuclear plant and knowledge of associated requirements; for instance, the Swiss heating reactor (Case #18).

One way of overcoming the lack of human resources is to establish joint working groups, both nationally and internationally.

- The MOX development in Belgium (Case #1): A joint working group from industry and research, the so-called Group Mixte Belgonucléaire-SCK•CEN started the plutonium laboratories inside the SCK•CEN premises at Mol.

In small countries, dispersion of human resources among competing alternatives is not desirable, since nuclear innovation usually requires a critical mass of human resources. The Swiss SHR case (Case #18) illustrates this.

C. Finance

Most cases had adequate funds, although the funding sources are diverse – government, organisation itself, industry and their combination. In most cases, the role of government as a direct funder (Cases #1, 4, 5, 9, 12, 20) or as a coordinator of various industry fund sources (Cases #10, 11, 13, 14) was crucial.

However, too much dependence on the government fund, especially in the demonstration stage of big projects, worked as a barrier to success.

- The US Clinch River breeder reactor (Case #20): The federal government should not be the primary source of funding for energy technology commercialisation demonstration projects. Funding should be dominated by the potential industrial beneficiaries of the demonstrated technology. Massive federal funding of mega-projects galvanises legislative, bureaucratic, and regional champions of the projects to a level beyond the point of productivity or economic justification and invites federal interference in project management.

As promoters of the project with clear requirements, utilities played an important role in funding (Cases #6, 10, 13, 14, 17, 19). System suppliers also provided funds in some cases (Case #17, 18, 20). However, sometimes the funding from industry was limited.

- The Swiss heating reactor (Case #18): Although in the mid-80s globalisation was already emerging, the financial constraints coupled with international competition were still not so strong and the domestic industry was quite healthy financially. Nevertheless, only limited funds were invested by the industry in the development of the SHR. Moreover, this project was regarded by the industry and the A&E companies as an opportunity to receive public funding for their in-house R&D.

Often the cost of a project escalates over what was estimated at the beginning. Whatever is the cause of the escalation, it contributes to the decision to stop the project.

- The US Clinch River breeder reactor (Case #20): Escalation of the CRBR costs led to even more controversy because by the end of the 1970s an additional $1.7 billion was estimated to be required for the CRBR to achieve commercialisation. The Senate killed the project in 1983 after $1.6 billion had been spent, with an estimated cost to completion of at least another $2.5 billion.

D. Physical inputs

No case was reported to have difficulty in acquiring physical inputs, which, however, does not mean this is not an important factor. Some physical inputs needed for nuclear R&D such as nuclear materials and sensitive nuclear equipment are under export control, which sometimes makes international transfers of those items difficult or impossible. Compliance with the international non-proliferation regime is prerequisite for acquiring those kinds of physical inputs.

- The MOX development in Belgium (Case #1): A batch of 250 grams of weapon-grade plutonium was purchased in the United Kingdom and delivered in 1959. However, the international non-proliferation regime had not been rigorously established at that time there.

E. Access to science, technology and business best practice

In many cases required knowledge was self-sufficient in the organisation or in the country, which implies relatively free and easy access to existing knowledge.

- The ACR design project (Case #3): The project has priority access to AECL's scientific and technical expertise and to its R&D facilities. Also, as and when required, access to off-shore irradiation facilities for activities such as material test irradiations is organised and is facilitated by existing co-operation arrangements. In fact, the availability of in-house R&D capability and scientific expertise is an essential factor to ensuring successful innovative approaches to ACR design challenges.

In some cases where the knowledge was not self-sufficient, it was accessed from outside the country through close international co-operation.

- The Swiss heating reactor (Case #18): Nuclear technology was considered as confidential in the times of the SHR project; nevertheless, the Swiss participation in the construction of the

Swiss NPPs had resulted in good bilateral contacts and collaboration and opened the doors to the technological knowledge of the big nuclear suppliers. In particular, extensive exchange of information has taken place with the German nuclear industry (Siemens), even on sensitive issues, such as nuclear fuel design.

- The MOX development in Belgium (Case #1): The early MOX development was conducted in a co-operative research and development agreement between Euratom and the US Atomic Energy Commission, more particularly with the Hanford National Laboratory "plutonium utilisation programme" and the Westinghouse "Saxton" programme.

F. Ability and propensity to innovate

In many success cases, the development was based on relevant and sound technologies accumulated from the previous experiences in the organisation or in the country, especially in evolutionary approaches.

- The EPR (Case #10): The EPR is a PWR resulting from the most recent models: the French N4 type reactor of the power plants of Chooz and Civaux and the Konvoi, the most recent plants built in Germany. It profits from the experience feedback of more than 30 years of operation of nuclear power plants.
- The Japanese LWR improvement and standardisation (Case #13): Electric utilities and nuclear industrial companies have accumulated knowledge and experience through construction and operation of LWRs. Already in the 1970s, most LWRs in Japan were constructed by domestic technology.

Regarding unsolved technical problems, when the project is initiated, there should be some ideas and expectations on how to solve the technical problems expected. However, the planned solutions may not work or the project can face unexpected technical problems. The Swiss heating reactor (Case #18) and the Spanish DON project (Case #16) are examples of this case.

Regarding efficiency issues, a technical break-through with too high cost (for instance, due to unnecessary requirements) may be meaningless. Especially, cost escalation of the project during the process, as in the US Clinch River breeder reactor (Case #20), undermines greatly the viability of the project and leads to the interruption of the project.

