INNOVATIVE NUCLEAR REACTOR DEVELOPMENT

Opportunities for International Co-operation

INTERNATIONAL ENERGY AGENCY

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The International Energy Agency (IEA) is an autonomous body which was established in November 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme.

It carries out a comprehensive programme of energy co-operation among twenty-six* of the OECD's thirty Member countries. The basic aims of the IEA are:

- to maintain and improve systems for coping with oil supply disruptions;
- to promote rational energy policies in a global context through co-operative relations with non-member countries, industry and international organisations;
- to operate a permanent information system on the international oil market;
- to improve the world's energy supply and demand structure by developing alternative energy sources and increasing the efficiency of energy use;
- to assist in the integration of environmental and energy policies.

**IEA Member countries:* Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, the Republic of Korea, Luxembourg, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom, the United States. The European Commission also takes part in the work of the IEA.*

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, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, 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.

INTERNATIONAL ATOMIC ENERGY AGENCY

The Agncy’s Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is ”to accelerate end enlarge the contribution of atomic energy to peace, health and prosperity throughout the world”.

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand(29th May 1973), Mexico (18th May 1994),the Czech Republic (21st December 1995),Hungary (7th May 1996), Poland(22nd November 1996), the Republic of Korea (12th December 1996) and Slovakia (28th September 2000). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

FOREWORD

A number of countries wish to expand their use of nuclear energy or keep open the option of doing so in the future. Any new nuclear generating capacity will be built in the context of increasingly privatised and deregulated energy markets coupled with heightened public concern over nuclear power. New nuclear power plants must maintain or exceed current levels of safety and must be economically competitive with alternative ways of generating electricity. They must address other challenges as well, among them waste disposal and nonproliferation concerns.

This report reviews how some of the innovative nuclear-fission technologies being developed today attempt to address the challenges facing nuclear energy. It suggests some areas for collaborative research and development that could reduce the time and cost required to develop new technologies.

The report is a product of the "Three-Agency Study", a joint project among the International Energy Agency (IEA), the OECD Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA). The main contributors to the project were Madeline Woodruff from the IEA, Evelyne Bertel from the NEA and Peter J. Gowin from the IAEA. The agencies have appreciated the opportunity to work together on the study and look forward to future collaboration.

The Three-Agency Study team is grateful to Mr. Ralph Hart for his contributions to the background documents that form the basis for this report. The contributions of innovative reactor designers, who responded to the study's questionnaire, are also gratefully acknowledged, as are the valuable inputs of experts who reviewed the draft report. Responsibility for the report, however, rests with the secretariats of the IEA, the NEA and the IAEA. The report does not necessarily reflect the views or policies of the Member countries or states of the three agencies. References to specific designs or companies should not be construed as recommendations on the part of the IEA, the NEA or the IAEA.

CONTENTS

LIST OF TABLES

EXECUTIVE SUMMARY

The context in which any new nuclear power generating capacity will be built is one of increasingly privatised and deregulated energy markets coupled with heightened public concern over nuclear power. New nuclear plants must maintain or exceed current levels of safety and must be economically competitive with alternative means of generating electricity. Improved ways of dealing with the waste generated by nuclear plants and of addressing nonproliferation concerns will also be important. Resource efficiency and flexibility of application may provide additional advantages.

New nuclear-fission technologies aimed at meeting these challenges are being researched today by companies, research institutes, universities and government organisations worldwide. Most designs build on the substantial body of work that has been carried out since the early days of nuclear power. In some cases, several research groups are working on the same or similar technologies. International co-operation could potentially help technology developers make the most effective use of the limited research funds available today.

This report is a first step in examining the scope for enhanced international co-operation in developing nuclear-fission reactor technologies. It shows how new technologies are being developed to address the challenges facing nuclear power today and identifies potential areas for co-operation among technology developers. The focus is on “innovative” fission reactor technologies, which are those that go well beyond the incremental, evolutionary changes to current technology that have been developed and are the subject of ongoing work.

The report reviews specific reactor design proposals so as to identify how they are addressing the challenges facing nuclear power and to examine the underlying “enabling” technologies that might constitute fruitful areas for research collaboration. The study is a “first step”, in that it reviews only a limited number of reactor designs. Many of the findings, conclusions and recommendations reported here should be regarded as tentative until confirmed by a more comprehensive survey.

Several international projects on nuclear power have been initiated in recent years. The International Atomic Energy Agency (IAEA) recently launched an "International Project on Innovative Nuclear Reactors and Fuel Cycles" (INPRO). Work on innovative nuclear designs is also ongoing within the Generation IV International Forum (GIF), supported by the United States and several other countries, and through the Michelangelo Initiative Network, a part of the Framework Programme of the European Commission. Such initiatives are appropriate forums for considering the outcomes of this study and for expanding the analysis to more designs.

Findings

Indicative findings resulting from this study are as follows:

- Countries wishing to expand their use of nuclear energy will be able to choose from a range of technologies making use of a wide variety of innovations. Many of the innovations and innovative approaches are common to several designs. In addition, many different approaches have been adopted for different reactors to meet the same basic design requirement under similar circumstances.
- A wealth of information is available on several decades of research in the field of nuclear fission and on the operation of prototype and demonstration reactors in the 1950s and 1960s. Yet current reactor designers do not always have easy access to this information and may not fully incorporate it into their research and development (R&D) programmes.
- Many components and technologies that have been commercialised by the aerospace, automotive, petro-chemical and other industries may be useful in the nuclear industry.

- Most of the design activities reviewed here focus on the nuclear steam supply system (NSSS). Because the balance-of-plant (BOP), where heat from the nuclear reactor is converted to useful energy, represents a major portion of both capital and operating costs, its design must be given careful attention if economic objectives are to be met.
- All else being equal, economies of scale favour large nuclear power plants. To be economically viable, small plants must achieve simplifications in both the NSSS and BOP or they must offer higher reactor-core outlet temperatures that enable higher thermodynamic efficiency and energy utilisation.
- Specific attention is needed to reducing the cost of operation, maintenance and inspection, especially for small reactors. Because of their compact design or the type of coolant they use, several of the innovative reactor designs considered here present new challenges to the provision of cost-effective maintenance and inspection of the reactor system components.
- Several of the designs considered in this study were developed on the assumption that, in future energy markets, demand may not be driven solely by the need for electricity. New demand will arise for process heat, district heating or seawater desalination for the production of potable water. Taking advantage of co-production options and improving the flexibility of application can improve the competitiveness of nuclear power plants.
- The R&D and design efforts underway on innovative nuclear reactors receive little funding compared with the R&D efforts of the 1950s, 1960s and 1970s to develop the current generation of reactors. Nuclear R&D expenditures today are aimed primarily at maintaining and enhancing the performance of operating reactors. Assuming that low investment will continue, commercial availability for most of the designs considered here could require 10 to 15 years or longer.
- Further collaboration in developing innovative fission reactor designs is warranted. Collaboration could help designers make the most effective use of limited R&D resources and could reduce the time and

cost required to make technologies available commercially. It could also help increase cross-fertilisation among development efforts and ensure fuller use of the broad experience base developed to date.

Recommendations

The following recommendations are offered to reactor design teams and to organisations engaged in fostering collaborative R&D on energy technologies:

- **Make better use of experience to date.**
- **Increase cross-fertilisation of ideas among those working on various reactor types.**
- **Take greater advantage of components and technologies developed in other industries.**
- **Increase co-operation in R&D.** The three recommendations above would benefit from being addressed via collaborative efforts among research groups. Specific "enabling" technology areas are also good candidates for collaboration because they are relevant to the development of several types of innovative designs, and because they may be amenable to joint development without necessitating the sharing of proprietary information or know-how. The following areas are good candidates for developing new, broad-based collaborative efforts:
  - natural circulation;
  - high-temperature materials;
  - passive (safety) devices;
  - in-service inspection and maintenance methods;

- advanced monitoring and control technologies;
- delivery and construction methods;
- safeguards technologies and approaches.

Other enabling technologies would be good candidates for more limited co-operation among a few design groups. These include advanced coolants; advanced fuel design, processing and fabrication; subcritical systems; and component development.

- **Continue the analysis begun in this study.** The INPRO, the GIF and other international projects on innovative reactor designs may find these recommendations useful in planning the collaborative elements of their work. The analysis begun in this study should be expanded to a broader set of designs.

CHAPTER 1
INTRODUCTION

"Business as usual" projections for electricity generation show the share of nuclear power decreasing over time, as existing nuclear power plants reach the end of their operating lives or are shut down for other reasons and only a small amount of new nuclear capacity is built. But a number of OECD countries, as well as others, wish to expand their use of nuclear energy or keep open the option of doing so in the future. Concerns over energy security and the need to reduce emissions of greenhouse gases and other atmospheric pollutants are among the reasons cited by several industrialised countries for wishing to keep this option open. Developing countries, many of which lack indigenous energy resources, are interested in enhancing their standards of living while minimising energy imports.

The context in which any new nuclear generating capacity will be constructed is one of increasingly privatised and deregulated energy markets coupled with heightened public concern over nuclear power. At a minimum, new nuclear plants must maintain or exceed current levels of safety and must be economically competitive with other means of generating electricity, especially natural-gas combined-cycle plants. Improved ways of dealing with the waste generated by nuclear plants and of addressing nonproliferation concerns will also be important.

Nuclear energy technologies incorporating incremental, evolutionary changes to today's operating reactors are one option for the future. They will certainly continue to be developed and used. But additional, innovative technologies are likely to be needed if new nuclear power plants are to compete successfully in highly-competitive energy markets and to overcome the other challenges facing nuclear power.[1]

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[1] *For an assessment of the challenges facing nuclear power in the OECD, see, for example, IEA 2001 and NEA 2000.*

New nuclear-fission technologies aimed at meeting these challenges are being studied today by companies, research institutes, universities and government organisations worldwide. Most designs incorporate the substantial body of work that has been carried out since the early days of nuclear power. In some cases, several research groups are working on the same or similar technologies. International co-operation could potentially help technology developers make the most effective use of the limited research funds available today.

This report is a first step in examining the scope for enhanced international co-operation in developing new nuclear-fission reactor technologies. It is a product of the "Three-Agency Study", a joint effort of the International Energy Agency (IEA), the OECD Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA). The objectives of the study were:

- to describe how new technologies are attempting to address the challenges facing nuclear energy today; and
- to begin identifying potential areas for co-operation among technology developers.

The study focused on "innovative" nuclear-fission reactor technologies as defined by the IAEA.[2] These go well beyond the incremental, evolutionary changes to current fission reactor technology that have been developed and are the subject of some ongoing work. Nuclear fusion technologies were excluded from the scope of the study.

Approach to the Three-Agency Study

To accomplish the Three-Agency Study's objectives, the study team developed a list of six general "characteristics" of nuclear reactors that could help overcome the obstacles facing nuclear energy today. It then

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[2] *According to IAEA 1997, "The key attribute of an innovative design, sometimes also called a novel design, is that it is based on radical conceptual changes in design approaches or system configuration in comparison with established practice."*

reviewed how features of innovative designs currently under development could contribute to enhanced performance on each of these characteristics.[3] It also identified "enabling" technologies important to one or several designs and evaluated the possibility of international collaboration on further developing these technologies. Information on how designs contribute to enhanced performance on the six characteristics, and on research and development (R&D) programmes currently underway, was sought from reactor designers using a questionnaire.

Although this approach entailed looking at specific innovative reactor designs, the main purpose of the study was not to evaluate specific design proposals from particular vendors or designers. It seems clear that each design "idea" could be developed, not only by the institution currently proposing it, but also by others. Each idea could also be used in different design concepts. The outcomes of the study are applicable to the general ideas underlying the specific designs considered – in only a few cases are findings specific to particular designs.

The study team compiled a list of innovative reactor designs under development today. A limited number of designs was chosen from this list for detailed consideration. The purpose of our limited effort was in part to develop a consistent methodology that could later be applied to additional designs.

We now envision that an effort to expand this work to additional technologies will take place under several international projects that have been created to foster co-operative nuclear technology development. Among them are the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO); the Generation IV International Forum (GIF), initiated by the U.S. Department of Energy; and the Michelangelo Initiative Network, a part of the Framework Programme of the European Commission. This report is the final product

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[3] *While current reactor designs have also been developed according to characteristics such as those identified here, and have demonstrated good performance, further improved performance of innovative designs vis-à-vis these characteristics could help overcome the obstacles facing nuclear energy today.*

of the Three-Agency Study and is intended as a building block for these and other international projects.

This report is a summary highlighting the results of the study. More detailed information is available in a three-volume Background Report (3A 2001), as follows:

- **Volume I** contains detailed information on how the innovative reactor designs considered in the study are expected to perform in terms of safety, economic competitiveness and other characteristics; a review of the enabling technologies for these designs; an overview of the R&D programmes under way for the designs and the further work needed to make them commercially available; and a tentative assessment of the potential for international co-operation to facilitate R&D and enhance its cost-effectiveness.
- **Volume II** contains a lightly edited compilation of the replies received to the questionnaire sent to developers of innovative reactor designs.
- **Volume III** contains notes on factors affecting the development of small and medium-sized reactors and innovative designs.

