SMALL AND MEDIUM REACTORS

I. STATUS AND PROSPECTS
Report by an Expert Group

NUCLEAR ENERGY AGENCY

PARIS 1991
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NUCLEAR ENERGY AGENCY
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) and New Zealand (29th May 1973). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention). Yugoslavia takes part in some of the work of the OECD (agreement of 28th October 1961).

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 all European Member countries of OECD as well as Australia, Canada, Japan and the United States. The Commission of the European Communities takes part in the work of the Agency.

The primary objective of NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

- encouraging harmonisation of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;
- assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;
- developing exchanges of scientific and technical information particularly through participation in common services;
- setting up international research and development programmes and joint undertakings.

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

Until recently the thrust of power reactor development has been to take advantage of the economies of scale, which has led to the deployment of reactor of over 1000 MWe. However, there is now considerable interest arising in small reactor types.

Small and Medium-sized Reactor (SMRs) are being designed in several countries for three purposes: electric power production, heat generation (both for industrial process heat and space heating) and cogeneration of both heat and electric power. These designs, in some cases, have evolved from larger reactors currently used for power production; in other cases, more radical design changes have been introduced.

The Nuclear Development Committee of the NEA believed it was timely to prepare an analysis of the role of these newer reactor concepts in OECD countries, in relation to both electricity and heat production. In the context of current concerns over the fuel sources and technologies that will be available to provide reliable low-cost energy with minimal environmental impact, it is desirable for high-level decision makers in government and industry to have an objective view of the state of development of these reactor concepts, their potential to open up new applications, their likely costs, and steps to be taken before they are deployed commercially.

This study, published under the responsibilities of the Secretary General of the OECD, has been prepared by experts nominated by the Agency’s Member countries. The report does not necessarily represent the views of those countries nor of other participating organisations. Volume 2 of the report is a technical supplement which contains information on User Requirements as well as descriptions of various reactor projects.
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EXECUTIVE SUMMARY

The Nuclear Energy Agency (NEA) of the OECD undertook a study to evaluate the potential of Small and Medium-sized Reactors (SMRs) based on their technical features and country-by-country considerations in order to provide decision-makers with a reference work on SMRs. The study considered nuclear reactors of a novel design with outputs up to 600 MWe for electricity generation and up to 400 MWth for heat. The motivation for undertaking the study was to understand the rationales for and against the development of SMRs, giving particular weight to economic aspects which have not been extensively considered so far for this class of nuclear reactors.

The report concludes that SMRs could provide a valuable contribution in improving public acceptance and in increasing the share of nuclear energy in energy market sectors provided certain prerequisites are satisfied.

Reasons for the study, scope and approach

While large plants will continue to play a major part in the production of nuclear power, SMRs in the power range of 10 MWth to 600 MWe are being designed in several countries both for heat and/or electricity generation. The concepts considered in this study provide substantial design simplifications from their generic precursors, and their protagonists claim to satisfy higher safety requirements than those valid today. SMRs have been promoted essentially as being "Smaller, Simpler, Safer".

However, policy makers in different countries and for different reasons are not unanimous on the need for SMRs. Moreover, SMR data are sometimes incomplete or difficult to obtain, especially economic data. Therefore, the NEA believed that the present situation was very suitable for collecting and evaluating information on existing SMR concepts. An Expert Group was set up to study the following main issues:

- Rationales for the development of SMRs;
- Main technological features;
- Economic and market aspects;
- Factors impeding the deployment of SMRs.

The study was based on information provided by the participating countries according to a scheme agreed by the Expert Group. Additional information in particular for technical issues, economic data and users' requirements has been gathered by means of specific questionnaires and so-called "case studies".
Rationales for the development of SMRs

The incentive for the development of SMRs has a twofold origin. In some countries the R&D efforts have been the result of economic considerations:

- SMRs could open up additional energy market sectors (e.g. heat production), not accessible to large reactors, also offering a valuable contribution to CO₂ reduction;
- SMRs can provide a better response to slow growth rates of energy demand;
- SMRs fit better into small electricity distribution grids and are good candidates for the replacement of older (usually small) fossil fuelled plants;
- SMRs present specific economic advantages that offset the economies of scale.

In other cases SMRs have been or are being developed as an answer to "Users' Requirements", mostly in relation to safety and public acceptance issues. Common points in the requirements issued in different countries are:

- A simpler and more rugged design;
- Increased safety margins leading, for example, to longer grace periods, i.e. longer times before operator actions are needed;
- Lower core damage risks;
- Small (if any) accident consequences for the population.

In some countries it is believed that SMRs are particularly suitable to fulfill these requirements because:

- SMRs allow for design simplification and for introduction of new features like passive components and systems and inherently beneficial physical processes;
- The design of some SMRs allows for easily understandable safety arguments to demonstrate very low radioactive release to the environment even in the worst case;
- SMRs are believed to be more easily understandable to the public, thus enhancing their public acceptance.

Main technological features

There are some fifteen SMR concepts for electricity (or combined heat production) generation and seven heating reactor concepts developed in the OECD countries. Rather than describing in detail all the concepts considered, this report puts more emphasis in identifying the different designs and the general trends in the technological solutions common to them.

Common to SMR developments is the pursuit of passive safety systems based on the premise that such systems are easier to implement in plants smaller than the current large nuclear power plants (NPPs). In addition, there is no new design which does not lay emphasis on simplification and the benefits that it is expected to produce. Examples of such simplifications include:

- Elimination of external primary system recirculation loops and pumps (integrated design);
- Reduction of large bore primary piping;
- Elimination of safety-grade coolant make-up systems;
- Increased in-vessel heat storage capacity;
- Application of passive emergency cooling;
- Application of passive residual heat removal systems;
- Location of reactor pressure vessel (RPV) penetrations in the upper part of the vessel;
- Incorporation of large pressurisers (internal or external);
Minimisation of the number of seismic structures, simplification of the building concept and use of seismic isolation.

Although designed to satisfy different energy boundary conditions and following different technological lines, nuclear heating plants (NHPs), have several characteristics in common: They all have very low power densities which, along with the required low operating conditions for temperature and pressure, further enhance simplification; the operation schemes proposed for all NHP are considerably simplified, up to a totally unmanned operation; all concepts have been designed as site independent, standardized products.

Economic and market aspects

There is potential for substantial penetration of SMRs into the world's energy markets, provided certain prerequisites are satisfied.

In the electricity sector the scope for penetration is constrained by the need to be cost-competitive with alternative sources, including the well established large nuclear plant. However, the nuclear industry is not unanimous in accepting the "economies of scale" argument that favours large plants, and there appear to be some SMR designs emerging that show prospects of competing with larger designs through design simplifications and increased factory fabrication. Additional factors that could favour a reasonably competitive SMR in electricity markets are:

- Ability to fill niches or meet demands not readily open to large reactors;
- Especially for regions with a rather slow increase in electricity demand or for companies with small distribution networks, SMRs might represent a better solution. This aspect is generally valid but is perhaps more important for developing countries;
- Lower initial capital investment and correspondingly reduced investment risk that could appeal to utilities and their backers;
- SMRs might be more readily accepted by the public and could enable a faster penetration into power markets.

There is extensive scope in the heat sector (both district and industrial) where there has been little penetration of nuclear power to date. Current environmental issues could lend support to arguments for SMR expansion in this sector that is not, in general, open to large reactors.

District heat markets are currently restricted to specific northern countries, such as Finland, Germany, Sweden and Switzerland where there are heat distribution networks already in existence in certain regions. The obvious immediate market for SMRs is replacement of existing fossil fuelled systems. Further expansion would require a concerted effort within OECD countries to install new distribution networks. Industrial (or process) heat markets lie mainly with large industrial complexes. Furthermore, the economics favour a cogeneration (CHP) system rather than a dedicated plant. Small (and modular) reactors have a definite advantage over large ones in this sector where multiple heat units would be required to guarantee supply -- loss of energy supply meaning loss of production. The main competitor for SMRs is thus fossil fuels; at price levels of the late 1980s, especially of natural gas, there was no strong incentive for commercialisation of SMRs. However these low fossil fuel prices can be expected to increase and continuing development should bring reduction in SMR costs.