To address lead-time issues, the innovative item should be delivered in time. Otherwise, it can degrade the credibility of the project and lose competitiveness to alternative technologies. For instance, the Spanish Mobile Robotic Devices (Case #17) took so long that alternative products already prevailed in the market when it was developed.

Sound project management capability is also crucial, including visioning and planning, budgeting, implementation oversight and performance evaluation. Before a project begins, the proposing industrial team must produce realistic cost, performance and schedule estimates, including commitment to its portion of the cost of the project. These estimates must be reviewed by an independent and knowledgeable team before project approval. The US Clinch River breeder reactor (Case #20) is an example of lack of adequate oversight process.

When the management structure does not fit the innovation project, it should be fixed and redirected.

- The Swiss heating reactor (Case #18): EIR as the leader of the SHR activities has not extensive experience in using external resources to generate innovative products. R&D was moreover oriented towards generation of basic knowledge necessary for the development of domestic competence for the operation of the Swiss NPPs and little was done regarding in-house innovation. Prior to SHR, future-oriented R&D was generally performed through participation in larger foreign projects. Although a first restructuring of the EIR had already taken place before the start of the SHR project and a matrix structure had been introduced to follow the general trend at that time, no profound change in the ways of thinking could be observed and most researchers were still focused on their narrow disciplines and "traditional" objectives. Also, rather inflexible structures were predominant within the industrial partners and led later to considerable re-dimensioning measures.

G. Institutions and infrastructure

Since the 1950s, most advanced countries established their national nuclear research institutes, which later played a major role of R&D performer in the nuclear innovations in the Case Studies. SCK•CEN in Belgium (Case #1), AECL in Canada (Cases #3, 4), CEA in France (Case #9), PNC (now JAEA) in Japan (Case #12), KAERI in Korea (#14, 15), PSI in Switzerland (Case #18), and NRI Rez in Czech Republic illustrate this kind of PRIs.

Maturity of nuclear industry in a country such as in France (Case #10) and in Japan (Case #13) is also a key factor for the success of the innovation.

In some cases, international organisations such as EURATOM, IAEA, and OECD/NEA provided support for the innovation project.

- The MOX development in Belgium (Case #1): Feedback from operating reactors as well as information exchange facilitated by international organisations such as IAEA and OECD/NEA are important for continuous improvement.
- The ACR design project (Case #3): Key networks for transmission of information on market needs and innovative design approaches are feedback from operation of current generation reactors as well as information exchange facilitated by existing international organisations such as IAEA and OECD/NEA.
- The MYRRHA project (Case #2): The MYRRHA reactor design serves as reference design for the experimental transmuter in the Euratom IPEUROTRANS project.

H. Networks, collaboration and clusters

Most success cases showed strong partnerships among the government, research institutes and industry. Participation of system suppliers was critical. The Swiss high burn-up fuel project (Case #19), the MOX fuel in Belgium (Case #1), the Japanese LWR improvement and standardisation (Case #13), the US ALWR programme (Case #21), and the Korean Standard Nuclear Power Plant programme (Case #14) are examples of good partnerships among the different actors. On the other hand, the development of mobile robotic devices in Spain (Case #17) is an example of exclusion of final industrial manufacturers from the research group.

Many existing national and international networks were also utilised to complement the innovation competency. Also, in some cases, new networks were established for the project.

- The Swiss heating reactor (Case #18): Networking around innovative nuclear projects has taken place in Switzerland already in the 1970s with the creation of the "Interessengemeinschaft für Nukleare Technologien – IGNT" (Interest Group for Nuclear Technologies) pooling essentially the partners who later participated in the SHR project. Existing networking and clustering was then strengthened for the development of the heating reactors and, in particular, of the SHR.

- The MYRRHA project (Case #2): The MYRRHA design is embedded in the EUROTRANS project incorporating the 29 most relevant European scientific and industrial actors in the field as well as 17 universities.
- The Canadian Slowpoke Energy System (Case #4): Networks and collaborations were established particularly for the purpose of assessing markets and defining user requirements.

I. Effectiveness of market processes

The market for new NPPs is conservative and may be characterised as risk averse. While this does not encourage market penetration by novel designs, it does underscore the need for innovative approaches of an evolutionary nature. In this sense, innovation may be viewed as a means to an end, which is safe, reliable and cost-efficient electricity, rather than to obtain the most innovative technology. The ACR design development (Case #3), EPR development (Case #10), the Japanese LWR improvement and standardisation (Case #13) and the US ALWR programme (Case #21) illustrate this.

To a large extent, the domestic and international market drives innovation in nuclear power plant design. Innovative approaches are increasingly necessary to meet demanding and challenging user requirements that are being set by the market, especially in terms of economics, safety, reliability, and public and political support. Key international vendors are thus being driven to compete with a key measure of success being determined by the firm's aggressiveness to successfully achieve innovative approaches to respond to user/market demands. For instance, for the ACR design development programme (Case #3), international market processes and competition were key motivators of innovation.

However, competition often hinders the concentration of resources at a national level, which is quite crucial for small countries.

- The Swiss heating reactor (Case #18): Swiss industrial companies have quite early shared the market among themselves in such a way that domestic competition was not the predominant issue. In the case of heating reactors, the different industrial partners even joined their efforts. However, competition was present in the form of the three projects pursued in parallel (SHR, GHR and GEYSER) – an efficient innovation motor on the one hand but also a heavy burden for a small country with limited resources.