The Background Report is not an official publication of the three agencies but is being made available as “working material”.[4]

Characteristics of Innovative Nuclear Reactors

The study team asked design developers to provide information on how the features of their innovative designs contribute to enhanced performance relative to the current generation of reactors on six characteristics:

- **Safety** – features that contribute to enhanced safety, including those that reduce the probability and severity of both core damage and radioactive release following core damage;

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[4] *The Background Report is available from the OECD Nuclear Energy Agency (http: //www.nea.fr) or from the International Atomic Energy Agency (http://www.iaea.org).*

- **Economic competitiveness** – features that contribute to improved economic competitiveness relative to other methods of generating power, including those that reduce overnight construction cost,[5] construction time, operating and maintenance costs, or fuel-cycle costs, and those that improve the reliability or capacity factor;
- **Proliferation resistance and safeguards** – features that contribute to enhanced proliferation resistance, including reduced generation or transport of fissile materials, particularly plutonium; increased technical difficulty of extracting weapons-grade fissile materials from spent fuel; and increased ease of implementing international safeguards;
- **Waste management** – features that contribute to enhanced performance with respect to waste management, including those that reduce the generation of some or all categories of radioactive waste or ease the management or disposal of such waste;
- **Efficiency of resource use** – features that contribute to the efficient use of nuclear fuel(s) through means such as higher fuel burnup, recycling, increased plant efficiency or use of fuels other than uranium;
- **Flexibility of application** – features that facilitate flexible use of the reactor – for example, for electricity generation, cogeneration applications and process-heat applications.

Each of these characteristics is described above in terms of only a few key sub-characteristics. So a description of a reactor design in terms of these characteristics will not be a full description of every aspect of its safety performance, its economic performance and so forth. Rather, it will show qualitatively how these designs, by attaining high levels of performance in these areas, may achieve an enhanced probability of being sold in competitive energy markets.

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[5] *Overnight construction cost is the instantaneous cost, not accounting for interest accrued during the period of construction.*

CHAPTER 2
INNOVATIVE REACTOR DESIGNS

A list of 34 innovative reactor designs was used as the starting point for the study (see Table 2-1). This list is far from exhaustive. Nevertheless, the designs listed form a base set of concepts that reflects a range of innovative potential.

Selecting Reactor Designs for Initial Assessment

A subset of the designs in Table 2-1 was chosen for initial assessment in order to test the study's methodology and questionnaire and to provide some early results. The following criteria were applied to select these designs:

- Only designs for which ongoing, funded R&D programmes could be identified were included;
- All major design types were included, based on variations in primary coolant, operating conditions and moderator[6] characteristics;
- Various applications of nuclear energy were covered, such as electricity generation, high-temperature heat and district heating, as were both single-purpose and cogeneration concepts;
- Only complete[7] designs were included – work on individual reactor or power plant components was not considered, unless the component was a key portion of a complete design.

If more than one design was available in a given reactor category, we chose the designs that appeared to have the most comprehensive and

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[6] *The moderator slows down the high-energy neutrons produced in the fission reaction. Moderators are used in those reactors – such as water-cooled reactors – in which most fissions result from the absorption of slow neutrons. Fast reactors do not use moderators.*

[7] *With the exception of the Radkowsky Thorium Fuel Reactor (RTFR).*

well-defined R&D programmes and that appeared to be the most innovative.

In addition to these criteria, the following considerations were relevant:

- A regional and global balance of designs was sought, as was a wide variety of R&D institutions and designers;
- An attempt was made to reflect the needs of the countries that are members of the participating agencies, considering both the country of origin of each design and the countries where the designs might be used.

Fourteen designs were selected for initial assessment, and questionnaires were sent to the developers of these designs. (The questionnaire is included in the Background Report for this project, 3A 2001.) Responses were received for 11 designs; alternative sources of information were available for a twelfth design. These 12 designs are covered in this report and are listed in Table 2-2. As noted previously, we expect that more designs will be covered as needed under other international projects.

Table 2-1

Illustrative List of Innovative Reactor Designs

Name	Country	Type[1]	Capacity[2]	Developer
Light-Water Reactors				
B-500 SKDI	Russia	PWR	515 MW_e	RRC-KI/Hydropress
CAREM-25	Argentina	PWR	27 MW_e	CNEA/INVAP
MRX	Japan	PWR	Up to 300 MW_{th}	JAERI
RMWR	Japan	BWR	1,000 MW_e	JAERI
SCLWR	Japan	PWR	1,100 MW_e	University of Tokyo
SLP-PWR	France	PWR	600 MW_e	CEA
SMART	ROK	PWR	100 MW_e	KAERI
SPWR	Japan	PWR	600 MW_e	JAERI
SWR 1000	Germany	BWR	1,000 MW_e	Siemens
Heavy-Water Reactors				
APHWR	India	PHWR	200	BARC
CANDU X	Canada	PHWR	350 – 1150 MW_e	AECL
Liquid-Metal Fast Reactors				
4S	Japan	LMR	50 MW_e	CRIEPI
ALMR (PRISM)	USA	LMR	150 MW_e	General Electric
BN-800	Russia	LMR	800 MW_e	Russian Ministry for Atomic Energy
BREST 300	Russia	LMR	300 MW_e	RDIPE
DFBR	Japan	LMR	660 MW_e	JAPC
EFR	Europe	LMR	1,500 MW_e	EU Consortium
Energy Amplifier	Europe	Hybrid LMR/ Accelerator	675 MW_e	CERN
LFBR	Japan	LMR	625 MW_e	JAERI
SAFR	USA	LMR	450 MW_e	Rockwell Int./CE
Gas Reactors				
GT-MHR	USA/Russia	HTGR	286 MW_e	General Atomics
HTGR-MHD	Japan	HTGR	860 MW_e	JAERI
HTR-Module	Germany	HTGR	80 MW_e	Siemens-KWU
PBMR	South Africa	HTGR	110 MW_e	ESKOM

Table 2-1

Illustrative List of Innovative Reactor Designs

Name	Country	Type[1]	Capacity[2]	Developer
Molten-Salt Reactors				
FUJI	Japan/Russia/ USA	MSR	100 MW_e	ITHMSO
MSR-NC	Russia	MSR	470 MW_e	RRC-KI
USR	USA	MSR	625 MW_e	ORNL
Thorium-Fuelled Reactors				
RTFR (Radkowsky Thorium Fuel Reactor)	Russia/USA/ Israel	Thorium fuel concept only, applicable to LWRs and HWRs	Small to Large	RCC-KI/BNL/BGU
District-Heating Reactors				
KNDHR	ROK	LWR	10 MW_{th}	KAERI
MARS	Italy	PWR	600 MW_{th}	Rome University
NHR-200	China	PWR	200 $M_{th}W_{th}$	INET
RUTA	Russia	LWR	20 MW_{th}	RDIPE
SECURE-H	Sweden	PWR	400 MW_{th}	ASEA
Decentralised Nuclear-Heating Power Reactors				
Compact HTGR Gas Turbine	USA	HTGR	29 MW_e	General Atomics
Ship Reactors				
Barge-Mounted KLT-40C	Russia	PWR	35 MW_e	OKBM
BBR	France	MSR	5,000 MW_{th}	CEA

1. PWR: pressurised-water reactor; BWR: boiling-water reactor; PHWR: pressurised heavy-water reactor; LMR: liquid-metal reactor; HTGR: high-temperature gas-cooled reactor; MSR: molten-salt reactor; LWR: light-water reactor; HWR: heavy-water reactor.

2. MW_{th}*: the thermal power produced by the reactor, before conversion to electricity;* MW_e*: the electrical power produced by the power plant.*

Table 2-2

Innovative Reactor Designs Covered in This Report

Name	Country	Type	Capacity	Developer	Style	Current Use
Light-Water Reactors						
Barge-Mounted KLT-40C	Russia	PWR	35 MW_e	OKBM	PV/Loop[8]	Ship Power
CAREM-25	Argentina	PWR	27 MW_e	CNEA/INVAP	Integral[9]	N/A
MRX	Japan	PWR	Up to 300 MW_{th}	JAERI	Integral	N/A
NHR-200	China	PWR	200 MW_{th}	INET	Integral	Desalination and District Heat (NHR 5)
SMART	ROK	PWR	100 MW_e	KAERI	Integral	N/A
Heavy-Water Reactors						
CANDU X	Canada	PHWR	350-1150 MW_e	AECL	PT[10]	N/A
Liquid-Metal Fast Reactors						
BREST 300	Russia	LMR	300 MW_e	RDIPE	LPV/Loop[11]	N/A
Energy Amplifier	Europe	Hybrid LMR/ Accelerator	675 MW_e	CERN	Pool	N/A
Gas Reactors						
GT-MHR	USA/Russia	HTGR	286 MW_e	General Atomics	PV/Loop	N/A
PBMR	South Africa	HTGR	110 MW_e	ESKOM	PV/Loop	N/A
Molten-Salt Reactors						
FUJI	Japan/Russia/ USA	MSR	100 MW_e	ITHMSO	LPV/Loop	N/A
Other						
RTFR	Russia/USA/ Israel	PWR/ PHWR	Small to Large	RCC-KI/BNL/ BGU	PV and PT	N/A

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[8] Pressure-vessel (PV)/loop reactors house the reactor core in a high-pressure vessel and accommodate reactor coolant pumps and any steam generators in external circuits or loops.

[9] Integral reactors house all principal NSSS components, including the reactor core, the pressuriser, the primary heat exchangers and any reactor coolant pumps, in a single pressure vessel.

[10] Pressure-tube (PT) reactors accommodate the fuel and reactor coolant in several hundred tubes in the reactor core. The tubes are surrounded by a moderator.

[11] Low-pressure vessel (LPV)/loop reactors house the reactor core in a low-pressure vessel or tank, and accommodate steam generators and reactor coolant pumps in external circuits or loops.

Overview of Twelve Innovative Reactor Designs

The innovative reactor groups covered in this report are described briefly below. More detailed descriptions, provided by the designers in response to the Three-Agency Study questionnaire, are included in Volumes I and II of the Background Report (3A 2001).

All of the innovative reactor designs in Table 2-2 can be used in small and medium-sized reactors,[12] although some of the designs are also appropriate for large reactors. Several of the designs offer temperatures well above those available from current water-cooled reactors.

Light-Water Reactors

Barge-Mounted KLT-40C, CAREM-25, MRX, NHR-20, SMART

The five light-water reactors (LWRs) in Table 2-2 have outputs of 300 MW_e or less. They use traditional pressurised-water reactor (PWR) technologies, such as a pressure vessel housing the reactor core, fuel enriched to approximately 3.5 % in ^{235}U, and light-water coolant, but they incorporate innovative configurations and features to achieve their design objectives.

The KLT-40C, like today's operating PWRs, is a pressure-vessel/loop (PV/loop) reactor. In this configuration, hydraulic loops that include a circulation pump and a steam generator connect to the pressure vessel and provide coolant circulation through the reactor core. The other four designs are integral reactors, in which all components of the nuclear steam supply system (NSSS) and the reactor system, including the pressuriser, the primary heat exchangers and any reactor coolant pumps, are housed within a single pressure vessel.

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[12] The IAEA classifies reactors according to their electrical output as follows: less than 300 MW_e as small reactors, 300 MW_e to 700 MW_e as medium-sized reactors and greater than 700 MW_e as large reactors.

The CAREM-25, which produces 100 MW_{th}/27 MW_e, is a demonstration or prototype reactor.[13]

The designers of all five reactors strive to enhance safety by increasing the amount of water (on a per-MW basis) in the pressure vessel, reducing the core-power density and increasing the use of passive systems, relative to current PWRs. All of these reactors use fuel and have fuel cycles similar to those of current PWRs.

Small reactors of traditional design may be penalised by economies of scale, which cause the per-MW cost to decrease as reactor size is increased, if they are simply downsized versions of plants with larger generating capacities. The reactors in this group strive to overcome these economies of scale while achieving advantages in safety and operation. To this end, the four integral reactor designs reduce the number of pressure vessels and support components below those of current LWRs and eliminate large amounts of reactor-coolant system piping. The KLT-40C reactor incorporates the nuclear power plant in a barge – referred to as a floating power unit (FPU) – that is assembled in a factory. At the end of each 12-year operating cycle, the FPU is taken to a central facility for overhaul and the disposal of accumulated waste and spent fuel. At the end of its operating life, the FPU is delivered to a central facility for decommissioning.

For heat applications, the temperature capabilities of three of the integral reactors and the PV/loop reactor are in the same range as that of current LWRs. The temperature capability of the other integral reactor (the NHR-200) is substantially lower, as it is designed specifically for low-temperature applications such as district heating and desalination.

These designs do not incorporate any innovative technologies in the systems that convert reactor heat to a useful form of energy.