What therefore is the prospect of SMRs over the next three decades? In the current climate of public opinion, it is unlikely that construction of new stations in close proximity to areas of high population will be as readily acceptable as it was in the past -- even with the argument of increased safety levels. Consequently, the first priority of the nuclear industry will have to be to regain the confidence and support of the public.
In most cases the process will almost certainly be slow and will probably come through construction of nuclear power plants -- at a distance from centres of population. This would suggest that the first market opportunity for SMRs would be, most probably, towards the upper end of the size range. The next (perhaps concurrent) stage could be to tackle the industrial heat market. Installation of SMRs (in cogeneration mode) in large industrial complexes offers not only expansion of the SMR market but also enlarges gradually the number of people gaining familiarity with nuclear plants. It is to be hoped that this would lead to an increase in public confidence generally -- to the ultimate stage where penetration of SMRs into district heat markets would become widely accepted.

Factors impeding deployment of SMRs and potential remedies

Factors impeding the further development and deployment of SMRs have been identified to be of a technological, economic and institutional nature.

Technological factors impeding SMR-deployment are:

- Their first-of-a-kind nature, which in most cases implies the necessity for demonstration of the main new features (additional costs and time);
- The multitude of the concepts currently proposed, which results in a split of effort and investment on many, sometimes only insignificantly different concepts.

A potential remedy to this would be to aim as soon as possible at a demonstration of the advantages of SMRs. This would be most effective in the framework of an international joint venture; an important consideration would be to reduce the number of concepts available for each application.

Economic factors impeding SMR-deployment are:

- Economies of scale favour large reactors: Large reactors fit well into long-term programmes for countries with centralised energy supply and well developed networks.
- Regulatory aspects: The currently long and costly licensing procedures are expected to be simplified in order to reduce construction time and costs; the proximity of SMRs to densely populated areas could lead to more stringent safety requirements in some countries; differences in the regulations among different countries make technology transfer difficult.
- Lack of capital for development: The uncertainty of market conditions in the medium term leads to preferential investments in well established technological lines rather than to riskier R&D efforts.
- Heat generation faces additional problems: Nuclear heat is currently generally not cost-competitive against fossil fuels; district heating is additionally burdened by the distribution costs; optimisation of electricity and heat production according to the demand is seldom easy in cogeneration plants.

Possible remedies to this could be: To consider SMRs as complementary to rather than as competitors of large reactors in the energy market; to consider parks of several small units on the same site; to aim at a standardization of plant construction and type licensing; to share financial risk by international co-operation; to calculate cost-competitiveness of all alternative solutions based on the same rules. Moreover, cogeneration plants can take additional advantage from the improved thermal efficiency when compared to dedicated power plants.
There are in addition the following *non-technological aspects* impeding the deployment of SMRs as of all nuclear plants:

- SMRs suffer from the general opposition of part of the population to any form of nuclear energy: uneasiness about complex technology; fears of radiation; confusion as to the real permissible limits of radiation exposure due to the different regulations from country to country; lack of confidence in the scientific community.
- Opposition to SMRs in particular may be due to the greater number of people involved because of the larger number of plants and to confusion about the real merits of SMRs vis-a-vis large reactors.

This opposition led in some countries to political decisions against a further development of nuclear energy, especially in countries where no clear evidence of a strategic requirement for nuclear could be demonstrated.

Potential remedies to this situation would be to complement the usual probabilistic assessments by deterministic statements understandable to the public; to co-ordinate safety approaches among countries; to intensify public information programmes; and to invest more effort into explaining the specific safety features of small heating reactors to decision makers and the public, because severe accidents can be completely ruled out for most of the designs.

**Conclusions and perspectives for the future**

It is believed that the Study has fulfilled its goal, namely: to collect and sort the information needed for a clear demonstration of the features unique to SMRs with respect to safety, public acceptance, economics and contribution to environmental issues; to identify the market potential for the deployment of SMRs; to establish the economic conditions necessary; and to find a consensus on other prerequisites for a substantial penetration of this class of reactors in the energy market.

It was found that:

a) SMRs could provide a valuable contribution in:
   
   i) improving public acceptance,
   ii) increasing the nuclear share of the electricity market,
   iii) opening up heat markets.

b) SMRs are still facing problems in connection with:

   i) demonstrating economic competitiveness,
   ii) the lack of any operating plants.

Although the potential of SMRs has been identified, no concrete results have been achieved so far. In order to break this deadlock the construction of an operating plant is desirable. In view of the aforementioned problems it is possible that joint efforts and international co-operation could make a valuable contribution.
1. INTRODUCTION

This study was undertaken by an Expert Group, representing twelve OECD Member countries as well as the IAEA and the CEC, under the auspices of the Nuclear Energy Agency's Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle. When putting this study in the work programme the Committee was well acquainted with the several studies done within the IAEA closely related to this topic (in particular references 1, 2 and 3; all references are detailed at the end of this report) as well as more recent studies on advanced reactors (Refs. 4 and 5). The Committee wanted to give more weight to economic aspects and assess the real potential of markets for various kinds of small and medium-sized reactors (SMRs) in the next few decades. As such it is directed at government and industry leaders to help in formulating the relevant policy and marketing decisions.

Small and medium-sized reactors considered in this study are advanced reactors in a power range up to about 600 MWe or equivalent thermal power (about half the size of the water-cooled power reactors entering service in recent years).

SMRs are being designed in several countries for three purposes: Pure electric power production; heat generation only (both for industrial process heat and space heating); and co-generation of heat and electric power. These designs, in some cases, have evolved from reactors currently used for power production and, in other cases, they are of a more "revolutionary" nature introducing novel design features. Until recently the thrust of power reactor development has been to take advantage of the economies of scale, which has led to reactors of over 1 000 MWe. However, there is now considerable interest arising in small reactor types and it was therefore thought useful to study their future role in OECD countries, as sources of heat as well as of electricity. Therefore the NEA believed that the present situation was very suitable for collecting and evaluating information on existing SMR concepts.

The main objective of this study is to evaluate the potential of SMRs based on their technical design and country specific economic, political and social considerations, including public acceptability (particularly as these SMRs have features that may help to gain better public acceptance of nuclear power), in order to provide decision-makers with relevant data on the potential of this alternative.

This study was based on the data provided from the members on a variety of relevant issues. Respondents were invited to present the opportunity for, or the capabilities of a SMR as far as possible in the context of national, political, institutional, economic and other factors. Other main sources of information were OECD and IEA statistics and the earlier studies of SMRs carried out by the IAEA and the NEA's Advanced Water-Cooled Reactors study (Ref. 6).

Chapter 2 of this report serves as an introduction to the study by putting SMRs in the global energy context, WHERE are we? Chapter 3 then defines the WHYs of SMRs, what are the reasons for developing them. Chapter 4 describes WHAT is available. The new basic design principles and SMR specific technical or safety features are reported to illustrate the actual status and tendencies. More detailed information is given in the Technical Supplement (Ref. 7). Chapter 5 then elaborates on HOW SMRs would fit into the market, what are the economics. Chapter 6 looks at the ways to facilitate their introduction, WHAT are the impediments and HOW to remove them. Chapter 7 looks at the broader international context, WHO are the players, WHAT is being done and WHAT could be done. Chapter 8 summarises the conclusions and looks at the future perspectives.

Reference 7 is attached to this document and contains additional information, in particular on technical issues, economic data and users requirements gathered by means of specific questionnaires.
2. TENDENCIES IN ENERGY DEMAND

2.1 Evolution of energy demand

It is widely accepted that the world's energy consumption will continue to rise at a significant rate for several decades. With an increasing population and normal human desires for improved standards of living, it seems unlikely that the trend of increasing demand for energy is going to be reversed.

The oil crises of the early 1970s showed how vulnerable OECD economies are to disruptions in the flow of power generating fuels, how more efficient use of heat and electricity can temporarily reduce the need for additional generating capacity, and that some viable options exist that can be used in special applications to vary the mix of fuels consumed. However, it also demonstrated that growth of electrical power consumption remains very steady and closely tracks the Gross National Product (GNP) of industrialised countries (Ref. 8). The availability of electricity continues to be a major, if not the most significant, factor influencing the rate of economic growth in developing countries. Therefore the generation of electricity is expected to continue its steady increase in absolute quantities and as a percentage of the energy consumed throughout the world.