Some cases encountered resistance from the market, which makes the market entrance very difficult.

- The Canadian Slowpoke Energy System (Case #4): Market processes were not effective in overcoming market resistance. Although different firms were undertaking programmes, at the time, to design and market district heating reactors, competition amongst these firms was not sufficient to sustain programmes.

As the innovation process goes on, often major RDD&D players change according to the stage of the innovation. The smooth transition between the stages is crucial, including technology and personnel transfers.

- Japan's ATR programme (Case #12): The project was advanced by JAERI and agreed by PNC. The result of the research of ATR in JAERI was passed to PNC, and PNC executed the development using PNC's test facilities etc. As for the demonstration reactor, PNC agreed to collaborate with EPDC on the demonstration reactors. The results of the R&D and the operation experience of FUGEN were reflected in a basic design of the demonstration reactor.

J. Business environment

As already mentioned in Section 5.1.4, the social and political environment plays a key role in nuclear innovation. Despite innovation potential and good market chances, developments have been stopped because of social and political pressure. This was the case of the VVER-1000 project in the Czech Republic (Case #6), an example of combination of international political and social influence (international anti-nuclear opposition on the one side, international expert assistance on the other side), national political and social influence (revolutionary changes in the state politics and economy) that caused reduction of the planned number of Temelín NPP units, construction delay and increase of the budget. On the other hand, the seemingly negative effects brought positive results in the end – a technologically updated NPP with a high safety standard as a result of combination of western and eastern technologies. Also, innovative projects in pre-competitive phase have been abandoned because of political pressure as was the case of Superphenix NPP in France (Case #9).

On the other hand, the Canadian advanced CANDU reactor development (Case #3) and the KSNP Programme in Korea (Case #14) are good examples of the result of decision makers' commitment.

Economic and market conditions provide a context for the innovation. Their change greatly affected the progress of the innovations.

- The MOX development in Belgium (Case #1): The general business environment in Belgium was favourable. The present day decisions on non-reprocessing and nuclear phase out are unfavourable for nuclear business development.
- The Japanese LWR improvement and standardisation (Case #13): Due to the oil crisis in 1973, the movement to escape from oil dependency for energy supply became active, and nuclear energy was defined as one of the important candidates for supply energy in Japan. Since 1970s till beginning of 1990s, the construction of LWRs continued constantly; therefore, industrial companies could keep sufficient numbers of engineers. Also, the results of development and improvement could feed-back immediately into existing LWRs and those under construction and in planning.

6. CONCLUSIONS AND RECOMMENDATIONS

Nuclear technology has considerable potential for innovations, which is needed first with regard to existing nuclear power plants to satisfy:

- constant demands to maintain and strengthen the safety of nuclear installations;
- power uprates and higher thermal efficiency, which imply more stress on materials and components; and
- optimisation of costs, both of operation and fuel cycle.

This potential is particularly important given the upcoming challenges regarding:

- closure of the nuclear fuel cycle; and
- penetration of the heat market with nuclear systems of the fourth generation.

Innovation has characterised also the whole nuclear technology development in the past driven by many actors. Continuous feedback of successful operation and lessons learned from abnormal events have been significant sources of inspiration for innovative technological approaches and solutions throughout the history of nuclear technology. Technological improvements and innovative management approaches have led to considerable increase of the availability and reliability of nuclear power plants, to a reduction of the occupational exposure as well as of the probability of severe accidents. The nuclear energy sector was one of the first to introduce on a broad scale the probabilistic safety approach. Major innovations in more recent years were the gradual introduction of passive safety systems and of digital control rooms. Innovative approaches were also followed for continuous improvements of structural materials and fuels and for monitoring and non-destructive testing of the material condition.

However, innovative approaches in nuclear technology have not always been successful. Some of the reasons for less successful developments are similar to those in other technology sectors: lack of competitiveness to alternatives already in the market, lack of focus on one project, failure to respond to prevailing market requirements, no industry participation from an early stage, lack of clear decision criteria of stopping or redirecting the R&D, lack of an oversight process for the use of public funding, radical changes of the political and economic environment, lack of transferability of results from a R&D facility to industrial scale. Other causes are specific to nuclear energy like the effects of nuclear accidents (reduction of competitiveness due to excessive requirements for safety features, politically driven decisions), too long lead times, concerns of neighboring countries, etc.

From the analysis in this study, a series of recommendations can be drawn for decision makers willing to exploit in the future the innovation potential of nuclear energy technology.

Policy aspect

Decision makers should recognise the importance of energy issues and take a position regarding the use of nuclear energy in their countries' energy mix. They should promote and facilitate a holistic approach to nuclear innovation systems that includes innovative approaches to nuclear safety regulation, the development and maintenance of required infrastructures and international nuclear relations and co-operation. They should inform the public on nuclear energy in a balanced way and create a stable legal environment where the high investments that are needed can be risk-managed. This implies the need for long term energy policies, with an adequate framework of national policies and international principles and rules.

Governments that are interested in ensuring that nuclear power has an ongoing and enhanced role in their energy supply mix should provide policy and funding support for the development of innovative nuclear energy systems. In particular, Governments need to trigger innovation when it is uncertain who (public research organisations, vendors or utilities) will take the initiative or when nobody seems prepared to grasp apparent market opportunities. The Generation IV International Forum is an example of the role that Governments have taken to initiate, promote and facilitate international R&D collaboration on next generation nuclear energy systems. This effort needs to be sustained.