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[13] *After the preparation of this report, the designers reported that the commercial version will have an output in the range of 100 MW_e. Nevertheless, the 100 MW_{th}/27 MW_e model version is the basis for the discussion in this report.*

Heavy-Water Reactors

CANDU X

The CANDU X is a pressure-tube (PT) reactor. No pressure vessel is used – rather, the reactor coolant boundary within the core consists of a large number of pressure tubes, surrounded by a moderator. The design uses the traditional CANDU equipment configuration for the NSSS; innovative features in the Mark I model include the use of supercritical heavy water for the reactor coolant and of supercritical light water to power the turbine-generator. Supercritical coolant substantially increases the pressure and temperature of the reactor coolant system over those in current CANDU plants. Further innovations proposed for later CANDU X models include the use of supercritical light water as the reactor coolant and the use of a direct cycle.[14]

The CANDU X retains the passive safety features of current CANDU reactors, such as the two passive shutdown systems, and its design strives to enhance safety by incorporating additional passive decay heat removal capabilities.

The net output of the CANDU X is in the range of 350 MW_e to 1150 MW_e, depending on the number of fuel channels used. For heat applications, the temperature capability of the design is greater than that of current pressurised heavy-water reactors (PHWRs), but well below that of high-temperature gas-cooled reactors and liquid-metal fast reactors.

Liquid-Metal Fast Reactors

BREST 300, Energy Amplifier

The two liquid-metal fast reactor designs have outputs of 300 MW_e and 675 MW_e. They are lead-cooled, pool-style reactors, in which the core is housed in a pool that has near-atmospheric pressure at the coolant surface. The BREST 300 uses a loop configuration for the primary heat

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[14] The questionnaire response covered several CANDU X models. Since the preparation of this report, the CANDU-X developers have defined the "reference" CANDU-X design as incorporating these two innovations. Nevertheless, the Mark I model is the basis for the discussion in this report.

removal system, while the steam generators for the Energy Amplifier are housed within the reactor pool.

The BREST 300 uses a mononitride mixed (uranium-plutonium) fuel that is compatible with the lead reactor coolant.

The Energy Amplifier is a hybrid reactor that integrates accelerator and metal-cooled reactor technologies to produce power using a sub-critical reactor core. A beam of high-energy protons from the accelerator is directed at a lead target, which ejects neutrons. The neutrons are only slightly moderated by the lead in the target, are multiplied under sub-critical conditions in the reactor core and contribute to the breeding process taking place in the mixed $ThUO_2$ oxide fuel.

The reactor designs in this group benefit from five decades of research, technology development and prototype or commercial reactor operation in several countries, and from work specifically on lead-cooled fast reactors, largely in the Russian Federation.

The two designs strive to enhance safety through the use of passive decay heat removal systems and the simplification of safety systems. The use of lead coolant avoids the potential for fires and for water-coolant reactions associated with sodium.

These designs offer temperatures substantially above those available from current water-cooled reactors, increasing thermodynamic efficiency. They take advantage of this feature as well as of passive safety features to reduce capital and operating costs, and they have lower fuel-cycle costs than current water-cooled reactors. They can operate as breeders or near-breeders to increase resource utilisation and can ease the management of radioactive waste by consuming plutonium and transmuting minor actinides into stable isotopes.

Gas Reactors

GT-MHR, PBMR

The two gas-cooled reactor designs are PV/loop reactors that use helium as the coolant and graphite as the moderator. They build on developments in high-temperature gas-cooled reactor (HTGR) technology over the last 40 years. They also benefit from the operating experience of the AVR and Peach Bottom prototype/demonstration reactors, the THTR demonstration reactor and the Fort St. Vrain[15] demonstration/commercial reactor, as well as recent advances in gas-turbine technology. The Fort St. Vrain plant experienced major problems with water ingress via the helium circulators. The designs considered here incorporate features to avoid this problem as well as other problems encountered during the operation of prototype and commercial reactors.

These designs use the TRISO[16] fuel-particle design that has been developed over the past 40 years, largely in the United States and Germany. Designers believe that traditional containment structures of the type used with water-cooled reactors are not needed with this fuel, which would reduce construction and operating costs.

The GT-MHR core structure consists of stacks of hexagonal graphite blocks that have passages for the helium coolant flow and columns of graphite pellets that contain the TRISO fuel particles. In the PBMR, the active core consists of a large number of "pebbles" about the size of billiard balls surrounded by columns of graphite reflector blocks. Some pebbles are graphite and serve a moderator function; others contain TRISO particles with fissile material; still others may contain TRISO particles with fertile fuel.

The designers of both reactors strive to enhance safety by exploiting the inherent and passive safety features made possible by the technology. These include negative temperature-reactivity coefficients sufficiently strong to shut down the reactors, low power density and high heat capacity, as well as the capability of the TRISO fuel to retain high-temperature fission products.

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15. The AVR and THTR reactors operated in Germany, the Peach Bottom reactor operated in Pennsylvania in the United States, and the Fort St. Vrain reactor operated in Colorado in the United States.

16. TRISO particles, with an outside diameter of less than one mm, have a uranium or thorium oxide core with four coatings. Designers believe that silicon carbide coatings can serve the containment function that is provided by the containment buildings of water-cooled reactors. A porous, pyrolytic-carbon inner coating accommodates fission gases. The pressure-retaining capability of the TRISO particle is maintained up to about 1,600°C, which is above the temperature reached under the most severe accident scenarios.

Both designs use direct cycles and modern, high-efficiency gas-turbine technology to simplify the energy conversion equipment and to increase thermodynamic efficiency. The compact configuration of the reactors and of the helium-turbine power conversion systems reduces area requirements for plants.

With net electrical outputs in the range of 100 MW_e to 300 MW_e, the GT-MHR and PBMR are considered small reactors. Compared with current water-cooled reactors, they offer a substantial increase in temperature for heat applications.

Molten-Salt Reactors

FUJI

The FUJI is a low-pressure vessel (LPV)/loop-style reactor. It uses a graphite moderator and a molten-salt coolant. The design builds on the molten-salt reactor technology developed at Oak Ridge National Laboratory (ORNL) in the United States and the operating experience of the Molten-Salt Reactor Experiment (MSRE), which was operated by ORNL for over 32 months in the late 1960s.

A unique feature of molten-salt reactors is that the uranium and thorium fuel is dissolved in the molten-salt coolant. The salt mixture can include $^{232}ThF_4$ (which is fertile), $^{233}UF_4$ (which is fissile) and $^{7}LiF\text{-}BeF_2$ (the principal solvent salt). These reactors have very strongly negative temperature-reactivity coefficients, stemming from the combination of the strong negative temperature-reactivity coefficient provided by the graphite moderator and the reduction in molten-salt density, and hence in the amount of fuel in the core, that accompanies increasing temperature.

The FUJI, with an electrical output of 100 MW_e, is considered a small reactor. Its designers strive to enhance safety by exploiting the inherent and passive safety features made possible by the technology. The design ensures that no materials with moderating capability are located in the vicinity of the reactor vessel, so that the molten-salt/fuel fluid cannot achieve criticality outside the core in the event of an accident involving leakage of molten salt from the vessel. The design offers a substantial increase in temperature capability for heat applications as compared with current water-cooled reactors.

Other

RTFR

The Radkowsky Thorium Fuel Reactor (RTFR) concept is not a reactor design, but rather a fuel and fuel-cycle concept that can be adapted for use in water-cooled reactors. Although applicable in principle to both light-water-cooled and heavy-water-cooled reactors, the design focus to date has been on LWR applications (PWRs).

The RTFR fuel concept consists of a seed-blanket unit fuel assembly containing enriched uranium (less than 20 % ^{235}U) in the central region and thorium in the surrounding blanket. The blanket material also contains a small amount (about 0.1 %) of enriched uranium.

The principal benefits of the concept include the use of abundant thorium fuel, which preserves uranium resources, and a substantial reduction in the quantities of uranium-derived actinides that are produced during reactor operation.

CHAPTER 3
APPROACHES TO MEETING GOALS FOR INNOVATIVE REACTORS[17]

Innovative nuclear reactors can achieve high performance on each of the six characteristics – safety, economic competitiveness, proliferation resistance and safeguards, waste management, efficiency of resource use, and flexibility of application – in a number of ways. This chapter describes, for each characteristic, the goals that innovative reactors are designed to meet and the general approaches to meeting them taken by the reactor designs covered in this report. It includes a table (Table 3-1) summarising briefly how each design makes use of these approaches. A more detailed version of this table is available in Volume I of the Background Report (3A 2001).

Not all of the general approaches to achieving goals that are described here are applicable to all innovative reactor designs. Moreover, the benefit derived from applying an approach to a given design depends on the specifics of that design. The fact that a specific approach is included in this study cannot be interpreted as a finding by the study team that this approach indeed yields specific results with regard to one of the characteristics. Rather, the approaches included here should be seen as proposals that are currently under discussion or development.

Safety

Safety Goals

The safety design goals of future reactors are three-fold: to reduce the likelihood and severity of core damage and of radioactive release following core damage, to achieve the safety objectives in a cost-

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[17] The terms "enhance", "reduce", "increase" and "decrease" as used in this chapter are relative to the current generation of reactors.

effective manner, and to achieve them in a manner that is sufficiently obvious and transparent to reassure the public.

Specific safety goals for new nuclear reactor designs include the following:

- **Simplify and reduce costs.** Safety in current nuclear power plant designs is achieved through considerable complexity and cost, incurred at all stages of the project – design, construction and operation. Simplifying and reducing the cost of safety systems and processes, from hardware systems to inspection and testing, is therefore a goal of new designs.

- **Address public concerns.** Another goal of future nuclear power plant designs is to address public concerns over safety, which were aggravated by the Three-Mile Island and Chernobyl accidents. Public concerns extend to power plants, fuel-fabrication facilities, fuel-reprocessing plants, nuclear waste-management activities and the transport of radioactive materials. Specific goals may include limiting the effects of any accident to the local area or to within the site boundary. The ability to demonstrate the safety of a new reactor type by simulating an accident in a prototype plant may also be important.

- **Ensure that all *new* potential threats to safety are considered.** Modern nuclear power plants are considered safe by the regulatory bodies that have jurisdiction over them and by experts in the nuclear industry. But the introduction of new technologies may bring new threats that must be considered. For example, there is increasing use of computer-based control, safety and information systems in new nuclear power plant designs; at the same time, there is a rapidly-expanding move to connect nuclear plant-data systems electronically to a variety of external organisations, ranging from other company locations to contractors and service organisations. These factors may allow a “hacker” to gain access to such systems at a nuclear power plant. A specific goal of new nuclear power plants is to assure that all potential *new* threats to safety are considered. This may require an increase in the scope of the probabilistic safety assessment carried out for each plant.

- **Protect against human error and actions.** Human error has been a significant or dominant factor in most nuclear accidents. A goal of future nuclear plants is to gain immunity from human error as well as from malicious actions.

General Approaches to Achieving Safety Goals

The designers of the innovative reactors considered in this report have proposed a number of approaches to achieving safety goals (see Table 3-1). They include:

- **Limiting the maximum power that can be reached under all circumstances.** This can be achieved, for example, by
  - ***operating with a sub-critical core:*** Precludes criticality accidents when used in conjunction with other features. The core does not "go critical" at any time.
  - ***incorporating inherent features that limit power to 100 % of the rated power of the unit:*** Precludes power excursion[18] accidents.
  - ***incorporating inherent and passive features that limit power to a safe level:*** Assures that the reactor power cannot rise to levels that would threaten the operating staff or the public. This safety benefit is achieved through features that shut the reactor down without the need for operator action or the initiation of special systems.
- **Using passive decay heat rejection.** Heat may be transferred to the environment passively in several ways:
  - ***directly to the environment:*** Decay heat is transferred directly from the reactor vessel to the environment by a combination of radiation and conduction, without operator action or the use of

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[18] A power excursion is an abrupt increase in power.

  special systems. This approach prevents the fuel from reaching temperatures that could pose a threat to station staff or the public.

  - ***to the environment via an intermediate circuit:*** An intermediate circuit conducts heat from the reactor coolant to the environment using natural convection.
  - ***in the absence of coolant in the reactor vessel and/or the reactor coolant system:*** Avoids reliance on active emergency core-cooling systems as the last defence against fuel melting.

- **Incorporating robust reactor coolant systems.** Designs may incorporate features such as

  - ***coolant circulation by natural convection at all power levels:*** Eliminates the requirement for reactor coolant circulation pumps, thereby improving the reliability of fuel cooling.
  - ***increased reactor-coolant system inertia:*** Passive features are used to extend the time required for reactor coolant circulation to stop after a loss of power to the circulating pumps, thereby increasing the time available to activate decay heat removal systems.
  - ***increased specific coolant inventory (volume of coolant per MW):*** Increases a reactor's tolerance to loss of cooling and extends the time available to activate decay heat removal systems.