The Gulf crisis of 1990 again shows the vulnerability of being overdependent on a single source of energy. While the outlook is uncertain, oil prices will certainly be more volatile and higher in the future.

The IEA/OECD analyses on a continuing basis the outlook for world energy demand and supply for periods of 15 to 20 years into the future under a host of alternative assumptions. In the latest study (Ref. 9) completed in early 1989, a case is considered in which crude oil prices (in constant 1987 US dollars) are assumed to rise to about US$30 per barrel by the year 2000 and remain at that level thereafter. This value of $30 per barrel is about equivalent to the price in the mid-1970s and is significantly less than the 1980-81 peak. Additionally the analyses assume that other energy prices are related to the price of crude oil, a continuation of current government energy policies and practices, and a continuation of current trends in environmental protection. Economic growth is assumed to be slightly inversely related to changes in crude oil prices in OECD and developing countries, but to be independent of oil prices in centrally planned economies (though most of these economies are in transition which may change the validity of this assumption).

Looking at the results of this analysis, Figure 2.1 shows the projected primary energy requirements by fuel and major region. Table 2.1 gives the corresponding data. This table covers near-term projection (to the year 2005), Figure 2.1 the percentage annual growth rate, the market share of fuel within a region and the percentage of the world requirements in any region. (Additional data can be found in Appendix C.)

The contribution of nuclear power in meeting the world's electricity needs has increased rapidly in the recent past: it has more than quadrupled between 1973 and 1982, and has nearly doubled again in the five years to 1987. Nuclear power capacity is currently concentrated in the OECD region, which accounts for nearly 80 per cent of world nuclear power production, and where it has played a major energy supply role in the marked reduction of dependence on imported fuels. However, a slowdown in the rate of growth of nuclear generated power is anticipated over the next 15 to 20 years, as compared to the very rapid growth since 1973. The reasons for this slowdown in expansion are manifold and are only briefly summarised here.
Figure 2.1. World Primary Energy Requirements

MARKET SHARE

OECD
1987

1995

2005

CPE
1987

1995

2005

DEV. COUN.
1987

1995

2005

Legend:
- Oil
- Gas
- Coal
- Nuclear
- Hydro
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<td>24.0</td>
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<td>19.3</td>
</tr>
<tr>
<td>NUCLEAR</td>
<td>244</td>
<td>256</td>
<td>314</td>
<td>1.4</td>
<td>1.7</td>
<td>1.0</td>
<td>5.4</td>
<td>4.2</td>
</tr>
<tr>
<td>HYDRO AND OTHERS</td>
<td>1 442</td>
<td>1 931</td>
<td>2 861</td>
<td>3.9</td>
<td>9.8</td>
<td>8.9</td>
<td>26.5</td>
<td>33.1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>14 759</td>
<td>21 622</td>
<td>32 310</td>
<td>4.4</td>
<td>100.0</td>
<td>100.0</td>
<td>16.5</td>
<td>23.4</td>
</tr>
<tr>
<td>WORLD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OIL</td>
<td>35 102</td>
<td>41 348</td>
<td>47 292</td>
<td>1.7</td>
<td>39.5</td>
<td>34.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NATURAL GAS</td>
<td>18 015</td>
<td>23 332</td>
<td>34 719</td>
<td>3.7</td>
<td>20.2</td>
<td>25.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOLID FUELS</td>
<td>26 146</td>
<td>30 694</td>
<td>40 080</td>
<td>2.4</td>
<td>29.3</td>
<td>29.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NUCLEAR</td>
<td>4 524</td>
<td>6 188</td>
<td>7 490</td>
<td>2.8</td>
<td>5.1</td>
<td>5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HYDRO AND OTHERS</td>
<td>5 443</td>
<td>6 560</td>
<td>8 642</td>
<td>2.6</td>
<td>6.1</td>
<td>6.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>89 231</td>
<td>103 122</td>
<td>136 223</td>
<td>2.5</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Non-commercial fuels in centrally planned and developing economies not included. Source: IEA.
With the fall in fossil fuel prices (before 1990) (Ref. 10), and previous expectations for these price levels to continue into the medium term, nuclear power faced greater competition on the basis of cost from the alternatives for the generation of base load electric power. This development has on some occasions been exacerbated by regulatory power pricing regimes, which have discouraged capital intensive supply sources. The long lead times between investment decisions and commercial operation have also meant that by the mid-1980s, when electricity demand was growing only moderately, a few OECD countries found themselves with a larger share of nuclear capacity than was originally anticipated as optimal, and have therefore had to scale down future programmes. Safety concerns following the Three Mile Island, and particularly the Chernobyl accident, have produced a climate where siting and licensing have become more difficult. Lead times and hence interest payments have increased, and the cost of the nuclear plants themselves has risen substantially as higher safety standards were sought. In general, the economic, political and regulatory environment for large power plants and particularly nuclear power investment has become uncertain to the extent that many utilities have been opting out of nuclear expansion.

Growth in nuclear electricity output in OECD countries is therefore expected to slow down to about 2.9 per cent per annum in the 1987-1995 period and to fall further to an average of 1.4 per cent per annum in the decade 1995-2005 when the effects of present decisions will be most strongly felt.

Around 45 per cent of net additions to world nuclear power from 1987 to 2005 are projected to occur in the Soviet Union and Eastern Europe. Major cancellations as well as a pronounced lengthening of the already considerable construction times have been incorporated in the outlook. The importance of the USSR and Eastern Europe in world nuclear power developments to 2005 stems largely from the sheer mass and scope of their current nuclear programmes, the largest part of which is actually already in the construction stage though some are temporarily halted. However, any forecast about the Soviet Union and Eastern Europe tend to be speculative at this time, due to the large transitions occurring in these countries.

As for most developing countries (there are notable exceptions), the prospects are that nuclear power will still be making a relatively small overall contribution to energy requirements by 2005 although its impact will be considerable in a few places. The highly capital intensive nature of this energy form, its technological complexity, and the shortage of suitably trained personnel, imply a very high dependence on external (and often, for security reasons, reluctant) sources and a subsequent serious drain on scarce hard currency earnings which only a handful of developing countries can seriously contemplate.

However, experience has shown that there is a link between GNP and electricity consumption and that for developing countries electricity demand increases faster than primary energy demand i.e. increased electrification. It can therefore be expected that developing countries would want to increase electricity production at an even faster rate than OECD countries based on economic considerations.

The IEA/OECD study concludes among other things:

- Total world energy consumption (total primary energy requirement) is likely to grow at an average rate of about 2.4 per cent per annum to 2005. The growth rate will be highest in developing countries (4.3 per cent), followed by the centrally planned economies (3.0 per cent) and least in the OECD (1.3 per cent). Energy-related greenhouse gas emissions can thus also be expected to rise. Note that this is higher than the assumptions used at the World Energy Conference (Figure 2.2 from Ref. 11 where Medium & Low cases are WEC estimates) but the main points that consumption is bound to rise and rise faster in developing countries has been true of all forecasts.
Figure 2.2. WORLD PRIMARY ENERGY CONSUMPTION

- Overall energy intensity (i.e., total primary energy consumption per unit of real GDP) is expected to decline at a rate of about 1.3 per cent per annum in OECD countries. Overall energy intensity in developing countries, as a whole, is not expected to decline and may, in fact, rise slightly. Also, no decline in energy intensity is envisaged for the centrally planned economies.

- The mix of fuels consumed in the world is expected to change over time: Natural gas' share of total world energy consumption is expected to rise, while that for oil is expected to decline. The share of coal and other solid fuels is likely to remain constant while the shares for nuclear and hydro power are expected to rise only slightly. Overall, this implies a slight shift in consumption toward lower carbon fuels. Note that the Third World is proportionately more dependent on oil and that gas is not an international commodity in the same category as coal or oil and tends to be used more locally. Therefore care should be taken in applying these generalisations.

At present, nuclear power plants are operated for electricity generation in 12 of the 24 OECD countries (Belgium, Canada, Finland, France, Germany, Japan, the Netherlands, Spain, Sweden, Switzerland, the United Kingdom and the United States, Ref. 12). The total electricity generation in OECD countries in 1989 was 6 286.5 TWh, including 1 482.7 TWh from nuclear generation. The proportion of nuclear generation relative to the total electricity generation has reached 23.6 per cent.