Governments should share efforts with the international community to advance the research of new alternatives for nuclear based energy production, with better performance than the current designs. Thus, innovation can drive policies if new designs solving the current problems come to light.

Research related to nuclear power plants is not a specific area, but has to do with other research disciplines, such as fossil power plants and aerospace industry. Governments should create incentives to increase communication among technological sectors and to encourage international and interdisciplinary contacts and collaboration among those involved in the development of innovative systems and components, in order to trigger additional ideas and mutual enrichment.

Visioning and planning

Innovation needs initiation. Who will take the initiative is like the chicken and egg problem. Utilities would not invest in heavy research equipment that may not be profitable. Also, system suppliers would not invest in the development of systems for which the demand is not known. R&D performers cannot afford the development of new systems by themselves. They suggest advanced ideas, but are not in a position to implement them on an industrial scale. In some countries (e.g. France, Finland, United States), governments have taken proactive actions to trigger and support innovative R&D for future nuclear energy use. Some triggering effort from governments in support to the development of nuclear innovative product development, in co-operation with vendors, should be considered within national energy policy measures.

Although innovative ideas come typically bottom-up, their realisation needs strong leadership and direction in a top-down approach, especially in a controversial environment. For current nuclear systems this leadership should come primarily from the industry. For long-term developments, direction should come from public institutions, at least during the pre-competitive phase. For near-term developments coordinated leadership from industry and Governments seems more appropriate and adequate forms of such a combined guidance should be identified and pursued.

In all nuclear R&D programmes, especially in the long-lasting ones, success criteria and adequate milestones should be defined in an early phase, ideally before launching such programmes. Independent periodic review of the achievements should be mandatory.

In such approaches, the roles of promoters and R&D performers should be clearly defined from the very beginning: the role of promoters is to define objectives, success criteria and milestones, to provide the funding agreed upon and to perform an independent periodic review following a pre-defined schedule. The role of performers is to follow the planning agreed upon with the promoters and to report timely and openly about necessary modifications and/or delays. Obtaining a "critical mass" within each of these parties through adequate collaboration schemes should be an objective associated with the particular type of research related to nuclear energy (long-term and resource intensive).

R&D strategy

Governments, regulators and industry need to ensure that policies and programmes are in-place for short, medium and long term nuclear R&D. International organisations could serve as a platform for the coordination of national policies and programmes. The strategy of research organisations and their funders for implementing structures dedicated to R&D towards innovative nuclear designs, systems and components should be based on a step-by-step approach including mid-term solutions as well as long-term products. It is not sufficient to focus on promising long-term solutions only, without providing any intermediate results in between, as this may discourage promoters and funders.

It is wise to start with exploring a large scope of different technological paths to help ensure that optimal solutions do not remain unidentified. However, the strategy should include a down-selection process at a time point defined a priori and not too far in the future. This allows focusing on the most promising pathways and making best use of the available R&D resources.

A market evaluation for the foreseen products should take place at an early stage of the short and medium term R&D projects, and efforts should be focused on products with clear market horizons. Such market analyses should be updated periodically.

The strategy should also include appropriate measures at strengthening the co-operation with non-nuclear R&D sectors. This creates opportunities for non-nuclear spin-offs of nuclear R&D while, at the same time, providing access to novel technological possibilities developed in other sectors (e.g., materials, process and information technologies).

Funding and implementation instruments

R&D on innovative solutions requires – at least partially and in particular during its starting phase – considerable public funding. The preparedness of Governments to allocate such funding should increase if progress and success controls (oversights) similar to the ones implemented for industrial R&D are in place. Governments should also couple the allocation of funding with the request for the implementation of adequate oversight mechanisms. Public funding should evolve towards substitution by industrial funding going through public and private partnerships (PP/P).

However, contrary to normal industrial practice with its short-term perspectives and expectations for rapid return of investment, funding of innovation oriented R&D should be as stable as possible in a long-term perspective. It should not be revised as long as the milestones agreed upon at the beginning and the promised intermediate deliverables are fulfilled. Governments and private funders should, therefore, enter into long-term funding commitments. Nevertheless, strict controls should be established to ensure that partial goals are fulfilled and that modifications of the objectives can be made. The French 15-year programme on waste management is a good example of long-term governmental and industrial commitment for research.

Infrastructure

NEA member countries are facing possible demographic downturns in their nuclear industries. In spite of many initiatives in the area of nuclear education and training, they still require more engineers and scientists with nuclear knowledge than are actually graduating. This is of concern to the nuclear industry as already the majority of the scientists and engineers working in it do not have a specialised nuclear education. These concerns would become more prominent in case of a large-scale deployment of non-electrical applications of nuclear energy. On the other hand, it seems likely that advances in technology development could increasingly attract talented young people.

An indispensable pre-condition for the deployment of future innovative solutions, in particular in a sector such as nuclear technology with its long development and implementation times, is, therefore, the preservation of specific knowledge accumulated so far and the transfer of relevant information to the next generation of specialists.

Instrumental to this objective is the availability and mobility of specialised people (scientists, engineers, and skilled technicians). This implies a mutual recognition of education, training and R&D activities of different institutions in different countries. To achieve this, a globally accepted common qualification system is desirable, as well as an agreed-upon mode for sharing of results generated by "moving" specialists and for licenses and corresponding conditions (see also below suggestions for partnerships and collaborations). R&D policy and decision makers should establish this harmonised framework with priority.