- **Reducing the power density in the core:** Increases a reactor's tolerance to power excursions and loss of cooling by operating the fuel at a lower normal power level. The capability of the fuel to retain heat before temperatures that could damage it are reached is increased, thereby increasing the time available for safety systems to be activated and/or for operators to act. Peak fuel temperatures are reduced under accident conditions.

- **Reducing the number of components in the primary and secondary systems:** Innovative technologies are used to reduce the number of components while still meeting safety objectives, resulting in increased reliability and reduced capital and operating costs.

- **Using advanced and compatible materials.** For example,
  - ***using in-core materials with increased thermal capability:*** Coolant and/or moderator materials can be used that have one or more of the following properties: high temperature capability, high heat capacity and high thermal conductivity. Such materials, which include graphite, lead and helium, can increase the core heat capacity and allowable temperature, thereby increasing the time available for safety systems to be activated and/or for operators to act.
  - ***using moderators, coolants and in-core materials that are resistant to reactions with air or water:*** Reduces the potential for chemical reactions that could accelerate and/or increase the severity of accidents.
- **Designing reactors to have negative temperature and void coefficients:** Causes the reactor power to fall with increasing core temperature and with the loss of coolant from the core.
- **Incorporating two independent and diverse shutdown systems:** Reduces the potential for a single failure to disable the capability to shut down the reactor.
- **Increasing protection of the pressure vessel from neutron flux-induced embrittlement:** Reduces the potential for rupture of the pressure vessel.
- **Providing a comprehensive containment system:** Prevents or minimises radioactivity release to the environment following specific design-basis accidents.
- **Operating at pressures substantially lower than those of current water-cooled reactors:** Facilitates a robust design and may reduce the probability of component failure.
- **Operating with minimum excess reactivity in the core:** Minimises the potential for uncontrolled reactivity[19] excursion accidents.

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[19] Reactivity is a measure of the departure from criticality of a reactor core. A core is "critical" when its nuclear-fission chain reaction is just self-sustaining.

- **Providing a large volume of water within the containment structure:** Helps assure adequate fuel cooling following several design-basis events by providing additional emergency water for fuel cooling.
- **Operating without soluble neutron absorbers (poisons) in the core:** Precludes reactivity transients that could result from the addition to the core of coolant that does not contain poisons.[20]
- **Increasing passivity of reactor shutdown systems:** Increases shutdown system reliability by reducing or eliminating reliance on external power supplies and control actions.
- **Using design features that preclude events that normally would have to be considered:** An example of this approach is using design features that preclude ejection of control rods from the core. The approach reduces the number of potential accident scenarios.

Economic Competitiveness

Economic Goals

The main economic goal of future nuclear power plants is to achieve competitiveness with other ways of generating electricity, especially natural-gas combined-cycle plants.[21]

Compared with other energy sources, the nuclear power plant designs currently available have very high capital costs per MW_e. These costs are not fully offset by the low fuel cost of nuclear power plants within an economically competitive time frame (normally 5 to 15 years). In addition, the nuclear power plants now available have high total capital costs as a result of their large outputs (in the range of 600 to 1500 MW_e). As a result, nuclear power is too expensive for most private investors and developing countries.

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[20] Poisons absorb neutrons so that they cannot cause fissions. When liquid coolant contains soluble poisons, the addition of coolant without poisons decreases the overall neutron absorption of the coolant, increasing reactivity.

[21] Nuclear plants designed to sell heat, potable water or hydrogen as well as power must be economically competitive with other means of manufacturing these products.

Current nuclear power plants typically require five years or more to build and commission. Combined-cycle gas facilities may require only two years. A long construction period imposes a substantial financial burden on the investors, since cash outflow is high and no income is earned during the construction and commissioning period. The resulting high interest charges are detrimental to overall plant economics. A long project schedule also generates financial risk; many things can change over the span of a nuclear power project, including governments, public opinion, the demand for energy, and the financial circumstances of the utility or host country. As a result, financial institutions generally demand higher interest rates on loans for nuclear power plants than they do for non-nuclear facilities.

Specific goals of new nuclear power plant designs are therefore to use features that improve economic competitiveness, including those that reduce overnight construction cost, construction time, operating and maintenance costs, and fuel-cycle costs, and those that improve reliability or capacity factor.

General Approaches to Achieving Economic Goals

The designers of the innovative reactors considered in this report have proposed a number of approaches to achieving economic goals (see Table 3-1).

In some cases, innovative reactor designs have taken opposite approaches to economic competitiveness – for example, some concepts increase the primary-system pressure, while another reduces it.

Approaches to achieving economic goals include:

- **Operating at increased core-outlet temperature:** Increases thermodynamic efficiency when the unit is operated for electricity production and may increase energy utilisation in process-heat and cogeneration applications. The energy available from a reactor with a particular thermal output is increased relative to a reactor operating at lower temperature, thereby reducing the capital cost per MW.

- **Reducing the number of components in the primary and secondary systems:** Lowers capital and operating costs.
- **Using factory assembly and modularisation:** Reduces construction cost and time.
- **Using advanced and innovative technologies:** Encompasses the use of technologies ranging from computer-aided design to Brayton cycle-based power generation. Benefits include lower design, construction, component and operating costs and shorter construction schedules.
- **Operating at low primary-system pressures:** Avoids the capital costs associated with high-pressure nuclear components, and may reduce the cost of maintenance and inspection activities.
- **Reducing containment-system structural requirements:** Involves using coolants and moderators that have a very high boiling point and/or temperature capability, or providing the containment function in a non-traditional manner. This approach minimises the cost of the reactor containment system.
- **Increasing the power density in the core:** Increases the power produced by a reactor core of a particular size, thereby reducing the capital cost per MW.[22]
- **Increasing fuel-cycle duration or using on-power refuelling:** Tends to increase the capacity factor, which improves plant economics.
- **Using innovative approaches to waste management:** Reduces the cost of routine waste-management operations.
- **Increasing the reliability and/or redundancy of key components:** Can result in higher capacity factors and lower maintenance costs, although increased redundancy raises the capital cost per MW_e.

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[22] *The opposite approach is used to increase safety.*

- **Reducing the reactor size to 300 MWe or less:** Reduces the total cost of the generating unit and can shorten the construction schedule by facilitating a simplified design and the use of advanced construction techniques.

Proliferation Resistance and Safeguards

Proliferation Resistance and Safeguards Goals

There are two different public and government concerns about nuclear proliferation. The first is the possible production of one or more nuclear weapons by states that do not currently have them. The second is the threat posed by fissile material's being obtained by terrorist organisations and used to manufacture one or more nuclear explosive devices. The goal of future nuclear power plants and their related fuel-cycle facilities is to minimise the potential for both these activities.

There is historically little connection between commercial nuclear power plants and the production of military explosives. However, there is a technical link between enrichment and reprocessing plants and the ability to produce weapons-grade materials.

The threat posed by terrorist organisations that might obtain fissile material has received a great deal of consideration to date. The existing IAEA safeguards programme would assure detection of the diversion of fissile material. However, the material could cross one or more borders, and there is no international protocol in place covering the actions needed to locate and recover stolen fissile material.

A goal of new nuclear reactors is to minimise the potential for proliferation and terrorist activities through proliferation-resistant design approaches in combination with IAEA and other safeguards.

General Approaches to Achieving Proliferation Resistance and Safeguards Goals

The designers of the innovative reactors considered in this report have proposed a number of approaches to achieving proliferation resistance and safeguards goals (see Table 3-1). Those cited here and in Table 3-1 are examples. Some of them might provide a benefit under one set of circumstances, whereas they might have detrimental effects under a different set of circumstances. A careful review will hence be needed to assess the non-proliferation benefit obtained from applying a specific approach in a specific situation.

The approaches taken to achieving proliferation resistance and safeguards goals include:

- **Simplifying the accommodation of IAEA safeguards equipment:** This approach, which is applicable to reactors, fuel-enrichment plants and reprocessing plants, incorporates the provision of IAEA safeguards in the basic design of the facility, thereby reducing cost and assuring effectiveness.

- **Operating on a once-through fuel cycle:** Treats spent fuel as waste, eliminating the need for fuel reprocessing and the associated requirements for safeguarding and monitoring the reprocessing facilities. It also eliminates the need to store, monitor and dispose of the products and byproducts of the reprocessing facilities. On the other hand, this approach leads to the need to store, monitor and dispose of spent fuel in a final disposal facility. It increases the total plutonium inventory and may encourage future plutonium mining.

- **Operating on a closed fuel cycle, using a reprocessing method that returns actinides to the reactor for consumption:** Avoids the separation of actinides during reprocessing and thus the need to store them.

- **Operating at a breeding ratio of (near) 1:** This approach, which is applicable to breeder reactors, avoids the need for a uranium blanket around the core or the installation of other devices for fissile material production.

- **Using features that make it difficult to extract fissile material from spent fuel:** Provides an additional barrier to the production of nuclear weapons, and thereby discourages diversion. On the other hand, material accountancy – keeping track of the amounts and locations of nuclear materials – may become more complicated if such features are implemented.
- **Using features that ensure a very low amount of plutonium in the spent fuel:** Makes it difficult to extract sufficient plutonium to build a nuclear weapon, due to the very large volumes of spent fuel that must be processed.
- **Reducing the amount of actinides produced:** Reduces the amount of fissionable and fissile actinides that could be extracted from the spent fuel.
- **Reducing the amount of fuel stored at a site:** Reduces the amount of material that could potentially be diverted to weapons production or terrorist activities. On the other hand, this approach may lead to an increase in the number of storage sites, each with sufficient fissile material for the production of one or more nuclear weapons or other nuclear explosive devices. It might also increase transport requirements with a consequent increase in the risks of theft or sabotage.

Waste Management

Waste Management Goals

The goals of future nuclear power plants and their related fuel-cycle facilities include minimising the burden of radioactive-waste management, transport, storage and disposal.

The management and disposal of radioactive waste affect several aspects of nuclear energy competitiveness and raise public concern. Radioactive-waste management and disposal increase the overall capital cost of nuclear systems. They also increase the operating costs of power plants and fuel facilities and add to the total fuel-cycle cost. Public concern is broad-based, encompassing the storage, transportation and long-term disposal of radioactive waste, particularly high-level waste.

General Approaches to Achieving Waste Management Goals

The designers of the innovative reactors considered in this report have proposed a number of approaches to achieving waste management goals (see Table 3-1). They include:

- **Using thorium as a major component of the reactor fuel:** Reduces the quantity of higher actinides, such as plutonium, produced in the reactor.

- **Operating at very high fuel (uranium) burnup, and/or as a breeder or near-breeder:** Reduces the volume of waste fuel per kWh produced by the reactor.

- **Reducing the volumes of low- and medium-level wastes produced per kWh:** Reduces the volumes of low- and medium-level waste that must be stored at the site and transported to storage facilities.

- **Operating on a once-through fuel cycle:** Eliminates the need for transport of irradiated fuel to a reprocessing facility and avoids the waste-generation and -management problems associated with fuel reprocessing. On the other hand, this approach fails to exploit the benefits of sorting waste materials, extracting and recycling valuable components, and selectively conditioning waste for disposal. It also leads to the need to store, monitor and dispose of spent fuel in a final disposal facility and increases the volume of waste that must be disposed of.

- **Operating on a closed fuel cycle with non-aqueous fuel reprocessing:** Actinides are not separated during reprocessing, but returned to the reactor, where they are consumed.
- **Avoiding the need to remove fuel from the reactor over the operating life of the plant.**
- **Storing all spent fuel generated during the plant operating life on-site:** Removes constraints on operation that may arise due to lack of storage space or lack of final disposal arrangements for spent fuel.

Efficiency of Resource Use

Efficiency of Resource Use Goals

More efficient use of fuel resources than in the current generation of reactors may offer several benefits to future nuclear power plants, particularly if there is a significant increase in the use of nuclear energy. Potential benefits include moderating uranium prices, extending the lifetime of uranium resources, and reducing the quantity of radioactive waste produced by a nuclear power plant and its related fuel-cycle facilities. Increased resource utilisation is therefore a long-term goal for future nuclear power plants.

Another goal for future plants is to reduce the use of land, water and other resources per MW of capacity and per MWh produced. This goal, however, is not treated here.

General Approaches to Achieving Resource Efficiency Goals

The designers of the innovative reactors considered in this report have proposed a number of approaches to increasing resource efficiency (see Table 3-1). They include:

- **Adding thorium, a fertile material, to the fuel:** Under this approach, a large portion of the reactor's output is produced by fissioning of the ^{233}U resulting from neutron capture by thorium, which results in reduced requirements for naturally-occurring fissile uranium (^{235}U).