The NEA's latest published statistics (1990 Brown Book, Ref. 13) estimate the electricity generation of all OECD countries to be about 8 820 TWh by the year 2005, including 1 925 TWh from nuclear generation in 2005, or 22 per cent of the total generation, as shown in Table 2.2.
Looking at the growth by main region, the total electricity generation is expected to increase by 1 338 TWh to 4 482 TWh in OECD America, by 960 TWh to 2 985 TWh in OECD Europe, and by 392 TWh to 1 152 TWh in OECD Pacific, respectively, by the year 2005. The proportion of nuclear generation to total electricity generation in OECD Europe was the highest among the three regions in 1987. However, it is predicted to decrease by 2.9 per cent to 27.2 per cent in 2005. Also, in OECD America, the share of nuclear generation is predicted to decrease by 1.4 per cent. On the other hand, in OECD Pacific, nuclear generation is expected to increase at a rather high pace. The forecast shows that nuclear generation in OECD Pacific will increase 220 TWh to around 400 TWh in 2005, meaning 125 per cent increase compared with the year 1987. The proportion of nuclear generation to the total electricity generation will be expected to reach 35 per cent in 2005 in OECD Pacific.

This forecast did not, however, take into consideration the current environmental problems. Rather, in many countries, since there is a lack of public confidence in nuclear safety, it has become difficult to expand the nuclear programme. In addition, in the 1980s the fall in the price of oil and coal has reduced the economic attractiveness of nuclear generation. Several countries have moratoria, either in practice or by political choice. Sweden has decided to phase out nuclear generation by the year 2010. The forecast should be highly realistic, particularly in the year 2000, although there is still some risk that the plants included in the forecast will not be completed.

The forecasts past 2005 to 2020 are more uncertain as shown in Table 2.3 and Figure 2.3 (Ref. 14). Depending on assumptions the proportion of nuclear is expected to increase substantially. In 1987 80.2 per cent of the world's nuclear capacity was in OECD countries. This is expected to decline (Table 2.1) to 69.7 per cent in 2005 as other parts of the world increase their nuclear capacity. This trend is expected to continue and explains much of the increased capacity shown in Figure 2.3. A large part of the present NPPs will have been decommissioned and great demands could be made on the nuclear industry to supply the replacement reactors.
Figure 2.3. PREDICTIONS FOR 2020

TWh (Thousands)

Table 2.3. WORLD PRIMARY ENERGY REQUIREMENTS (TWH)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>1987</th>
<th>2005</th>
<th>WRI</th>
<th>WEC</th>
<th>IIASA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>19 972</td>
<td>21 576</td>
<td>28 032</td>
<td>28 908</td>
<td>48 180</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>8 491</td>
<td>9 351</td>
<td>28 032</td>
<td>28 908</td>
<td>23 032</td>
</tr>
<tr>
<td>Solid Fuels</td>
<td>10 887</td>
<td>12 306</td>
<td>30 660</td>
<td>65 700</td>
<td>44 676</td>
</tr>
<tr>
<td>Nuclear</td>
<td>3 629</td>
<td>4 548</td>
<td>6 132</td>
<td>20 148</td>
<td>33 288</td>
</tr>
<tr>
<td>Hydro &amp; Others</td>
<td>2 966</td>
<td>3 396</td>
<td>5 256</td>
<td>24 527</td>
<td>12 264</td>
</tr>
<tr>
<td>TOTAL</td>
<td>45 945</td>
<td>51 177</td>
<td>98 112</td>
<td>168 192</td>
<td>166 440</td>
</tr>
</tbody>
</table>

WRI: World Resource Institute
WEC: World Energy Conference
IIASA: International Institute for Advanced System Analysis

Sources:
1. BP Statistical Review of World Energy - 1987
2. Goldemberg et al., Energy for a Sustainable World - 1988 (WRI)
The increased demand will not only be for electricity production but also for other applications. The oil supply picture is an interesting example. North America, the North Sea and the Soviet Union will see declining oil output as from about the year 2000. After that time there will be a greater reliance on OPEC. If after 2015 a gap between supply and demand occurs (as some predict, Ref. 15) advanced oil recovery techniques and hydrogen production would become more desirable in the future and certain reactor types could be a source of the necessary process heat.

A large part of the present and future energy demand is for heating purposes. Due to the methods of collecting data, statistics for heat usage are not consistent between all countries and some work will be needed in the future to define the precise needs. However certain examples can be stated. Of all the electricity used in Ontario (Canada) in 1987, 49.4% of the residential needs were for space and water heating, 11% of the commercial needs were for the same purpose and 16% of the industrial needs were for process heat and electrolysis (Ref. 16). Taking another example from Germany, heating amounts to almost two thirds of final energy consumption (Figs. 2.4 and 2.5).

The penetration of nuclear into this area in OECD countries has been fairly limited with one site, Beznau in Switzerland, furnishing district heating; and four sites, Bruce in Canada, Tricastin in France, Goesgen in Switzerland and Stade in Germany, furnishing respectively greenhouses and a heavy water plant, a greenhouse, a paper plant and a salt plant.

Figure 2.4. TOTAL ENERGY CONSUMPTION IN THE FRG (1987)
2.2 Energy and the environment

Currently the world uses over 12 TW year/year (over 100 000 TWh/year) of primary energy of which almost 90 per cent is based on fossil fuels (coal, oil and natural gas), the balance being provided by hydro and nuclear power (Table 2.1). The problems of acidic gas emissions (oxides of sulphur and nitrogen) from the combustion of coal and oil have been recognised for a long time and international action is gradually leading to their reduction - but at a cost, through installation of flue gas desulphurisation equipment on power stations and catalytic converters on road vehicles for example. Over the past decade there has been increasing realisation of a potentially more serious problem, that of global warming and associated damage to the world's ecosystem as a result of emissions of carbon dioxide, one of the so-called "greenhouse" gases.

Carbon dioxide is released during the combustion of all fossil fuels, although natural gas, and oil to a lesser extent, emit less per unit of useful energy than does coal. Whilst other man-made gaseous emissions also contribute to this greenhouse effect, carbon dioxide from energy sources is estimated by the Intergovernmental Panel on Climate Change (the IPCC, set up by the United Nations Environment Programme and the World Meteorological Office) to be responsible for about 45 per cent of current global warming (Ref. 17). The IPCC also concluded that an immediate reduction of over 60 per cent in emissions of long-lived gases (of which carbon dioxide is one) would be required to stabilise atmospheric concentrations at today's levels. This has to be seen against a growing worldwide demand for energy that could be alleviated to some extent by utilising fuel resources and energy more efficiently.

However, if stringent targets for reductions in carbon dioxide emissions are set, there will be an increasing demand for non-carbon dioxide emitting sources of energy to replace fossil fuels. Nuclear power is widely recognised as one such source. Already, at its current level of use throughout the world, it is
avoiding the emission of about 1.12 Gtonnes (metric tons) of carbon dioxide per year, that is almost 20 per cent of the level from the world's electricity generation plants had the nuclear plant been replaced by coal.

Not only does nuclear generated electricity contribute to the reduction of carbon dioxide emissions, it also contributes equivalently to reductions in emissions of the acid gases (without requiring massive quantities of limestone or producing waste gypsum) and to reductions in the large quantities of waste ash products - as shown in Table 2.4.

Table 2.4. **Solid and gaseous waste arising from energy sources**

<table>
<thead>
<tr>
<th></th>
<th>Coal (+FGD)</th>
<th>Nat. Gas</th>
<th>Nuclear</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>100</td>
<td>40</td>
<td>1*</td>
</tr>
<tr>
<td>NOₓ</td>
<td>100</td>
<td>20</td>
<td>1*</td>
</tr>
<tr>
<td>SO₂</td>
<td>100</td>
<td>1</td>
<td>1*</td>
</tr>
<tr>
<td>Ash</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Gypsum</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

* Including construction

Indeed, the increasing reduction of emissions of atmospheric products by an electricity industry using nuclear energy is well demonstrated by the growing use of nuclear power in France (Figure 2.6).