The exchange of expertise and available knowledge, as well as the sharing of R&D infrastructure, can be significantly enhanced if systematic and up-to-date information about existing facilities, ongoing R&D activities and knowledge-holders is easily available. Databases of available facilities with corresponding capacities, of ongoing R&D programmes with main milestones and deliverables, and an "address book" of experts with their specialisation are appropriate tools for this purpose. In this regard, the recent effort of the OECD/NEA on the establishment of a database on nuclear research and safety facilities is timely. Since this kind of effort demands the enthusiasm of the researchers to feed these databases, they should be, therefore, persuaded that this additional effort is for their own benefit as it strengthens their work and facilities by opening opportunities for an optimised and broader use. Research institutions should be encouraged to put this issue on their agendas and to use all existing collaboration structures to establish and maintain such databases.

Nuclear research requires specialised resources, both human and infrastructural. Concrete national strategies should be established for knowledge development and preservation and for building and maintaining the necessary infrastructures.

International projects for building and offering access to new infrastructures should be promoted. Sharing investment and operation costs should take place based on specific utilisation conditions. The

Halden reactor, the nuclear R&D infrastructure technology platform proposed in the 6th EU framework programme and the French initiative for the Jules Horowitz reactor are examples of this kind of collaboration.

Partnerships and clusters

Innovation and innovative R&D needs broad support involving all stakeholders – i.e. researchers, developers and potential users – to be successful. PP/Ps between state-owned (or controlled) research institutions and industry offer excellent opportunities to link the inventive spirit of researchers with the relevant issues to be resolved.

Industry involvement, however, is generally coupled to commercial opportunities and constraints. The political leaders responsible for R&D activities should facilitate the contacts between research institutions and industrial partners, for example, by establishing and maintaining adequate public structures dedicated to the initiation and promotion of innovation. Such institutions should be open to all technologies and not exclude a priori certain options based on political considerations. They should encourage researchers to approach industrials and reduce the risk of the latter by providing seed funding during the first and most uncertain phases of innovative R&D activities.

Such institutions should include in their duties the "education" of potential customers towards innovation by demonstrating to them possible long-term direct (i.e. economical) and indirect (e.g. preservation of national competence) benefits resulting from investments in innovative endeavors with no direct short-term return. For this purpose, it is necessary to include all actors from the outset of such activities to ensure a steady flow of mutual information and a dynamic adaptation of R&D to actual needs while maintaining the necessary level of research freedom and flexibility.

These institutions can also function as "Committees of Promoters", where industrial partners meet periodically to discuss their needs and priorities as well as their positive and negative experiences from their involvement in innovative R&D activities, and where research institutions are invited to report about their efforts, successes and failures and to establish new promising co-operative projects.

For each research initiative, the roles and responsibilities of all parties involved should be clear from the beginning. In the short and medium term, end-users of the technology should specify what their needs are and researchers and vendors (industry) should strive to develop adequate solutions for these needs. Thus, one of the roles of the end users is to trigger the research process, but it is the responsibility of industry and research centers to develop it. Developments for medium and long term applications should be led by Governments, in order to advance the research of new alternatives.

Regulators and utilities can trigger research through specific financing models. Industry should not look at R&D only as another way to obtain additional resources independently of the results obtained, but it should assign its own funds to R&D so that their products and services can evolve, and reach a better market position in their area of activity.

Each sector promoting nuclear R&D should work in a coordinated way. Research centres should specialise in specific areas (as many as their resources allow) and the constitution of clusters both at a national and international level should be encouraged. "Promoters" and industry should encourage this specialisation by using specific research centers for specific areas.

Education and training

R&D directed towards innovative solutions for current and upcoming problems is an excellent means to attract young specialists. Such research demonstrates, on the one hand, the belief of Governments and industry in the potential of a certain technology (here the nuclear technology) and, thus, helps to provide the perspective that young people need to decide to embark on a nuclear career. On the other hand, innovative R&D "naturally" responds to the need of young people to address future issues, relevant to them and to coming generations rather than to deal with the resolution of problems from the past.

Parallel to providing opportunities for enabling or encouraging innovative R&D, Governments need to ensure that policies and programmes are in place to support and encourage scientific and technical education and training to help provide the necessary personnel resources to implement nuclear innovation systems. Industry and utilities, on their side, should use the opportunity to fund or co-fund nuclear-specific education at all levels (technical and scientific) for their own benefit.

Safety regulation

Nuclear regulatory bodies have an essential part to play in the context of innovative nuclear technologies. They must, first, be prepared to examine, assess and eventually approve the implementation of such technological solutions. This implies that they are timely involved in innovative development activities to get familiarised with the novel products and to establish the necessary methods and tools for the assessment of the new technology systems. Such preparedness allows avoiding unnecessary delays in licensing that can discourage a potential future user of such systems.

With reactor designs significantly different from current ones, such as those being pursued by the Generation IV International Forum, regulators may face lack of familiarity. As any of the six concepts and fuel cycles being pursued would represent first-of-a-kind technology for many of the parties involved, it is likely that the review times and the need for information, tests and experimental facilities would be significantly greater than for current designs. This could present a significant challenge to the commercial deployment of innovative technologies [29].