- **Operating as a breeder or near-breeder:** Fertile ^{238}U or ^{232}Th is converted to fissile ^{239}Pu or ^{233}U during reactor operation. The total amount of fissile material produced is dependent on the reactor design, and can be less, in a near-breeder, or greater, in a breeder, than the amount of fissile material consumed.
- **Adding plutonium and/or recovered uranium to the fuel:** Allows the reactor to consume weapons-grade plutonium, and to use the plutonium and uranium recovered by LWR fuel-reprocessing plants. This serves to reduce the requirement for uranium resources.
- **Operating at increased core-outlet temperature:** Increases thermodynamic efficiency when the unit is operated for electricity production, and may also increase energy utilisation in process-heat and cogeneration applications. Operating at a high core-outlet temperature increases the useful energy available from a reactor, thereby reducing the amount of fuel required for a given thermal output.

Flexibility of Application

Flexibility of Application Goals

A goal of some designers is to increase the number of applications that nuclear power plants can serve, and thus to gain a significant portion of the non-electricity primary energy market.

Available nuclear power plant designs are not compatible with most process-heat applications due to their temperature limitations and/or their large heat output. A typical 1,000-MW_e nuclear power plant of current design produces about 3,000 MW_{th}, of which about 2,000 MW_{th} is rejected as waste heat. This is far in excess of the amount of heat that can be used economically by most process-heat applications. In addition, the heat, even if taken directly from the reactor cooling system, is at a relatively low temperature, typically under 300ºC. This temperature is below that needed for many process-heat applications.

Specific goals of at least a portion of future nuclear power concepts are viability in sizes less than 600 MW_{th} and the provision of temperatures above 600ºC so as to make a substantial contribution to meeting process heat demand.

General Approaches to Achieving Flexibility of Application Goals

The designers of the innovative reactors considered in this report have proposed a number of approaches to achieving flexibility of application goals (see Table 3-1). They include:

- **Operating at core-outlet temperatures much higher than those of current water-cooled reactors:** Allows the reactor to serve an increased range of process-heat applications, including those that require medium and high temperatures.
- **Reducing the reactor size to 300 MW_e or less:** Provides a better match between the amount of energy required by many process-heat and cogeneration applications and the reactor output than has been possible so far.
- **Using designs that are relatively robust and simple:** Facilitates integration of the nuclear unit into industrial facilities by reducing operation and maintenance demands.

Summary Table

Table 3-1 summarises briefly the approaches used by the reactor designs considered in this report to achieve the goals just discussed. A more detailed version of this table is available in Volume I of the Background Report.

Table 3-1

Approaches to Achieving Goals

	Safety	Economic Competitiveness	Proliferation Resistance	Waste Management	Efficiency of Resource Use	Flexibility of Application
Light-Water Reactors						
CAREM-25	Decay heat is rejected to the environment by passive systems. Natural circulation of coolant at all powers. Increased specific coolant volume. Reduced core-power density. Reduced number of components. Negative temperature- and void-reactivity coefficients. Two independent shutdown systems. Increased protection against flux-induced embrittlement of the pressure vessel. Comprehensive containment system. Large volume of water in the containment. No soluble poisons are used in the reactor coolant. Increased passivity of shutdown systems. Control rods do not penetrate the reactor pressure vessel, thereby precluding the potential for ejection.	Integral design, reducing the number of nuclear steam plant (NSP) components. Natural circulation at all power levels avoids use of reactor coolant pumps; self-pressurisation of the pressure vessel is used. Design facilitates modularisation and factory assembly. Design achieves a reduced containment-system design pressure. Uses advanced and innovative technologies. Compact, efficient layout. Increased component redundancy (full power maintained with one steam generator out of service). Small size (27 MW_e) offers low total capital cost.	Design features are intended to simplify application of IAEA nonproliferation safeguards. Operates on a once-through fuel cycle. Reduced quantity of spent fuel at a site, if a small number of units are installed at the site.	Reduced volumes of low- and medium-level waste. Operation on a once-through fuel cycle.	Does not incorporate features that change uranium resource utilisation significantly relative to current PWRs.	The temperature available is similar to that from current PWRs. Small size is suited to many process-heat and cogeneration applications. Design is simple and robust.

Table 3-1

Approaches to Achieving Goals

	Safety	**Economic Competitiveness**	**Proliferation Resistance**	**Waste Management**	**Efficiency of Resource Use**	**Flexibility of Application**
SMART	The same approaches followed by CAREM-25 are used, except: • Forced coolant circulation is used at power. • One safety shutdown system is used.	The same approaches followed by CAREM-25 are used, except: • Forced coolant circulation is used at power. • All steam generators are required for full-power operation.	Operates on a once-through fuel cycle. Reduced quantity of spent fuel at a site, if a small number of units are installed at the site.	Reduced volumes of low- and medium-level waste. Operates on a once-through fuel cycle.	Does not incorporate features that change uranium resource utilisation significantly relative to current PWRs.	The temperature available is similar to that from current PWRs. Small size is suited to many process-heat and cogeneration applications. Design is simple and robust.
NHR-200	The same approaches followed by CAREM-25 are used, except: • Spent fuel is stored around the core, further protecting the pressure vessel. • Steam generators are replaced by heat exchangers. • Operates at reduced temperature and pressure.	The same approaches followed by CAREM-25 are used. In addition: • Spent fuel (ten years of operation) is stored in the pressure vessel. • The reactor coolant system operates at reduced pressure.	Design features are intended to simplify application of IAEA nonproliferation safeguards. Operates on a once-through fuel cycle. Reduced quantity of spent fuel at a site, if a small number of units are installed at the site.	Reduced volumes of low- and medium-level waste. Operates on a once-through fuel cycle.	Does not incorporate features that change uranium resource utilisation significantly relative to current PWRs.	Small size is suited to many process-heat and cogeneration applications. The low core temperature relative to current PWRs further limits the potential for process-heat applications. Design is simple and robust.

Table 3-1

Approaches to Achieving Goals

	Safety	**Economic Competitiveness**	**Proliferation Resistance**	**Waste Management**	**Efficiency of Resource Use**	**Flexibility of Application**
MRX	Decay heat is rejected to the environment by passive systems. Increased specific coolant volume. Reduced core-power density. Reduced number of components. Negative temperature- and void-reactivity coefficients. Increased protection against flux-induced embrittlement of the pressure vessel. Comprehensive containment system. Large volume of water in the containment. No soluble poisons are used in the reactor coolant.	The same approaches as followed by CAREM-25 are used, except: • Forced coolant circulation is used at power. • All steam generators are required for full power operation.	Operates on a once-through fuel cycle. Reduced quantity of spent fuel at a site, if a small number of units are installed at the site.	Reduced volumes of low- and medium-level waste.	Does not incorporate features that change uranium resource utilisation significantly relative to current PWRs.	The temperature available is similar to that from current PWRs. Small size is suited to many process-heat and cogeneration applications.

Table 3-1

Approaches to Achieving Goals

	Safety	Economic Competitiveness	Proliferation Resistance	Waste Management	Efficiency of Resource Use	Flexibility of Application
Barge-Mounted KLT-40	Uses a conventional PWR NSP configuration. Decay heat is rejected to the environment by diverse, redundant passive systems. Increased specific coolant volume. Reduced core-power density. Negative temperature- and void-reactivity coefficients; self-regulation of reactor power at all power levels. Diverse and redundant shutdown systems. Increased protection against flux-induced embrittlement of the pressure vessel. Comprehensive containment system. No soluble poisons are used in the reactor coolant. Safety shutdown systems are activated by passive means.	Uses a conventional PWR NSP configuration. Factory fabrication is maximised by barge delivery of two complete units, including all NSP support facilities. Reduced containment-system design requirements. All radioactive waste generated over a 12-year operating cycle is stored in facilities on the floating power unit (FPU), which is returned to a central facility for overhaul and waste disposal. Uses passive systems and advanced technologies. Small size (35 MW_e) offers low total capital cost.	Design features are intended to simplify application of IAEA nonproliferation safeguards (but the barge-mounted concept may pose special challenges regarding theft and sabotage). Operates on a once-through fuel cycle. Reduced quantity of spent fuel at a site (maximum of 12 years' accumulation), if a small number of units are used at the site.	Reduced volumes of low- and medium-level waste. All radioactive waste generated over a 12-year operating cycle is stored in facilities on the FPU, which is returned to a central facility for waste disposal. At the end of its operating life, the FPU is delivered to a central facility for decommissioning.	Does not incorporate features that change uranium resource utilisation significantly relative to current PWRs.	The temperature available is similar to that from current PWRs. Small size is suited to many process-heat and cogeneration applications.

Table 3-1

Approaches to Achieving Goals

	Safety	Economic Competitiveness	Proliferation Resistance	Waste Management	Efficiency of Resource Use	Flexibility of Application
Heavy-Water Reactors						
CANDU X	Decay heat is removed by passive systems, even if there is no coolant in the reactor coolant system. A negative void-reactivity coefficient can be provided. Two independent and diverse passive shutdown systems are used. No pressure vessel is used (the CANDU X is a pressure-tube reactor). Comprehensive containment system. Operates with minimum excess reactivity in the core (on-power refuelling). Large volume of water in the containment. No soluble poisons are used in the reactor coolant.	Increased thermodynamic efficiency due to increased core-outlet temperature. Modularisation is used extensively. Uses innovative technologies and features, including supercritical coolants. Increased core-power density. On-power refuelling eliminates the need for refuelling outages. Increased use of passive systems. Smallest unit (350 MW_e) is about half the size of current CANDU plants, reducing total capital cost.	Operates on a once-through fuel cycle. Reduced amount of actinides is produced if operated on a thorium fuel cycle. (Note that on-power refuelling introduces nonproliferation safeguards issues that must be addressed.)	Use of thorium fertile material and slightly-enriched fuels would reduce the amount of higher actinides produced. Operates on a once-through fuel cycle. Reduced volumes of low- and medium-level waste.	Resource utilisation depends on the enrichment level and thorium content of the fuel. Can operate on plutonium and recovered uranium. Increased thermodynamic efficiency increases resource utilisation.	Increased core-outlet temperature increases the number of process-heat applications that can be served. Smallest version (350 MW_e) is better suited to process-heat applications than current CANDU designs.

Table 3-1

Approaches to Achieving Goals

	Safety	Economic Competitiveness	Proliferation Resistance	Waste Management	Efficiency of Resource Use	Flexibility of Application
Liquid-Metal Fast Reactors						
BREST 300	Decay heat is transferred to the environment by passive systems. Increased reactor-coolant system inertia. Reduced number of NSP components. Lead coolant with high temperature capability is used. Negative void-reactivity coefficient. The low-pressure vessel is protected from flux-induced embrittlement. Reactor coolant system operates at low pressure. Operation at a breeding ratio of near 1 provides minimal excess reactivity in the core. No soluble poisons are used in the reactor coolant.	Increased thermodynamic efficiency due to increased core-outlet temperature. Reduced number of components in the NSP. Uses innovative technologies – for example, a fast reactor, a lead coolant and a supercritical secondary coolant. Reactor coolant system operates at low pressure. Reduced containment-system design requirements. Small size (300 MW_e) reduces total capital cost relative to current plants.	Operates with a breeding ratio of near 1. Closed fuel cycle returns actinides to the reactor with new fuel, where they are consumed.	Operation as a breeder reduces the quantity of spent fuel produced. Closed fuel cycle returns actinides to the reactor with new fuel, where they are consumed. Reduced volumes of low- and medium-level waste.	Operation as a breeder reduces uranium resource requirements. Increased thermodynamic efficiency increases resource utilisation.	Increased core-outlet temperature increases the number of process-heat applications that can be served. Output of 300 MW_e is a better match for process-heat applications than that of current PWRs. Design is simple and robust.

Table 3-1

Approaches to Achieving Goals

	Safety	Economic Competitiveness	Proliferation Resistance	Waste Management	Efficiency of Resource Use	Flexibility of Application
Energy Amplifier	Reactor core is sub-critical at all times. Reactor power is limited to near 100% by inherent features. Two diverse and fully passive shutdown systems are used. Reactor coolant circulation by natural convection at all power levels. A very large specific coolant volume is provided. Reduced number of components in the NSP. Coolant (lead) has a high temperature capability. Reactor vessel is protected from flux-induced embrittlement. Minimum excess reactivity in the core at all times. No soluble poisons are used in the reactor coolant. The two safety shutdown systems are operated by passive means.	Increased thermodynamic efficiency due to increased core-outlet temperature. Reduced number of components in the NSP. Uses innovative technologies – for example, an accelerator- driven sub-critical core, a lead coolant and a supercritical secondary coolant. Reactor coolant system operates at low pressure. Increased use of passive systems. Reduced containment-system design requirements. Refuelling period extended to five years.	Operates with a breeding ratio of near 1. Closed fuel cycle returns actinides to the reactor with new fuel, where they are consumed. The plutonium fraction in the spent fuel is very low.	Thorium is a major component of the fuel, reducing the quantity of higher actinides produced. Operation as a breeder reduces the quantity of spent fuel produced. Closed fuel cycle returns actinides to the reactor with new fuel, where they are consumed. Reduced volumes of low- and medium-level waste.	Use of thorium as major component of the fuel reduces uranium resource requirements. Increased thermodynamic efficiency increases resource utilisation.	Increased core-outlet temperature increases the number of process-heat applications that can be served. Design is simple and robust.