Admittedly, the nuclear power industry has its own waste problem - that of the radioactive waste arising during the operational lifetime of a station and from its eventual decommissioning. But these issues are being widely addressed, are of a different nature and are of a smaller scale than those associated with a continuing and increasing massive use of fossil fuels. Fundamentally, it is not as much the technical issues that present difficulties but public perceptions and social acceptability. There can be little doubt that as the environmental issues gather momentum, the concern expressed in the reports of the various working groups of the IPCC will provide an important element in the debate of nuclear as an environmentally acceptable source of energy.

### 2.3 National policies and programmes

Whether the power is generated with fossil fuel or nuclear fuel will, naturally, depend upon the national policies of the countries producing the electricity. Other energy sources, such as solar, wind, geothermal, etc., will make some contribution but were not considered significant enough to impact the results of this study. Also, the expansion of hydroelectric energy is limited due the availability of potential sites and to environmental considerations and need not be considered within the context of this study. National policies are in turn influenced and/or governed by the nations' natural resources, their technological development, their sensitivity to the damaging impacts of contaminating the environment, and their concerns regarding energy independence. Countries with advanced technical capabilities have several possibilities and can make their energy source decisions on the basis of economics, environmental impact, and vulnerability to isolation from fuel sources.

In Appendix D a short outlook is given on the present (1990) situation and the near future concerning the national policies and energy programmes in OECD countries. Please note that these policies were those in effect before the 1990 Gulf crisis.
Figure 2.6. **Effects of Nuclear Use on the Environment in France**

As the number of French nuclear plants increased.....
France's nuclear energy programme went into high gear after the 1973 oil embargo. Today France has about 50,000 megawatts of nuclear capacity producing about 70 per cent of its electricity.

Utility emissions of SO₂ and NOₓ dropped dramatically.....
As clean nuclear energy displaced oil and coal-fired power, utility pollution dropped. Emissions of sulphur dioxide dropped from 978,000 tonnes in 1979 to 83,000 tonnes in 1987. Emissions of nitrogen oxides dropped from 209,000 tonnes in 1979 to 34,000 tonnes in 1987.

And so did utility emissions of CO₂ and dust.....
Carbon dioxide emissions by Electricité de France, the state-owned utility, declined from 82 million tonnes in 1980 to 13 million tonnes in 1987. Dust (particulate) emissions dropped from 77,000 tonnes in 1980 to 1,900 tonnes in 1987.
3. RATIONALE FOR THE DEVELOPMENT OF SMRs

The elements provided by the contributing countries in this area have been analyzed first to identify the different market sectors for nuclear reactor application (Section 3.1). Secondly, the main requirements for those market sectors have been identified and grouped (Section 3.2). As will be seen from the following, many requirements although characterising a market sector can apply also to other sectors. It will also be seen that there is no competition nor conflict between the different sectors. Section 3.3 is an attempt at comparing the general requirements for the reactors described.

3.1 Applications

The areas of application of nuclear reactors in the future can be summarised as in Table 3.1.

<table>
<thead>
<tr>
<th>Types of Applications</th>
<th>Large Utilities</th>
<th>Small Utilities</th>
<th>Users Municipal Utilities</th>
<th>Local Councils Tech. Branch</th>
<th>Industrial Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity production</td>
<td>LR (SMR)</td>
<td>SMR (LR)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cogeneration</td>
<td>SMR</td>
<td>SMR</td>
<td>SMR</td>
<td>SMR</td>
<td>SMR</td>
</tr>
<tr>
<td>District heating</td>
<td>SMR</td>
<td>SMR</td>
<td></td>
<td>SMR</td>
<td></td>
</tr>
<tr>
<td>Industrial application</td>
<td></td>
<td></td>
<td>SMR</td>
<td>SMR</td>
<td></td>
</tr>
</tbody>
</table>

LR: Large reactors
SMR: Small & medium-sized reactors

The main reasons for such potential applications are as follows:

a) Large units for electricity production

This is the typical application of countries having utilities with large electric distribution grids, enough installed reserve power and operating many nuclear units. The confidence in the managerial capacity and the safety record of the existing plants is so high that there is no need for major changes.

b) Small and medium sized units for electricity production

This is a market sector where needs originating from many different problems can converge. Some countries have experienced acceptability and operational problems and believe that the SMR can help overcome these; in other countries some utilities do not like to build large plants for various reasons as outlined in Section 3.2; developing countries may tolerate better a lower investment requirement.

The SMRs, being new concepts, may be engineered in such a way as to give a better answer to all those problems.
Points covered in 3.2 a), b), c), e), f), apply to this market.

c) **Small units for cogeneration**

This is the market of those utilities that operate an electric distribution grid and a district heating network at the same time and of industrial complexes that need both electric power and steam.

For reactors to be utilised in this application, the siting problem may impose safety requirements more stringent than today’s plant. As a consequence the points on environmental policy in Section 3.2 a) apply. Section 3.2 d) also applies to this market.

d) **Heat application**

This is an area that includes district heating, many industrial applications of process steam but also special applications like oil refining, heavy oil field recovery, aluminium production and water desalinisation. The potential in this area can be further increased by the need to displace fossil fuels due to the global warming problem. This area, although envisaged for many years, is becoming practical only now with the maturity of the technology.

Before closing this section it is worth emphasising that in any case the final most important element that will dominate most the development of an application will be economics. Sections 3.2 e) and f) provide some preliminary elements on this subject.

An important rationale for SMRs is to open up new markets that, because of a lack of suitable products, were not open to a nuclear option.

3.2 **Specific Issues for SMR development**

This section addresses the major motives for the development of SMRs; other reasons are presented in Section 3.3 and in Chapter 4.

a) **Safety**

During the 1960s and early 1970s most of the technically developed countries of the world were proceeding with major nuclear power plant development programmes. During the past decade this trend was reversed primarily due to the public concern over major accidents. The accident at Three Mile Island caused a reassessment of reactor safety. The one at Chernobyl caused a change in the public perception of nuclear power.

As a consequence, although the existing plants already have a very high level of safety, better mutual understanding between the relevant social groups and parties must be found to improve the acceptability of nuclear power. It is expected that such discussions will show that the limitation of radioactive releases will be the key point to be agreed upon in order to reduce the need for evacuation and decontamination of the surrounding area. Other aspects are longer periods for accident management and reduction of the importance of the human factor by using inherent plant features or passive shutdown and cooling measures.

It is expected that SMRs, based on currently used technology, will meet the above requirements, in particular through new core design, passive safety systems, and a stronger containment system. SMR designs could give improvements in a number of areas important for public acceptability:

- Safe shutdown of the reactor;
- Decay heat removal from the reactor and from the containment;
• Fission product confinement;
• Overall simplicity of the plant.

The adoption of a greater share of passively acting safety features is seen by many designers as the easiest way to accomplish the above requirements and to obtain a stronger and more robust design less sensitive to the operator actions.

District heating and process heat applications may imply a need for higher protection of the surrounding area (people and facilities). Note that in particular SMRs may demand a higher safety level due to their potentially greater numbers and the sites that may be used. This approach can also make available more sites for electricity production in densely populated areas.

b) Acceptability

The acceptability of nuclear power is dependent on all its aspects including uranium mining, fuel fabrication, power plant safety, waste treatment, reprocessing, final disposal, proliferation as well as economics, the real energy demand and perceivable technological alternatives, under the assumption that no further severe accident will occur worldwide. Noting that the weakest link determines the fate of the whole technology, progress towards acceptability must be achieved on all sectors. This study can only address one sector of this list.

For the purpose of public acceptance of a nuclear power plant, it would assist if one could find a simple and easily-understandable logic about reactor safety rather than presenting solely a probabilistic evaluation which is quite difficult to understand. Simple structures may be more easily understood by people than complex ones. Since the most important feature of SMRs is simplification, there should be a good possibility of greater acceptance. In addition to the transparency of the safety concepts adopted for the SMR it is quite possible that a dominant role will be played by the degree of harmonisation of the safety rules among the different countries. The availability of a unique set of basic safety rules will be particularly important also for standardization purposes.