To reduce this, significant governmental support likely will be required to overcome regulatory unfamiliarity. It may require that the government build and operate a prototype reactor for a period of time sufficient to inform and educate the regulator and the regulatory process before commercial firms are confident enough to invest in them. This governmental support should ensure adequate time and resources, including education and training of regulators and modifying regulatory processes, to create the environment and conditions where regulatory oversight will not be a barrier to the introduction of these new technologies.

Another barrier to innovation is caused by the differing national quality assurance and technical safety standards used by the world's reactor vendors. This can hinder innovative designs developed in one country from being available in another country.

Harmonisation of national regulations can enlarge the international market for innovative products and, thus, increase the attractiveness of a proposed innovative R&D activity for potential promoters or enlarge the circle of institutions interested in international collaboration. This is particularly important for new nuclear applications in new energy sectors, such as process heat, desalination and hydrogen production, with new regulatory challenges due to the close proximity of conventional and nuclear industrial installations.

The regulatory process itself has potential for innovations to keep pace with technological developments and new schemes of planning, construction and operation management of nuclear plants. Standardised procedures for life extension and power upratings are currently applied; risk-informed and risk-based regulation approaches are discussed; and new licensing schemes (e.g. COL) are foreseen for new reactor construction in some countries.

Finally, as innovative R&D in the current environment most likely will necessitate efforts in the framework of collaborative international activities, regulatory bodies should put increased emphasis at national level on compliance with international codes and standards and their development where these are missing. This is an important condition for successful and streamlined international collaborations.

Public acceptance

In general, the public is eager to believe in promises for better, safer, cheaper and sustainable technologies. Promoters of technological innovations should acknowledge this tendency and communicate clearly and timely the beneficial features of new nuclear technologies. However, in doing so promoters should make especially clear where are the limits of such systems, and what will never be possible: the risk of catastrophic events will never be zero – but much lower than risks of alternative solutions and other technical or natural risks; there will always be a need for nuclear waste storage – although for shorter times and for smaller volumes than today; even with reprocessing and breeding, nuclear fuels will remain a non-renewable energy source; and despite all technical and procedural measures, there will always remain a risk for proliferation of nuclear or radioactive weapons. Further, the availability of such new technologies should not be promised overly optimistically to avoid deception of the public, loss of credibility of the promoters and premature obsolescence of currently operating systems.

Communication itself has become a highly complex and sophisticated discipline, and innovative communication approaches will have to be sought in order to promote future nuclear energy systems with the burden of a highly controversial discussion on nuclear technology in the past.

International collaboration

International collaboration will be instrumental to the success of innovative R&D activities in the current context. The obvious advantages of such collaborations are a sharing of financial burdens, the optimisation of the use of existing personnel resources and research facilities, the avoidance of duplications and the exploitation of synergies. Further, indirect advantages are the mobility of specialists and knowledge – a direct response to the globalisation of the (nuclear) industry – and the facilitation of a harmonised regulatory approach to novel nuclear systems. The well-structured and targeted manner for conducting innovative collaborative R&D in the framework of GIF is promising and may become a prime example for good international collaboration in the nuclear sector.

Governments and international organisations should, therefore, encourage and facilitate international collaboration on innovative nuclear systems and information exchange on a broad cross-sector range of Government-supported and sponsored innovation initiatives with the aim of facilitating networking and cross-fertilisation of ideas, concepts and innovation processes.

A necessary precondition for the success of such international collaborative efforts is the establishment of clear co-operation rules and coordination instruments. These include, among others, coordinated R&D principles (organisation of the projects, planning and controlling, governance), adhesion to international codes and standards and clear provisions for a subsequent technology transfer and valorisation of R&D results obtained in an international framework by national industries (protection of intellectual property, rights of use, allocation of licenses etc.). These preconditions should be established in the framework of international bodies including representatives from both governmental and industrial entities.

Possible adequate instruments to create a favorable environment for and to promote international collaborations are among others international standard problems, coordinated research programmes and benchmarks. These take place mostly within international organisations such as the IAEA and the OECD/NEA and, being close to basic sciences, are easier to manage than technology development activities with associated large personnel and money investments. However, they enable contacts and the creation of an international community – a fertile soil, on which more important collaborations can develop later.

On a more institutional level, mutual and systematic information exchange about national R&D programmes, including e.g. activities within the EURATOM framework programmes or the US DOE Nuclear Energy activities, can highly promote the degree of awareness of the international community regarding ongoing R&D and the preparedness of research institutions to join, when possible and desired, such R&D programmes. Information on achieved results that are not yet mature for industrial patent application should be presented to the international community to help others to follow the right paths or to receive constructive criticism on the approach followed. This information can be provided in the framework of open workshops during or after the completion of projects; for example, the FISA workshops[1] organised by EURATOM. This presumes that innovative R&D activities are systematically monitored by independent international bodies (e.g. through OECD/NEA) and corresponding member country initiatives are appropriately facilitated.

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[1] The FISA (Fission Safety) workshops, which have been held biannually since 1995, cover the entire spectrum of reactor safety research (i.e. including operational reactor safety and evolutionary safety concepts). Conference proceedings of FISA-2006 ("EU Research and Training in Reactor Systems", Luxembourg, 13-16 March 2006) are available at http://cordis.europa.eu/fp6-euratom/ev_fisa2006_en.htm.