Table 3-1

Approaches to Achieving Goals

	Safety	**Economic Competitiveness**	**Proliferation Resistance**	**Waste Management**	**Efficiency of Resource Use**	**Flexibility of Application**
Gas Reactors						
GT-MHR	Inherent reactor shutdown at elevated temperature is provided by negative temperature-reactivity coefficient. Decay heat is transferred passively from the pressure vessel directly to the environment, even if there is no coolant in the pressure vessel. Low core-power density. Reduced number of components. Use of direct Brayton cycle reduces the potential for water ingress. Helium coolant, graphite moderator and fuel all have high temperature capability. Strong negative temperature coefficient. Pressure vessel is protected from flux-induced embrittlement. Containment function is provided by the TRISO fuel. No soluble poisons are used in the reactor coolant.	Increased thermodynamic efficiency due to increased core-outlet temperature. Reduced number of components in the NSP and balance-of-plant. Uses innovative technologies – for example, a helium coolant, a graphite moderator and a direct Brayton cycle. Increased use of passive systems. Compact, efficient layout. Refuelling period extended to three years. Small size (286 MW_e) reduces total capital cost relative to current plants.	Operates on a once-through fuel cycle. Fissile material is diffuse and difficult to remove from spent fuel. Amount of higher actinides produced is substantially lower than for current PWRs.	Provides a very high burnup (two to three times that of current PWRs). Can use thorium fertile material in the fuel; reduces the quantity of higher actinides produced. Operates on a closed fuel cycle. Reduced volumes of low- and medium-level waste.	Increased thermodynamic efficiency increases resource utilisation. Can use thorium fertile material in the fuel; reduces uranium resource requirements. Use of plutonium in the fuel is being studied.	Increased core-outlet temperature increases the number of process-heat applications that can be served. Low power output increases the number of process-heat applications that can be served. Design is compact and robust.

Table 3-1

Approaches to Achieving Goals

	Safety	Economic Competitiveness	Proliferation Resistance	Waste Management	Efficiency of Resource Use	Flexibility of Application
PBMR	The same approaches followed by the GT-MHR are used. In addition: • On-power refuelling maintains minimum excess reactivity in the core at all times.	The same approaches followed by the GT-MHR are used. In addition: • On-power fuelling is used, which eliminates the need for refuelling outages. • Small size (110 MW_e) offers low total capital cost.	The same approaches followed by the GT-MHR are used. (Note that on-power refuelling introduces non-proliferation safeguards issues that must be addressed.)	The same approaches followed by the GT-MHR are used. In addition: • Provision for on-site storage of all spent fuel generated over the design life.	The same approaches followed by the GT-MHR are used, except: • On-power refuelling provides a small increase in resource utilisation relative to the GT-MHR. • There are no current plans to use plutonium in the fuel.	The same approaches followed by the GT-MHR are used.

Table 3-1

Approaches to Achieving Goals

	Safety	Economic Competitiveness	Proliferation Resistance	Waste Management	Efficiency of Resource Use	Flexibility of Application
Molten-Salt Reactors						
FUJI	Inherent features (negative temperature-reactivity coefficient and fuel/coolant density reduction with temperature) limit reactor power. Decay heat can be transferred passively to the environment. The molten-salt coolant and graphite moderator have high temperature capability. On-power refuelling maintains minimum reactivity in the core at all times. The low-pressure vessel is protected from flux-induced embrittlement. No soluble poisons are used in the reactor coolant.	Increased thermodynamic efficiency due to increased core-outlet temperature. Reduced number of components in the NSP. Uses innovative technologies – for example, a molten-salt coolant, a fuel that is dissolved in the coolant and a graphite moderator. Reactor coolant system operates at low pressure Increased use of passive systems. Reduced containment-system design requirements. Compact, efficient layout. On-power refuelling eliminates the need for refuelling outages. Small size (100 MWe) offers low total capital cost.	Operates on a closed fuel cycle. Fissile material is difficult to remove from spent fuel. Operates with a breeding ratio of near 1. No spent fuel is stored at the site. Over the operating life no fuel is removed from the reactor and no fission products are removed from the fuel/coolant fluid.	Thorium is a major component of the fuel cycle, reducing the amount of higher actinides produced. Operates as a near-breeder. Reduced volumes of low- and medium-level wastes. Over the operating life no fuel is removed from the reactor and no fission products are removed from the fuel/coolant fluid.	Increased thermodynamic efficiency increases resource utilisation. Operates as a near-breeder, reducing uranium resource requirements. Thorium is a major component of the fuel cycle.	Increased core-outlet temperature increases the number of process-heat applications that can be served. Viable at low power output; increases the number of process-heat applications that can be served. Design is simple and robust.

Table 3-1

Approaches to Achieving Goals

	Safety	Economic Competitiveness	Proliferation Resistance	Waste Management	Efficiency of Resource Use	Flexibility of Application
Other						
RTFR	RTFR is a fuel-cycle option, applicable to both light-water and heavy-water reactors. The approaches adopted by these reactor types are therefore applicable.			Use of thorium fertile material reduces the quantity of higher actinides produced. Offers a very high burnup.	The use of thorium fertile material greatly reduces the amount of uranium resources required.	RTFR is a fuel-cycle option, applicable to both light-water and heavy-water reactors. The approaches adopted by these reactor types are therefore applicable.

CHAPTER 4
ENABLING TECHNOLOGIES, R&D NEEDS AND OPPORTUNITIES FOR COLLABORATION

Introduction

This chapter provides a brief review of some enabling technologies for the innovative reactors considered here, along with an assessment of the potential for collaboration on research and development (R&D). The discussion draws on the chapters on "Enabling Technologies" and "Opportunities for Collaborative Research and Development" in Volume I of the Background Report (3A 2001).

Enabling Technologies

The enabling technologies discussed here are used to varying degrees by a large number and variety of reactor designs. They fulfil generic functions or meet generic needs, such as heat removal, that are common to most reactors. Improvements in such underlying technologies and approaches can form the basis for substantial innovation in reactor technologies.

One way to consider reactors of the future is to identify principal and cross-cutting nuclear-system requirements and then to explore various available or possible approaches to meeting them. This gives reactor designers a range of options to examine.[23]

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[23] *This analytical approach has been satisfactory for reviewing the set of reactors considered in this study. It could be usefully applied to a broader range of designs and a more speculative set of scenarios for future industry developments. Researched approaches also would need to be subject to economic assessment whereby basic engineering data are converted to estimated costs, permitting researchers and reactor designers to ascertain early in the research process which approaches are likely to be uneconomic.*

The innovative reactors considered here encompass a wide and diverse range of technologies and various timetables for achieving commercial operation (see 3A 2001, Volume I). The enabling technologies that must be developed or improved to assure the success of these designs are equally diverse, ranging from the development of fundamental materials and chemistry-control processes to the design and performance verification of major components. In many cases, fundamental correlations and computer codes must be developed.

Some enabling technologies are not dependant on a particular reactor type. Their further development could be beneficial to many of the innovative reactors considered here. Examples include construction and delivery methods and some in-service inspection technologies. Others, such as those related to auxiliary and support systems, are common to several reactor designs using different configurations or coolants – for example, the use of supercritical water as the secondary-side coolant in the BREST 300, Energy Amplifier and CANDU X designs. Some enabling technologies, usually related to reactor systems, are common to, but also limited to, reactors of the same type and/or using the same coolant. Still others are unique to a particular reactor design (for example, the accelerator used by the Energy Amplifier).

The section titled "Past Experience with Fission Reactor Concepts, Design and Operation" and following sections describe some enabling technologies identified in this study.

Research and Development

Research programmes for each of the innovative reactor designs considered here are described in Volume I of the Background Report (3A 2001). As detailed therein, the R&D and design efforts on innovative nuclear reactors are funded at very low levels compared with the efforts made in the 1950s, 1960s and 1970s to develop the current generation of reactors, and compared with current R&D expenditures on maintaining and enhancing the performance of operating reactors. Assuming continuation of these low levels of investment, most of the designs considered here could require 10 to 15 years or longer to become commercially available (see 3A 2001, Volume I). Enhanced collaboration that makes effective use of current investments could reduce the time and cost required to make technologies available commercially.

The wide range of enabling technologies being developed limits the amount of collaborative R&D effort that is feasible. But ample opportunities remain, in support of or beyond the work being done on the innovative concepts reviewed here. Also, collaborative efforts could be of interest to other R&D groups active in the field that were not included here.

Collaborative research programmes could embrace many research and design teams and organisations, including those working on evolutionary as well as innovative reactors, as long as they have common interests in a given field or topic. This study, covering a limited number of concepts, has identified some potential areas of collaboration based on the enabling technologies described in the following sections. Possible collaborative R&D efforts are outlined briefly where applicable. Many other opportunities may exist. A more comprehensive review of ongoing R&D efforts worldwide would be needed for a thorough analysis of the potential for international endeavours to develop innovative reactor concepts and designs adapted to the needs of the 21st century.

Where collaborative research is suggested, it is based on the relevance of the area to the development of several types of innovative designs. The areas for which collaboration is suggested may be amenable to international co-operation among several research teams without necessitating the sharing of proprietary information or know-how.

In many cases, the suggested initial phase of a collaborative effort is the establishment of a comprehensive experience database. In subsequent stages, the database would be organised so as to facilitate easy access and reference by reactor designers and the data would be analysed to identify devices that have common operating principles or functions. More detailed examinations could follow, covering the advantages and disadvantages of devices, the range of conditions and circumstances under which they can be used, and their development status. This information could then be used to identify specific opportunities for collaborative R&D and design.

Past Experience with Fission Reactor Concepts, Design and Operation

During several decades of research on nuclear fission, virtually every feasible combination of moderator and reactor coolant has been considered by one or more teams, often in several countries. A large number of prototype and demonstration reactors were designed, built and operated in the 1950s and 1960s. The experience accumulated through the operation of those reactors, which in many cases performed very well, constitutes a wealth of valuable information. It should be considered "enabling information" for current design and development efforts, but discussions with some reactor design teams indicate that information and data from early development efforts are not being fully used in current design programmes.

The industrial development of nuclear power led to the abandoning of some designs and concepts, despite their promising technical performance, in light of the dominant position of a few reactor types, mainly light-water and heavy-water reactors. Potentially economic and technically viable reactor concepts that were dropped include the organic-cooled, heavy-water-moderated WR-1 reactor in Canada; the molten-salt-cooled, graphite-moderated MSRE in the United States; and the sodium-cooled, graphite-moderated Hallam reactor in the United States.

The acquired knowledge, know-how and lessons learned while building and operating prototype and demonstration reactors are relevant to scientific, technical, economic and safety aspects of designs as well as fuel-cycle characteristics and means to address non-proliferation. It is important to conserve this information and make it available to today's researchers and to future generations. Having this information readily available would help today's innovative reactor R&D teams assess its relevance to their work. Conserving it would ensure that, as the nuclear scientists and engineers active in the second half of the last century age and retire, valuable information on many technologies is not lost.

Potential Collaborative R&D

Although there is an extensive literature on the scientific and technical aspects of prototype and demonstration reactors operated since the beginning of nuclear power development, and on their operational performance, there is no comprehensive compilation of this information readily available to potential users. An international, collaborative programme could identify, compile and make available a comprehensive survey of this published literature.

The programme would not have to start from scratch. The ten-volume IAEA publication "Directory of Nuclear Reactors" (IAEA 1962) contains a wealth of relevant information. Volumes I and IV provide an excellent summary of the demonstration and prototype power reactors that were built and operated; Volumes II and III give similar information for research reactors. Other sources include the IAEA "Country Profiles", which provide lists and descriptions of the reactors constructed in each country, and literature searches.

The main outcome from the proposed programme would be a comprehensive compilation of information on experience acquired by demonstration and prototype reactors built and operated in the past. The survey would identify the technologies behind reactor concepts, catalogue the anticipated advantages and disadvantages of the concepts, and review their operating experience, including problems encountered.

The information could also be used to identify areas where recent scientific and technological progress may help overcome difficulties encountered in the 1950s and 1960s. Such assessments could justify revisiting concepts and designs that were not successful in the past or suggest new approaches to innovative concepts.

The programme could take advantage of computer databases and search engines to facilitate preliminary identification of information sources. The web sites of national laboratories and institutes active in the field of nuclear-fission research could also provide information. The main added value of the programme would be to establish a database supported by a large international network. Intergovernmental organisations having a mandate in the field of R&D on nuclear energy, such as the NEA, the IAEA and the IEA, could organise such an international co-operative programme.

Technology Assessment

The survey carried out for this study suggests that, in many cases, different approaches have been adopted by designers of various reactors to meet the same basic design requirement under similar circumstances. For example, in integral reactors, self-pressurisation and nitrogen pressurisation are both used in the reactor coolant system, as are forced circulation and natural convection. The self-pressurisation feature adopted by several integral reactors may be applicable to PWRs of conventional configuration, allowing the elimination of a pressure vessel and several nozzles.