On these subjects however there are considerable differences of opinion within the nuclear industry (as demonstrated in Ref. 18).

c) Flexibility toward the utility needs

In the past, due to economies of scale, the tendency has been toward plants of increasing size. This approach, valid for utilities with big distribution networks, demonstrated some limitations and lack of flexibility in other cases.

An additional rationale derives from the well known fact that many regions of the world either do not have access to a large grid or do not have financially strong utilities which can afford large plants, or both, such that they could be interested in small nuclear units if they were available at low specific capital costs. In addition, due to the low growth rate, it can be convenient to install a series of small reactors instead of one large one that would be in full use only years after start-up.

The installation of a nuclear plant of today’s generation requires in addition a large skilled operational and maintenance workforce, and the availability of organisation and procedures not required for other types of power plants. This imposes the need for sizable sophisticated training programmes essentially undertaken by the country that sells the plant. The advantages of new less demanding designs which require fewer personnel are evident.
Since SMRs have less environmental impact, they increase the number of available sites and favour in the future the use of sites of decommissioned fossil fuel plants for nuclear use. The simplicity and limited size of the SMR may also allow a higher seismic qualification designed to resist larger earthquakes.

d) Heat market

In the majority of countries a large amount of the final energy consumption is in the heating sector in the form of space heat, domestic water and process heat. While space heating, that forms the majority of the heat consumed, is at temperatures around 100°C, industrial processes have a demand for higher temperatures. In both sectors due to the increasing concern about atmospheric pollution, there is a potential for nuclear application.

An additional use of SMRs that should be considered in more detail is its use for cogeneration of electric power and heat for desalination of water. The very good safety properties of most SMRs are prerequisites for nuclear reactor utilisation in this area.

e) Economics

Several economic aspects specific to SMRs are to be noted, the first being the overall financial commitment by a utility. Since the plant capital cost is in any case lower, the difficulties in financing the construction activities and also the financial risks are lower. For instance the financial problems faced to build two units with, say, a three-year pause between the two units should be lower than waiting three years and building a single station with double the power. An additional financial advantage comes from a better adaptation of the investment plan to progressively increasing needs. Smaller plants with smaller capital cost and possibly shorter construction time can simplify the financial problems to the utilities and be more attractive for private investors who look for earlier returns of investment. This is covered in more detail in Section 5.1.

Some other financial advantage for SMRs can arise from the construction time. If the SMRs are built in much shorter time periods than today’s plant, they should better address two factors that for instance played an important role in the recent privatisation effort in the UK, that is: discount rates (including risks due to time) and return on the investment.

The long construction schedules of nuclear plants made the projects vulnerable in some countries to interveners’ actions for extended periods, that in turn, resulted in design modification, that further extended schedules and compounded the effects of interveners’ actions. With large construction staffs and schedule delays, the cost escalates dramatically causing both increases in the magnitude of required financing, and extensions of the periods when capital is tied up prior to plant operation. These added costs offset the anticipated efficiency from improvements and resulted in high and unpredictable busbar costs for electricity.

Experience from large reactors shows that construction sites may have to remain open for many years (of the order of ten years, depending on the country) with a number of workers in the range of several thousand. The presence of such numbers of people represents usually a heavy disturbance to the style of life of the rural area where the nuclear sites are usually located. In the case of developing countries this means also having to relocate (or obtain from abroad) thousands of highly specialised workers at large expense. Owing to their reduced size and to the potential for extensive use of modularisation and prefabrication, SMRs can dramatically modify the situation.
f) Site factory work

In addition, the potential for modularisation and prefabrication needs to be investigated for two aspects:

- Field versus shop fabrication
- Series production.

Prefabrication of all critical components can be done under attentive, extensive quality control. As a consequence, complicated work and costly inspection at the plant site can be virtually eliminated, resulting in a significant reduction of the plant construction costs and times. It is also plausible that the general requirements for achieving high quality assembly are more favourable in a suitably equipped shop than at a temporary construction site. Of course, this could be true for both large and small reactors (though much more difficult for large reactors). Showing a particular benefit for small reactors would require a very detailed comparative analysis which is not within the scope of this study.

The benefits of series production which is not per se restricted to small reactors or small components, can be very significant. It can be concluded that modularisation and increased shop-fabrication are desirable goals and may to a certain degree be easier to accomplish with smaller reactors.

3.3 Users' requirements

The considerations given in the previous section are part of a world-wide discussion on the requirements for the next generation of nuclear power plants. All involved parties, but in particular the potential users of nuclear energy, are building on experience gained with the construction of more than 400 plants and more than 5 000 years of plant operations. It is very important to note that many organisations feel the need of a wide international co-operation providing as general a guidance as possible to the vendors. In this context it is highly desirable that the regulatory bodies utilise the opportunity given by the development of a new generation of reactors to harmonise as much as possible their safety requirements.

It is foreseeable that for electricity generation there will be available, by the end of 1990, four high level sets of requirements which have been discussed on an international basis. Although to a large extent discussed with some plant designers, those requirements will possibly need fine tuning and interpretation in the next few years on the basis of the finalisation of the designs that in many cases are still in evolution as demonstrated in Chapter 4. There is already a very clear indication of the overall tendency that the nuclear plant designs will meet these requirements. Of course the availability of a few sets of requirements does not mean there will be only a few designs but at least there will be a very much higher degree of harmonisation. The plants in operation represent some hundreds of unique designs. Table 3.2 provides some of the requirements as presented to this Expert Group. As the presentation of these requirements has not been harmonised, comparisons are difficult and the reader should turn to Reference 7 for more details.

It is desirable that equivalent efforts at harmonisation be also carried out for the foreseen new areas of application. There is also some effort under way, in particular by the IAEA, to seek an even higher level of harmonisation of the requirements for all designs.

In the remaining part of this section are listed the areas covered by the top-tier requirements with some remarks added for explanatory purposes. It is not the purpose of this report to provide either a complete list of the top-tier requirements nor an exact formulation of them. Note that many of them are of a more qualitative nature. Again it is suggested to the reader to use Reference 7 for more details.
Design margins

The design margins are to be reconsidered in order to simplify operation. In particular the new designs shall provide to the operators a very long grace period (of the order of days) to assess and handle the upset conditions that could lead to a severe plant damage.

Simplicity

Simplicity of the design is important to ease and facilitate manufacturing, construction, operation and maintenance and thus to enhance the quality of the plant.

Standardization

The purpose is again the enhancement of the quality of the plant. It is clearly important to reuse the experience gained during design, manufacturing, construction and operation on successive plants.

Environmental impact

For normal operation the plant shall be designed to further reduce the already very low environmental impact. In particular the need for off-site disposal shall be minimised. For transients and accident impact the basic requirement, as discussed in Section 3.2 a), is to re-examine, enhance, improve and simplify the various elements of the defence-in-depth concept so as to gain greater assurance of public protection while reducing the need for evacuation.

Transparency of the design

In the new plants all efforts shall be made to reduce the amount of equipment and systems necessary to meet the safety requirements, to minimise the need for interactive instrumentation and control between systems and to simplify the role of the operator in meeting the technical prescriptions.

The intent of this requirement is to broaden and enhance the perception that nuclear power is a benign and acceptable energy source and to facilitate efforts to describe this benign nature to the public in a simple, easily understood and transparent manner.

Operational exposures and waste production

The new plants are expected to utilise, to the maximum extent possible, materials which minimise the generation of corrosion products and the production of radioactive materials due to activation. In addition the lay-out and the design of the equipment shall facilitate maintenance operation as much as possible.

As an example it is envisaged a whole body radiation dose per nuclear worker less than 10 mSv/year and an average of less than 1 mSv/year over the entire crew.

Plant availability

The plant shall be designed, and operation and maintenance activities shall be planned, so as to yield to very high availability factors. The capacity factor is envisaged to be over 80 per cent for the entire life of the plant.


Electricity generating costs

The new plant shall demonstrate, through evaluations that include all factors, that it is cheaper by at least 10 per cent in the first 10 years of operation over the most economic, comparably sized, fossil-fired alternative for the intended application.

Plant life

The new plants shall be designed for a longer commercial life of the order of 60 years.

Design development

Prior to the start of construction the status of the design development process shall be such as to give a high assurance that the construction schedule can be met.