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Appendix A

LIST OF EXPERT GROUP MEMBERS

BELGIUM	
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Mr. Frans MOONS	SCK•CEN
CANADA	
Mr. David TREGUNNO	AECL
CZECH REPUBLIC	
Mr. Josef KRALOVEC	NRI
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Mr. Reijo MUNTHER	Tekes
FRANCE	
Mr. Pascal ANZIEU (Co-Chair)	CEA
JAPAN	
Mr. Hiroyasu HIRANO	JAEA
KOREA (REPUBLIC OF)	
Mr. Tae Joon LEE	KAERI
Mr. Seong Won YUN	KAERI
SPAIN	
Mr. Pío CARMENA SERVERT	CIEMAT
SWITZERLAND	
Mr. Konstantin FOSKOLOS (Chair)	PSI
UNITED STATES OF AMERICA	
Mr. Jean-Pierre SURSOCK	EPRI
EURATOM	
Mr. Georges VAN GOETHEM	DG RTD (European Commission)
INTERNATIONAL ATOMIC ENERGY AGENCY	
Ms. Asami MIKETA (Observer)	Department of Nuclear Energy
OECD/NUCLEAR ENERGY AGENCY	
Mr. Kwang-Seok LEE (Secretary)	Nuclear Development Division

Appendix B

ACRONYMS

A

ABWR	Advanced boiling water reactor
ACR	Advanced CANDU reactor
ADS	Accelerator-driven system
AECL	Atomic Energy of Canada Limited
AFCI	Advanced fuel cycle initiative
AGR	Advanced gas-cooled reactor
ALMR	Advanced liquid metal-cooled reactor
ALWR	Advanced light-water reactor
ANDRA	Agence nationale pour la gestion des déchets radioactifs (French National Radioactive Waste Management Agency)
APROS	Advanced process simulator
AREVA	Industry group for nuclear reactors, fuels and services
ATR	Advanced thermal reactor

B

BWR	Boiling water reactor

C

CANDU	Canadian deuterium uranium
CEA	Commissariat à l'énergie atomique/Atomic Energy Commission
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CR	Centres of Reference
CRBR	Clinch River breeder reactor
CRIEPI	Combined Research Institute of the Electric Power Industries
CRP	Coordinated Research Project
CSTP	Committee on Scientific and Technological Policy

D

DOE	Department of Energy
DON	Deuterium water moderated, Natural uranium fuel, with Organic liquid as coolant
DUPIC	Direct use of power fuel in CANDU reactors

E

EC	European Commission
EdF	Électricité de France
EFR	European fast reactor
EIB	European Investment Bank
ELSY	European lead-cooled system
ENUSA	Empresa Nacional del Uranio, S.A
EPR	European pressurised water reactor (Europe)/Evolutionary power reactor (US)
EPRI	Electric Power Research Institute
ESBWR	European simplified boiling water reactor
ESP	Early site permit
ETWG	European technical working group
EU	European Union
EUR	European utility requirements
EURATOM	European Atomic Community

F

FBR	Fast breeder/burner reactor
FISA	Fission Safety
FP	Framework Programme
FR	Fast reactor
FY	Fiscal year

G

GA	General Atomics
GCR	Gas-cooled reactor
GCFR	Gas-cooled fast reactor
GFR	Gas-cooled fast reactor

GE	General Electric
Gen-IV	Generation IV
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership

H

HFP	European hydrogen and fuel cell technology platform
HLW	High-level waste
HPLWR	High performance liquid-water reactor
HTGR	High temperature gas-cooled reactor
HTTR	High temperature engineering test reactor
HWGCR	Heavy water-moderated gas-cooled reactor

I

IAEA	International Atomic Energy Agency
ICT	Information and communication technology
IEA	International Energy Agency
I&C	Instrumentation and control
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
INS	Innovative nuclear energy systems
IPR	Intellectual property right
IRO	Industry research organisation
IT	Information technology
ITER	International thermonuclear experimental reactor

J

JAEA	Japan Atomic Energy Agency
JAERI	Japan Atomic Energy Research Institute

K

KAERI	Korea Atomic Energy Research Institute
KAIF	Korea Atomic Industry Forum
KSNP	Korea Standard Nuclear Power Plant

L

LFR	Lead-cooled fast reactor
LILW	Low- and intermediate-level waste
LLW	Low-level waste
LWR	Light water reactor

M

MASCA	MAterial SCAling
MCCI	Melt coolability and concrete interaction
MICANET	Michelangelo Network
MOX	Mixed-oxide fuel
MSR	Molten-salt reactor

N

NDC	NEA Nuclear Development Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle
NDE	Non-destructive evaluation
NEA	OECD Nuclear Energy Agency
NGNP	Next generation nuclear power plant
NIS	National innovation system
NPP	Nuclear power plant
NPT	Nuclear Non-Proliferation Treaty
NSSS	Nuclear steam supply system
NTD	Near-term deployment

O

OECD	Organisation for Economic Co-operation and Development
OMB	Office of Management and Budget
ONDRAF/ NIRAS	Organisme national des déchets radioactifs et des matières fissiles enrichies/ Nationale Instelling Voor Radioactief Afval En Verrijkte Splijtstoffen (Belgian Agency for Radioactive Waste and Enriched Fissile materials)

P

P&T	Partitioning and transmutation
PP/P	Public and private partnership
PRO	Public research organisation
PSA	Probabilistic safety assessment
PUREX	Plutonium-uranium recovery by extraction
PWR	Pressurised water reactor

R

RDD&D	Research, development, demonstration, and deployment
RTD	Research and technology development