Assessment of the various approaches to meeting design requirements, and of their state of development, would help design groups.

Potential Collaborative R&D

A collaborative research programme could begin by identifying the main nuclear steam-plant system requirements and the technologies and methods adopted to meet them in the current generation of reactors as well as in evolutionary and innovative reactor concepts and designs. A comprehensive survey of the literature would be useful.

The programme could then select a subset of technologies and methods for more detailed examination. For each item, the programme would provide a summary of the advantages and disadvantages, the range of conditions and circumstances under which it can be used, and its development status.

Natural Circulation

Natural-convection circulation of coolant in the reactor cooling system is used to some extent in all the reactor concepts studied in this report. Many of these uses are innovative. What is now needed is to develop or confirm the design basis and to develop and qualify computer codes to enable reliable analysis.

All the ordinary-water-cooled and heavy-water-cooled reactor designs covered here rely on natural convection of the coolant to remove decay heat from the fuel after shutdown. (Today's operating water reactors also rely on natural convection to remove decay heat when forced circulation is lost.) The CAREM-25 and NHR-200 use natural-convection circulation of the ordinary water coolant at all power levels to remove the heat of fission from the reactor core. This has not been done before in a PWR, although some early boiling-water reactors (BWRs) used natural-convection circulation. The Energy Amplifier and BREST 300 use natural circulation of the lead coolant to remove decay heat from the core after shutdown, requiring design of a reliable system to accommodate the potential solidification of the lead in regions outside the core. The Energy Amplifier also uses natural circulation of the coolant to remove the heat produced by fission from the reactor core at all power levels, something that has not been done before. The FUJI uses natural circulation of the molten-salt reactor coolant to remove decay heat from the core after shutdown.

The ability to predict the performance of systems operating in the natural-convection circulation mode is of fundamental importance. Such predictions are more easily achieved with systems, such as air and lead systems, that operate only in a single-phase mode without the presence of non-condensable fluids. It will be harder to predict the behaviour of systems that can potentially contain two-phase fluids and/or non-condensable fluids or that involve other complicating factors. A significant effort is needed in some cases to develop the necessary correlations for heat transfer fluids under all postulated operating conditions. A large portion of this effort is currently underway. Test facilities are operating in many research institutes to establish the technical basis for designing natural circulation systems for advanced reactors of the evolutionary or innovative type.

Potential Collaborative R&D

Researchers in the field of innovative reactor design should have easy access to the information and data from previous work carried out worldwide. A collaborative effort to provide this access could begin with the establishment of a comprehensive database of natural-circulation experience. The database would cover all situations in which natural circulation has been tested. It would identify key parameters for each situation, such as heat capacity and fluid temperature, pressure and velocity. A second phase of the programme could develop "maps" and other tools to illustrate the regimes of temperature, velocity and so on over which natural circulation is effective (this has been done for some boiling-water reactor designs), with specific attention given to scaling effects and to flow stability.

A list of thermo-hydraulic computer codes and analysis tools that are applicable to natural circulation could then be compiled. Since most existing codes are designed to study high-power or accident-transient situations, they are ill-adapted for natural circulation. The codes would be characterised according to factors significant for natural circulation, such as applicable ranges for fluid composition, pressure, temperature, heat-transfer regimes, non-condensable content and flow regime. If possible, error ranges for each parameter would be identified.

Further steps, based upon the results of this work, could include conducting new experiments and developing new analytical codes.

High-Temperature Materials

Several of the innovative reactor designs reviewed in this study operate at relatively high core-outlet temperatures, often above the allowable limits in safety codes for materials currently used in nuclear power plant components. In addition, some coolants – supercritical water, lead and molten salt – can erode or corrode materials they contact. Since reliability of reactor components is essential to safety as well as good economic performance, improved material resistance is vital to the overall efficiency of innovative reactor designs. Collaborative R&D in this field would be of interest for design teams in several countries.

Potential Collaborative R&D

A collaborative effort could begin by building a database identifying all materials that could be used at high temperature or in the presence of innovative reactor coolants. The database would include information on the composition of each material and its anticipated performance, and would summarise the available experience and research base.

A second phase of the programme could compile information on measures, such as heat treatment or the application of protective coatings, to protect each material.

Further work could include development and qualification of new materials and protective measures for specific applications.

Passive Devices

Passive devices are increasingly used in advanced reactor designs to meet stricter safety requirements in most countries. The current generation of reactors as well as evolutionary designs already rely to some extent on passive safety devices and the experience acquired in these reactors provides a strong basis for further R&D. It would be useful to compile information from different countries and organisations for the benefit of research teams working on innovative reactor designs.

Potential Collaborative R&D

A collaborative effort could begin by establishing a comprehensive database identifying the passive safety devices used in current reactors and planned for use in evolutionary or innovative reactor designs. The database would include information on the function of each device, its operating principles and environment (temperature, pressure and surrounding fluid), its size and range of applicability, and its unique characteristics. The information could be sorted according to the type of device – for example, those requiring an initiation signal or the repositioning of valves, and those that are completely passive. Data and information could be checked for consistency before being entered into the database.

The programme would organise the information for easy reference by reactor designers and help identify devices that have common operating principles or functions. The database could then be used to identify opportunities for collaborative R&D to enhance existing devices or design new ones.

Advanced Coolants and Related Technologies

Supercritical Water Coolants

The CANDU X, BREST 300, Energy Amplifier, MSR and FUJI designs call for the use of supercritical water in the secondary system, which provides reactor heat to the turbine generator. This approach is adapted from coal-fired plants. In nuclear plants, the design of the primary heat exchangers, in which heat is transferred from the reactor coolant to the secondary-side coolant, will require special attention to material selection, construction methods and system chemistry, in order to avoid the frequent failures experienced by PWR steam generators.

The CANDU X also operates with supercritical water in the primary reactor-coolant system – heavy water in initial versions and light water in later versions. A unique aspect of the primary heat exchanger design is the presence of supercritical coolant on both sides of the primary heat exchanger tubes. In addition, there is no prior experience with the use of supercritical water in high radiation fields. The CANDU X design also calls for a fuel channel that can operate reliably with supercritical coolant at temperatures above 450ºC and at pressures roughly double those of current CANDU reactors.

The design of reliable primary heat exchangers for operation under supercritical conditions, and the establishment of appropriate chemistry conditions and chemistry-control processes for supercritical coolant, will require a substantial amount of development activity.

Lead Coolant

The BREST 300 and Energy Amplifier use lead as the reactor coolant. Lead coolant has rarely been used in nuclear reactors. Most experience has been in Russia. Significant effort may be required to develop and test the technologies and tools needed for use of lead coolant, including coolant chemistry specifications, reliable and economic chemistry-control systems, specifications for materials that minimise lead-induced stress-corrosion cracking in the coolant-system designs, and verification of the performance of those materials.

Molten-Salt Coolant

The FUJI design uses molten salt as the reactor coolant. Technologies needed for the use of molten-salt coolant include methods and system designs to purify the coolant and control its chemistry and composition over extended periods of reactor operation. Material specifications are also needed that will assure long and reliable life for all components that contact the molten-salt coolant. The experience base for the design of heat exchangers and other NSSS components that contact molten salt at high temperatures is limited.

Isotope Separation Technologies For Reactor Coolants

Economic isotope separation is essential to two of the innovative reactor designs. The lithium isotope ^{7}Li is a major component of molten-salt coolant. It must be separated from the naturally-occurring ^{6}Li, and large-scale commercial facilities will be needed to do this. Deuterium, an isotope of hydrogen, is used as a moderator and coolant in the CANDU X. Traditional technologies for separating deuterium from the naturally-occurring hydrogen in light water are expensive and energy-intensive. Lower-cost processes now under development need to be commercialised.

Advanced Fuel Design, Processing and Fabrication

Some of the innovative reactors use advanced fuels or have the ability to use them. For example, the BREST 300 uses mononitride fuel. Changes in fuel design may be as demanding, as substantial and as innovative as changes in coolant approach.

The need for development efforts in fuel design may be limited for reactors like the CANDU X that retain an existing fuel bundle but use it under substantially different operating conditions, or for gas-cooled reactor fuel, for which basic fabrication technology is established but for which there is limited large-scale fuel fabrication experience. Since HTGR fuel fulfils the containment function under postulated accident conditions, fuel performance must be assured, and appropriate quality control and inspection procedures must be developed for its manufacture.

The need for development efforts in fuel design applies most obviously to lead-cooled, molten-salt-cooled and thorium-adaptable reactors, for which there is only limited experimental experience in fuel design and virtually none in development of a commercial fuel cycle.

The aqueous fuel-reprocessing technologies currently used for LWR fuel have not advanced substantially over the years. These processes are costly. From a nonproliferation perspective, they have the disadvantage of separating plutonium and other higher actinides from the fuel stream. Innovative fuel-reprocessing technologies proposed to date include the DUPIC dry technology that processes spent PWR fuel for use in CANDU plants as well as electro-chemical and pyro-electric techniques.

In-Service Inspection and Maintenance Technologies

Several of the innovative reactor designs present new challenges to the provision of cost-effective maintenance and inspection of reactor-system components. Efficient and cost-effective technologies for in-service inspection and maintenance are important to limiting radiation exposure of the staff, to minimising down-time for refuelling and maintenance, and to reducing operation and maintenance costs as well as total generation costs. Innovative reactor designs, including several of the concepts reviewed in this study, pose new challenges for in-service inspection and maintenance owing to their geometry or the type of coolant they use. For example, integral and gas-cooled reactors such as the MRX and NHR-200, which feature very compact configurations, and hence restricted access and space, will require non-intrusive measurement techniques, continuous monitoring techniques, remote monitoring capabilities and other novel approaches. Lead-cooled reactors, such as the BREST 300 and the Energy Amplifier, and molten-salt reactors will require remote and robotic inspection and maintenance techniques because of their high operating temperatures. In these reactors, obstacles will also be posed by insulation (to help maintain the coolant in a liquid state) or solidified coolant (at lower temperatures).

Potential Collaborative R&D

Compiling the information available on existing in-service inspection technologies, covering their performance, advantages and drawbacks, would help designers. A collaborative research effort could focus initially on a survey of the literature covering current and potential in-service inspection needs according to the component type, the materials involved and the environment in which inspections must be conducted, including geometry and accessibility factors.

Based upon such a "state of the art" review, areas offering opportunities for collaborative R&D programmes could be identified. Joint projects could be undertaken on innovative in-service inspection technologies applicable to several reactor concepts and designs.

Advanced Monitoring and Control Technologies

The systems for monitoring and controlling nuclear power plants and fuel-cycle facilities are essential to the safety of these plants and their technical and economic performance. A significant part of the capital costs of nuclear facilities, as well as of their operation and maintenance costs, is related to monitoring and control devices.

Rapid scientific and technical progress has been achieved recently in monitoring and control technologies and techniques, including those for non-intrusive measurement, continuous monitoring and remote monitoring. In this field, nuclear research could benefit from collaboration with other sectors, since much work on these technologies is being carried out in non-nuclear industries such as the aircraft industry. Boeing, for example, has developed a simple, rugged, low-cost position indicator (used for indicating the positions of flaps, rudders, landing gear and so forth) that could possibly be used in nuclear plants (for example, to indicate the positions of control rods). Similarly, the electronic imaging technology used by race-car organisations to determine whether a car complies with size requirements may be useful in the maintenance and refurbishment of nuclear plants.

Potential Collaborative R&D

A comprehensive assessment of the monitoring and control requirements of innovative reactor concepts and designs could be undertaken. In parallel, a collaborative effort could compile and review information on state-of-the-art control and monitoring technologies, covering both the nuclear sector and relevant non-nuclear sectors. Emphasis would be placed on identifying established and emerging technologies that seem likely to meet the monitoring and control requirements associated with nuclear power.

Subsequent activities could include work to further develop particular monitoring and control technologies and to evaluate their use alongside existing technologies in innovative reactor designs.

Delivery and Construction Methods

The techniques used to deliver and build reactors may have a dramatic impact on the economics of nuclear power plants. Minimising the time between the start of construction and the commissioning date reduces the interest accumulated during construction and thus the total capital cost borne by the owner of the plant. Although some delivery and construction techniques may be reactor-specific, there are also generic methods to facilitate delivery of reactor components and to speed up construction.

Modularisation, which shifts part of the construction from the site to a factory or workshop, could be a very efficient means of reducing construction time and costs. Some design features of a nuclear power plant could also shorten construction time. Simplified designs and composite construction, for example, can reduce the amount of on-site work required. Other methods, such as the use of heavy lift cranes and open-top construction, can also reduce construction time.