Regulatory licensing status

Prior to the start of construction, the status of the regulatory licensing processes, both in the country where the plant was designed and the country where the plant is to be deployed, shall be such as to give high assurance that construction, fuel loading and operation will not be impeded by regulatory processes.

Universality of the design

The plant shall be designed so as to maximise commonality in operation, inspection and maintenance irrespective of country or mode of deployment. This requirement is intended to maximise the value of operation, inspection and maintenance in establishing data banks on operational experience, to assure availability of spare parts and equipment and to enable the sharing of potential future development costs.
<table>
<thead>
<tr>
<th><strong>Table 3.2. COMPARISON OF USERS’ REQUIREMENTS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SAFETY</strong></td>
</tr>
<tr>
<td><strong>OPERATOR GRACE PERIOD</strong></td>
</tr>
<tr>
<td>Canada (MFR Data)</td>
</tr>
<tr>
<td>10 hours to 3 days</td>
</tr>
<tr>
<td><strong>CORE DAMAGE FREQUENCY</strong></td>
</tr>
<tr>
<td>&lt;10^-3/year</td>
</tr>
<tr>
<td><strong>DOSE AT BOUNDARY (ACCIDENT)</strong></td>
</tr>
<tr>
<td>100 mSv</td>
</tr>
<tr>
<td><strong>SEISMIC</strong></td>
</tr>
<tr>
<td>.3g</td>
</tr>
<tr>
<td><strong>OPERATIONS</strong></td>
</tr>
<tr>
<td><strong>AVAILABILITY</strong></td>
</tr>
<tr>
<td>&gt;94%</td>
</tr>
<tr>
<td><strong>CYCLE/INSPECTION TIMES</strong></td>
</tr>
<tr>
<td>3 years/21 days</td>
</tr>
<tr>
<td><strong>RADIATION DOSE</strong></td>
</tr>
<tr>
<td>.4 - .7 man-Sv/year</td>
</tr>
<tr>
<td><strong>CONSTRUCTION TIME</strong></td>
</tr>
<tr>
<td>30 months</td>
</tr>
<tr>
<td><strong>kWh COST COMPARISON</strong></td>
</tr>
<tr>
<td>&lt;coal</td>
</tr>
<tr>
<td><strong>PLANT DESIGN LIFE</strong></td>
</tr>
<tr>
<td>100 years ***</td>
</tr>
<tr>
<td><strong>OVERNIGHT COSTS</strong></td>
</tr>
<tr>
<td>&lt;1640$(US 9)/kWe</td>
</tr>
<tr>
<td><strong>LEVELIZED COSTS</strong></td>
</tr>
<tr>
<td>32.6 mills/kWh</td>
</tr>
<tr>
<td><strong>FUEL COSTS</strong></td>
</tr>
<tr>
<td>4.9 mills/kWh (incl. D2O)</td>
</tr>
<tr>
<td><strong>O&amp;M COSTS</strong></td>
</tr>
<tr>
<td>10.5 mills/kWh</td>
</tr>
</tbody>
</table>

* 35 months for the first unit
** at the site for accidents with a cumulative frequency >10^-6/year
*** with component replacement

Due to the difficulties in comparison the reader is invited to read the details in the technical supplement, ref. 7
4. DESCRIPTION AND STATE OF EVOLUTION OF SMRs IN OECD COUNTRIES

4.1 Overview on different developments

Small and medium-sized nuclear heating and power plants being developed in OECD countries are indicated in Figure 4.1. Although this list is not exhaustive it depicts the multitude of new developments and shows that there are many reactors of a similar development line and presumably aimed at the same market. It is noted that the evolution of SMRs is rapid and that this is a changing picture. Only details on the SMRs received from the vendor-designer are provided. It should also be noted that the various SMR concepts have reached different stages of development, some still in a conceptual stage, others like the AP600, PIUS, modular HTGR, SBWR, SMR, CANDU 3 and others are further advanced, with some undergoing safety reviews.

Figure 4.1 DEVELOPMENT LINES OF NUCLEAR POWER AND HEATING PLANTS IN THE OECD

Abbreviations: see Glossary
The nuclear heating plants (NHPs) are all of the dedicated heating type having outputs ranging between 2 MWth to 400 MWth in line with the small size of district heating grids. Except for the gas cooled GHR 10 all are based on light-water, boiling or pressurised, reactor technology.

With a major development objective of tailoring a reactor to meet the needs of small electricity grids, the output capacity of the various nuclear power plant (NPP) concepts ranges between 80 and 600 MWe. As depicted in Figure 4.1, all technological lines, LWRs, heavy water reactor, gas and sodium-cooled reactors, are represented. All NPPs have the capability of supplying district and process heat additionally in cogeneration mode.

In Sections 4.2.1, the NHP concepts, and in 4.2.2 the NPPs based on water reactor technology, will be described respectively. Section 4.2.3 will be dedicated to gas cooled NPPs. Sodium cooled reactors will be treated in Section 4.2.4. Short remarks on the fuel cycle aspects are added under Section 4.2.5.

The reader should use Reference 7 to obtain an expanded description of the various reactors as well as key policy statements and requirements which influenced their design.

4.2 Technical characteristics

4.2.1 Dedicated Nuclear Heating plants (NHPs)

Some 10-15 different heating reactor concepts are known today throughout the world. Seven of them have been developed in OECD countries. Table 4.1 summarises the main technical data of these concepts. Although designed to satisfy different energetic boundary conditions, obeying different safety regulations and criteria and following different technological lines, they all present common characteristics:

- The power ranges of NHP (reaching from 2 to 400 MWth) are considerably lower than those of current power reactors and even than the power range of advanced electricity producing SMRs.

- The supply temperature of the district heating networks fed by these reactors does not exceed 130°C; the coolant temperature in the primary circuit (e.g. some 200°C for water-cooled NHP) is therefore considerably lower than for large NPPs (typical for LWR: about 350°C).

- The power density of most NHP lies in the range of 2 to 55 kW/I compared with about 100 kW/I for large NPPs.

- The low temperature required allows for lower operation pressures, which in turn, along with the smaller size, are leading to less massive RPVs and allow for the components of the primary circuit to be integrated within the RPV.

- All NHPs considered make as much use as possible of components and systems proven in the operation of large NPPs.

- The operation schemes proposed for all NHPs are considerably simplified as compared to large NPPs, including for some of them totally unmanned operation.

- The core residence times of fuel in NHPs are in general longer than in NPPs. Almost all concepts are based on existing fuel cycle technologies.

- Most of the NHP concepts considered make extensive use of passive systems and components and rely more heavily on natural processes rather than engineered safeguards.
All concepts considered are designed as site independent "standardized" products, i.e. suitable for large series production.

The following descriptions reflect the Expert Group's opinion of significant or interesting characteristics. The reader should use Ref. 7 for more complete descriptions.

**Slowpoke: Safe low-power critical experiment (Canada)**

Based on the experience with its proven small 20 kWth Slowpoke swimming-pool reactors in operation in half a dozen Canadian research centres, the AECL has developed a swimming-pool reactor for heating purposes. The SES-10 has been designed for a thermal output of 5-20 MW. Its core is situated in a metallic cylinder near the bottom of a water pool and consists of fuel elements with 5 per cent enriched uranium in a zircaloy cladding. Cooling and moderation is achieved by light water in natural circulation, which transfers the heat from the core to the slab heat exchangers located at the top. Atmospheric pressure prevails at the water surface. Core loading is regulated by means of a single central control rod. The long term reactivity compensation is achieved by means of a movable beryllium reflector. The reactor is designed to be operated unmanned. A particular safety feature is the lack of need for any pressure vessel, with the disadvantage that the supply temperature in the heating network is limited to 85°C. A 2 MWth demonstration plant of this type (SDR) has been in successful operation at Whiteshell/Manitoba since July 1987.

**NHP-200 (Germany)**

This KWU reactor concept relies on the long experience with the construction of PWRs and BWRs for nuclear power plants. The plant size has been fixed at 200 MWth. The primary circuit cooling water enters the core at a pressure of 15 bar and a temperature of 160°C. The core configuration is similar to a BWR.