S

SAM	Severe accident management
SARNET	Severe Accident Research Network of Excellence
SCK•CEN	Studiecentrum voor Kernenergie/Centre d’étude de l’énergie nucléaire (Nuclear Research Centre)
SCWR	Supercritical-water-cooled reactor
SETH	Senior Group of Experts on Safety Research (SESAR) Thermal-Hydraulics
SFR	Sodium-cooled fast reactor
SHR	Swiss heating reactor
SMART	System integrated modular advanced reactor
SRES	Special report on emissions scenarios
STUK	Säteilyturvakeskus (Radiation and Nuclear Safety Authority)
SWR	SiedeWasserReaktor

T

TIP	Working Group on Innovation and Technology Policy
TRU	Transuranic elements
TSO	Technical Safety Organisation

U

UNESA	Associacion española de la industria electrica
URD	Utility requirements document
UREX	Uranium extraction

V

VHTR	Very-high-temperature reactor
VTT	Technical Research Centre of Finland
VVER	Water-cooled, water-moderated reactor (vodo-vodianoï energuetitcheckiï reaktor)

W

WNA	World Nuclear Association

Appendix C

CONTENTS OF AND INSTRUCTIONS FOR COUNTRY REPORTS

1. INTRODUCTION

Explain the overall context of the country report such as overall national characteristics, overview of current nuclear energy programme and future prospects, overall needs for nuclear innovation in the country, and the focus of the study.

Indicators: *Number of power reactors (in operation, under construction, planned) with their total installed capacity and electricity generation; nuclear share of electricity generation and primary energy supply; energy import ratio, …*

2. NATIONAL EXPERIENCE OF NUCLEAR ENERGY DEVELOPMENT

2.1 Evolution of nuclear innovation performance

Describe past experience: success and/or failure stories related to innovation in support to energy technology. For each story, identify desired outcomes, environments, input resources and actual results as specific as possible. Results can be described in terms of real products (e.g., reactors, fuels, fuel-cycle facilities) or latent capacity. Also indicate as far as possible the reasons why it failed or succeeded.

Examples*: Refer to the success and failure stories presented in the literature review of innovation.*

2.2 Nuclear publications and patent trends

Describe the trends of nuclear publications and patents including the relevant data. If possible, an analysis on co-authorships among organisations, like in the Norwegian report for the OECD NIS energy case study, would be valuable.

Indicators: *Number of publications in extended-SCI journals; number of patents (national and international).*

3. CURRENT SYSTEM OF NATIONAL NUCLEAR INNOVATION

3.1 Relevant organisations, their roles and relationships

- Governmental and regulatory bodies, academic institutes, public research organisations, nuclear industry (utility, vendors), knowledge service organisations, non-governmental organisations

Describe all organisations that might be related to nuclear innovation. The description could include missions, related roles and activities, history and current status, capacity and other characteristics that might be important to nuclear innovation. The description also includes the relationships between organisations. To give an overall picture, utilise tables and/or charts.

***Indicators**: Number of employees (graduates); annual budget; number and scale of venture companies.*

3.2 Related public policies and infrastructure

- Governmental incentives: national research, development, demonstration and deployment (RDD&D) programme, subsidies, tax credits, government procurement …

Describe governmental incentives for nuclear innovation such as national programmes

- Investment capital: public RDD&D fund, venture capital, …

Describe funding mechanisms for nuclear RDD&D.

Indicators: Public nuclear R&D expenditures; business expenditure on R&D; venture capital invested in the nuclear area.

- Public/private partnerships

Describe all types of partnerships between public and industry for nuclear RD&D such as public-private network, jointly funded projects, clusters, etc. Refer to the description of PP/Ps in the literature review.

- Regulatory requirements

Describe regulatory processes and requirements to be fulfilled for the introduction of new products or processes. Refer to the description of regulations in the literature review.

Indicators: Average licensing time for a new product or process; ratio of backfits.

- Intellectual property right management

Describe intellectual property right management regulations and practices.

- Others

Describe other things that might be important to.

3.3 Current RD&D processes

- Nuclear RD&D management (visioning process, selection/execution/appraisal of projects, .),

Describe how nuclear RD&D programmes are managed including planning, selection, execution, and appraisal processes.

- Sources of knowledge, link with other sectors, mobility of human resources

Describe usual practices of knowledge creation, diffusion, and exploitation in nuclear RD&D.

- Others

4. NATIONAL PROGRAMMES FOR FUTURE INNOVATION

4.1 Supporting current NPP and fuel cycle plants

Present and describe, here and in the two following chapters, the current programmes in RD&D or industrial sectors which need innovation.

- Driving forces & limiting factors

Describe current and prospected national environments which would be positive and/or negative for the programme. In the description, identify driving forces for nuclear innovation (e.g., consumer demands, economic competitiveness, governmental policies for energy security and environmental preservation, social pressures for stricter safety requirements, regulatory needs) and limiting factors (e.g., low consumer demands, public acceptance, regulatory requirements, little interest of industry).

- Programme objectives
- Provisional budget and funding
- Schedule
- Collaborations between actors (including international actors)
- Institutional policies and regulations

4.2 Developing new concepts

Same as in 4.1

4.3 Other programmes outside electricity production

Same as in 4.1

5. CONCLUSION

- Summary
- Issues for Improvement

Discuss issues for the improvement of current innovation systems in the national perspective.

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