The methods considered by different designers for current and advanced reactors provide some insights on this issue. In the 1980s, for example, a proposal was developed by AECL to deliver barge-mounted CANDU 3 units using ocean vessels specially adapted to carry a plant barge on deck. This approach offered the advantages of fast delivery, low insurance rates and reduced cost. The AECL also assessed the feasibility of barges with air-cushion "skirts" to permit their towing over reasonably level terrain. The KTL-40 design incorporates two nuclear power plants on a barge that can be towed to the site. Modularisation and advanced construction technologies were studied extensively by Westinghouse for the AP-600. Mitsubishi developed composite construction techniques – such as using large, concrete-filled steel structures – for use in the APWR.

Lessons learned from experience in other industrial sectors may be of interest. For example, the designers of off-shore drilling platforms have developed advanced construction and delivery methods that may be applicable to nuclear plants.

Potential Collaborative R&D

Further work is needed to optimise delivery and construction methods. A collaborative R&D programme could be undertaken to identify innovative methods that could be applied to several designs. The initial stage of this programme would include a survey of the literature and the creation of a database listing the delivery methods and construction technologies used and proposed for reducing construction schedules. Subsequent stages could include collaborative work to develop innovative methods and technologies for delivery and construction that would complement or go beyond the methods identified in the first stage.

Safeguards Technologies

Improved technology is one major avenue envisioned for enhancing the effectiveness of safeguards. In the next ten years, before innovative reactors could be constructed on a broad scale, significant advances in the technologies relevant to the application of safeguards can be anticipated. These advances should facilitate the economically efficient provision of increasingly effective safeguards to future reactors and related fuel-cycle facilities. For example, advanced wireless communication technologies, used in conjunction with other advances, may provide immediate detection of fissile material diversion. (Note that the cost of applying safeguards depends on the type of reactor and, in particular, on the fuel-cycle activities that would be subject to inspection if a reactor were exported to a non-nuclear-weapons state. The cost also depends on the other nuclear capabilities and activities within a country and on whether the country has adopted a comprehensive IAEA Safeguards Agreement, including an Additional Protocol.)

Research is needed, particularly on the applicability of innovative safeguards approaches and technologies to small and medium-sized reactors and related fuel-cycle facilities, on means to reduce the cost of safeguards systems for small reactors, and on ways to increase the effectiveness of safeguards – for example, by reducing the time delay between diversion and detection.

Sub-Critical Systems

The use of an accelerator to maintain a critical reaction in a reactor core, proposed by the Energy Amplifier, makes it possible to produce power from a sub-critical core. Given the novel nature of this approach and the potential safety benefits, a collaborative effort to assess its feasibility and applicability would be useful.

Potential Collaborative R&D

A collaborative programme could review the Energy Amplifier design, and then evaluate the application of accelerators to other reactor concepts. The assessment would cover the feasibility of operating various reactor types in a sub-critical mode, using an accelerator, and of designing new and innovative reactor configurations appropriate to use of an accelerator.

Subsequent stages could include collaborative R&D and design activities to define and evaluate specific accelerator-driven concepts, as suggested by the first stage.

Component Development

Heat Recovery Heat Exchanger Development

The gas-cooled reactor designs reviewed here incorporate a large tube-in-shell heat exchanger to recover heat from the helium discharged from the gas turbine before it is compressed and recycled. This heat exchanger features a counterflow, with the helium stream from the power turbine passing through one side and the helium flow from the compressor passing through the other. The size of this heat exchanger could be dramatically reduced if an advanced plate-type heat exchanger design were developed and adopted.

Helium Turbine Development

To drive the generator, the gas-cooled reactors propose the use of a turbine operating on helium discharged from the reactor vessel. Helium turbines in the size range proposed have never been built or operated. Since the turbine and generator are located within a pressurised dry helium environment and operate at high temperatures, bearings pose a particular problem, both as to size and orientation. One design option, not noted by the questionnaire responses, is to increase the operating speed of the power turbine/generator, thereby dramatically reducing its size and weight and permitting the use of gas bearings. Regardless of the details of the design, a considerable development and performance verification effort is required in this area.

CHAPTER 5
FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

This initial effort to review how innovative nuclear-fission reactors are addressing the challenges facing nuclear energy, and to identify possible areas for collaborative R&D, led to several findings, conclusions and recommendations. They should be regarded as tentative until confirmed by a more comprehensive survey.

Findings and Conclusions

The main findings and conclusions of the Three-Agency Study, as documented in this report and in the Background Report (3A 2001), are as follows:

- This initial review of innovative reactor designs and their development efforts illustrates the range of technologies from which countries wishing to expand their use of nuclear energy will be able to choose. These designs use a wide variety of innovations to tackle the challenges facing nuclear energy today. Many of the innovations and innovative approaches are common to several designs.
- The methodology applied here – reviewing how specific reactor designs deal with the challenges facing nuclear power, and cataloguing the underlying enabling technology and information – was useful for the limited purposes of this study. It could fruitfully be applied to a broader range of designs.
- A wealth of information is available on several decades of research in the field of nuclear fission and on the operation of prototype and demonstration reactors in the 1950s and 1960s. Yet current reactor

designers do not always have easy access to this information and may not fully incorporate it into their R&D programmes.

- Many different approaches have been adopted for different reactors to meet the same basic design requirement under similar circumstances. Increased cross-fertilisation among reactor designs and design teams would be fruitful.

- Many components and technologies that have been commercialised by the aerospace, automotive, petro-chemical and other industries may be useful in the nuclear industry. Increased co-operation with non-nuclear researchers, and increased tracking of non-nuclear industrial developments, could benefit innovative reactor design efforts.

- The designs considered, except for the GT-MHR and the PBMR, focus on the nuclear steam-supply system (NSSS). They do not specifically address the balance-of-plant (BOP), where heat from the nuclear reactor is converted to useful energy. Since the BOP represents a major portion of both capital and operating costs, its design must be given careful attention if economic objectives are to be met.

- Several of the innovative designs considered in this study were developed on the assumption that in future energy markets, demand may not be driven solely by the need for electricity. New demand will arise for process heat, district heating or seawater desalination for the production of potable water. In general terms, taking advantage of co-production options and improving the flexibility of application can improve the competitiveness of nuclear power plants.

- All else being equal, economies of scale in construction, operation and maintenance favour large nuclear power plants. To be economically viable, small plants must achieve simplifications in both the NSSS and BOP or they must offer higher reactor-core outlet temperatures that enable higher thermodynamic efficiency and increase energy utilisation in process-heat and cogeneration applications.

- Specific attention is needed to reducing the cost of operation, maintenance and inspection. This is particularly important for small reactors, and can be partially addressed by siting several units together and using common support functions and facilities. However, placing more than about 2,000 MW_{th} of capacity at a single site reduces the potential for using a large fraction of the output for process-heat applications.

- Because of their compact design or the type of coolant they use, several of the innovative reactor designs considered here present new challenges to the provision of efficient, cost-effective and reliable maintenance and inspection of the reactor, the pressure and containment vessels, and other components important to safety. Obstacles to in-service inspection include restricted access and restricted space resulting from very compact configurations, and the presence of obstacles such as insulation or solidified coolant.

- The information provided by research and design teams in response to the questionnaire indicate that the R&D and design efforts underway on innovative nuclear reactors received little funding compared with the efforts made in the 1950s, 1960s and 1970s to develop the current generation of reactors. Nuclear R&D expenditures today are aimed primarily at maintaining and enhancing the performance of operating reactors. Assuming that low investment will continue, commercial availability for most of the designs considered here could require 10 to 15 years or longer.

- Further collaboration in developing innovative fission reactor designs is warranted. Collaboration could help designers make the most effective use of limited R&D resources and could reduce the time and cost required to make technologies commercially available. It could also help increase cross-fertilisation among development efforts and ensure fuller use of the broad experience base developed to date.

Recommendations

The following recommendations are offered to reactor design teams and to organisations engaged in fostering collaborative R&D on energy technologies:

- **Make better use of experience to date.** Design groups should consider directing strong efforts toward ensuring that previous design and operating experience with relevant coolants, moderators, systems, components, configurations and procedures is fully incorporated into current R&D programmes.
- **Increase cross-fertilisation of ideas among those working on various reactor types.** Design groups should consider familiarising themselves thoroughly with the features and technologies that are currently used or proposed by other design groups, and should consider evaluating potential alternative approaches to meeting their own design requirements.
- **Take greater advantage of components and technologies developed in other industries.** Design groups should consider how they can take advantage of relevant components and technologies developed by other industries.
- **Increase co-operation in R&D.** The three recommendations above would benefit from being addressed via collaborative efforts among research groups. Some of the enabling technologies described in Chapter 4 are also good candidates for collaboration because they are relevant to the development of several types of innovative designs, and because they are believed to be amenable to joint development without necessitating the sharing of proprietary information or know-how. The following areas are good candidates for developing new, broad-based collaborative efforts:
  - natural (unforced) circulation;
  - high-temperature materials;
  - passive (safety) devices;

- in-service inspection and maintenance methods;
- advanced monitoring and control technologies;
- delivery and construction methods;
- safeguards technologies and approaches.

Other enabling technology areas discussed in Chapter 4 would be good candidates for more limited co-operation among a few design groups.

- **The INPRO, the GIF and other international projects should continue the analysis begun in this study.** These findings and recommendations are only indicative. They represent a starting point for planning the collaborative R&D and analysis elements of the INPRO, the GIF and other international programmes. These programmes may find these recommendations useful in planning the collaborative elements of their work. But this survey should be expanded to cover a broader range of innovative reactor designs and concepts, so as to provide a more comprehensive set of findings and recommendations.

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ABBREVIATIONS

4S	Super-Safe, Small and Simple
AECL	Atomic Energy of Canada, Limited
ALMR	Advanced Liquid-Metal Reactor
APHWR	Advanced Pressurised Heavy-Water Reactor
APWR	Advanced Pressurised-Water Reactor
ASEA	Allemana Svenska Elektriska Aktienbolaget (Sweden)
BARC	Bhabha Atomic Research Centre (India)
BGU	Ben Gurion University (Israel)
BNL	Brookhaven National Laboratory (United States)
BOP	Balance of Plant
BWR	Boiling-Water Reactor
CANDU	Canada Deuterium Uranium (reactor)
CAREM	Central Argentina de Elementos Modulares
CE	Combustion Engineering
CEA	Commissariat à l'Énergie Atomique (France)
CERN	Centre Européen pour la Recherche Nucléaire (European Centre for Nuclear Research)
CNEA	Comisión Nacional de Energía Atómica (Argentina)
CRIEPI	Central Research Institute of the Electric Power Industry (Japan)
DFBR	Demonstration Fast Breeder Reactor
DHR	District-Heating Reactor
EFR	European Fast Reactor
ESKOM	South African electric utility
FPU	Floating Power Unit
GIF	Generation IV International Forum
GT-MHR	Gas Turbine-Modular Helium Reactor
HTGR	High-Temperature Gas-Cooled Reactor
HTR	High-Temperature Reactor
HWR	Heavy-Water Reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency

INET	Institute for Nuclear Energy Technology (Tsinghua University, China)
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles (IAEA)
INVAP	Investigacións Aplicadas (Argentina)
ITHMSO	International Thorium Molten-Salt Organisation
JAERI	Japan Atomic Energy Research Institute
JAPC	Japan Atomic Power Corporation
KAERI	Korea Atomic Energy Research Institute
KW	Kilowatt
KW_e	Kilowatt electrical
KWh	Kilowatt hour
KWU	Kraftwerk Union (Germany)
LMR	Liquid-Metal Reactor
LPV	Low-Pressure Vessel
LWR	Light-Water Reactor
MARS	Multi-Purpose Advanced Reactor Inherently Safe
MPa	Megapascal
MRX	Marine Reactor X
MSR	Molten-Salt Reactor
MSRE	Molten-Salt Reactor Experiment
MW	Megawatt
MW_e	Megawatt electrical
MW_{th}	Megawatt thermal
MWh	Megawatt-hour
NEA	OECD Nuclear Energy Agency
NHR	Nuclear Heating Reactor
NSP	Nuclear Steam Plant
NSSS	Nuclear Steam Supply System
OECD	Organisation for Economic Co-operation and Development
OKBM	Experimental Machine Building Bureau (Russian Federation)
ORNL	Oak Ridge National Laboratory (United States)
PBMR	Pebble-Bed Modular Reactor
PHWR	Pressurised Heavy-Water Reactor
PRISM	Power Reactor Innovative Small Module

PT	Pressure Tube
PV	Pressure Vessel
PWR	Pressurised-Water Reactor
R&D	Research and Development
RDIPE	Research and Development Institute of Power Engineering (Russian Federation)
RMWR	Reduced-Moderation Water Reactor
ROK	Republic of Korea
RRC-KI	Russian Research Centre – Kurchatov Institute
RTFR	Radkowsky Thorium Fuel Reactor
SAFR	Sodium Advanced Fast Reactor
SCLWR	Supercritical Light-Water Reactor
SMART	System-Integrated Modular Advanced Reactor
SPWR	System-Integrated Pressurised-Water Reactor
SWR	Boiling-Water Reactor (Germany)

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