The temperature of the water/steam mixture at the core outlet is 200°C. The rather low pressure of the primary coolant leads quite naturally to an integration of the primary heat exchangers, the hydraulic drives of the control rods and the storage racks for spent fuel within the pressure vessel. The core heat is transferred to twelve heat exchangers by natural circulation. The reactor pressure vessel is surrounded by a tight fitting containment. A particular safety feature is that the core cannot be uncovered in a case of a leakage in the primary pressure barrier, due to the small volume available between the RPV and the containment. Reactor shutdown is achieved by switching off the pumps of the hydraulic control rod drives. Residual heat removal is achieved by opening the valves to cooling circuits with natural circulation cooling towers. The main design principles are already demonstrated in a prototype heating reactor in China.

**Thermos (France)**

The French Commissariat à l'Energie Atomique (CEA) has developed the Thermos reactor since the beginning of the 1970s. It is a pressurised water reactor, designed for a thermal output of 100 MW. The reactor core is located in a stainless-steel vessel filled with water. This vessel is in turn located in a reinforced concrete pool full with borated water. The reactor vessel contains three coolant pumps. The fuel elements are of the slab-type, cladded with zircaloy. This fuel type has been developed for power reactors of submarines.
<table>
<thead>
<tr>
<th>Concept</th>
<th>Country of origin</th>
<th>Technological line</th>
<th>Power range (MW)</th>
<th>Power density (kW/l)</th>
<th>Primary circuit type</th>
<th>Primary coolant</th>
<th>Primary coolant pressure (bar)</th>
<th>Primary coolant temperature (inlet/outlet °C)</th>
<th>Network temperature (forward/return °C)</th>
<th>Heat removal by</th>
<th>Residual heat removal by</th>
<th>Ultimate heat sink</th>
<th>Fuel type</th>
<th>Fuel residence time (years)</th>
<th>Reactivity control by</th>
<th>Shutdown by</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHR</td>
<td>CH/FRG</td>
<td>HTGR</td>
<td>10-50</td>
<td>2</td>
<td>integrated helium</td>
<td>H₂O</td>
<td>15</td>
<td>250/450</td>
<td>120/160</td>
<td>pump</td>
<td>natural circulation</td>
<td>graphite</td>
<td>LEU</td>
<td>16</td>
<td>rods</td>
<td>rods</td>
</tr>
<tr>
<td>GEYSER</td>
<td>CH</td>
<td>PWR</td>
<td>10-50</td>
<td>5</td>
<td>integrated H₂O</td>
<td>H₂O</td>
<td>4.7</td>
<td>135/149</td>
<td>118/60</td>
<td>natural circulation</td>
<td>natural circulation</td>
<td>natural circulation</td>
<td>UO₂ or UZrH rods</td>
<td>15</td>
<td>boric acid</td>
<td>boric acid</td>
</tr>
<tr>
<td>NHP-200</td>
<td>FRG</td>
<td>BWR</td>
<td>200</td>
<td>20</td>
<td>integrated H₂O</td>
<td>H₂O</td>
<td>15</td>
<td>158/198</td>
<td>120/70</td>
<td>pump</td>
<td>natural circulation</td>
<td>air</td>
<td>UO₂</td>
<td>20</td>
<td>hydr. rods</td>
<td>hydr. rods</td>
</tr>
<tr>
<td>SECURE-H</td>
<td>S</td>
<td>PWR</td>
<td>400</td>
<td>45</td>
<td>2 loops</td>
<td>H₂O</td>
<td>20</td>
<td>150/190</td>
<td>150/70</td>
<td>pump</td>
<td>natural circulation</td>
<td>pool</td>
<td>UO₂</td>
<td>2.5</td>
<td>boric acid</td>
<td>boric acid</td>
</tr>
<tr>
<td>SES 10</td>
<td>CDN</td>
<td>PWR</td>
<td>2-10</td>
<td>55</td>
<td>tank</td>
<td>H₂O</td>
<td>1.7</td>
<td>60/90</td>
<td>70/120</td>
<td>pump</td>
<td>natural circulation</td>
<td>tank</td>
<td>UO₂ slabs</td>
<td>3</td>
<td>Re-reflector rods</td>
<td>rods</td>
</tr>
<tr>
<td>THERMOS</td>
<td>F</td>
<td>PWR</td>
<td>100</td>
<td>45</td>
<td>integrated H₂O</td>
<td>H₂O</td>
<td>11</td>
<td>131/144</td>
<td>130/110</td>
<td>pump</td>
<td>natural circulation</td>
<td>tank</td>
<td>UZrH</td>
<td>50</td>
<td>rods</td>
<td>rods</td>
</tr>
<tr>
<td>TRIGA</td>
<td>USA</td>
<td>PWR</td>
<td>50</td>
<td>100</td>
<td>integrated H₂O</td>
<td>H₂O</td>
<td>8</td>
<td>82/121</td>
<td>110/80</td>
<td>pump</td>
<td>natural circulation</td>
<td>tank</td>
<td>US</td>
<td>3.7</td>
<td>rods</td>
<td>rods</td>
</tr>
</tbody>
</table>
SECURE: Safe environmentally clean urban reactor (Sweden)

Secure plants have a power range of 200-400 MWth. The reactor core is located at the bottom of a prestressed concrete vessel, which contains some 1 500 m$^3$ of cold, heavily borated water. The pressure in this vessel is 7 bar. The "reactor tank" separates the heavily borated water of the pool from the less borated water of the primary circuit. The primary pumps and heat exchangers are located outside the prestressed concrete vessel. The cooling water is heated up by the core from 90°C to 120°C. Reactivity control is achieved by adjustment of the boron content of the primary circuit.

The particular safety feature of the Secure reactor is its primary circuit, which is open towards the borated water of the pool. During normal operation a pressure equilibrium is established between primary water and pool water. In case of disturbance of this equilibrium, after a pump failure or due to a temperature rise in the primary circuit, the borated water of the pool enters the primary circuit and shuts the reactor down.

GEYSER (Switzerland)

This concept developed at the Paul Scherrer Institute (PSI) makes use of the static pressure of a high water column and does not need a proper pressure vessel. The reactor is located at the bottom of a concrete well of some 50 m in depth and 5 m in diameter, which is leakproof against the ground. With this arrangement the coolant reaches a saturated state at 150°C at the core outlet. During its rising in a so-called diffuser, the coolant goes partially into the steam phase and transfers its heat to the primary heat exchangers, which are also located in the well. These operate on their primary side as condensers and coolers and on the secondary side as evaporators. The secondary steam thus produced, transfers its heat through condensation to the heating network. Primary and secondary circuits operate by natural circulation. A particular safety feature is the large amount of borated water in the well, which, depending on the equilibrium between the heat produced in the core and the heat demand by the network, can enter the primary circuit thus leading to a load depending self-control and when necessary to a shutdown.

GHR: Gas-cooled Heating Reactor (FRG/Switzerland)

The GHR belongs to the family of the gas-cooled pebble-bed high temperature reactors. Based on the HTR principle, HTR GmbH has developed a small, simple heating reactor with stationary pebble-bed. Control rods are located only in the reflector. A particularity of the design is the intensively cooled liner, which in addition to its normal function has the function of a primary heat exchanger, thus making additional components unnecessary. The heat removal capacity of such a system is however limited, resulting into a limitation of the power range of the reactor to some 15 MWth.

Higher power ratings could be achieved by using conventional heat exchangers. The high thermal capacity of the graphite in the core and the reflector and the integrity of the fuel elements up to temperatures far above the expected maximum values are an important safety feature of this reactor type.

TRIGA (USA)

The TRIGA heating reactor is based on the proven TRIGA research reactor developed by GA technologies, which has been successfully operated during more than 800 reactor years world-wide. The concept uses a reactor pressure vessel to achieve temperatures adequate for a district heating network. The primary system consists of a reactor unit and a heat exchanger unit. A primary coolant pump is located between these two systems. The RPV is located at the bottom of a large tank filled with water, which provides an emergency heat sink. Particular safety features of the TRIGA concept are on the one hand the uranium-zirconium hydride fuel with its prompt negative temperature coefficient, and on the other hand the transition from normal operation to decay heat removal after failure of the forced convection without any...
active intervention by means of a pressure balanced Venturi nozzle. Based on the same principles the 
TRIGA system can be used as a combined heat and power source (CHP) using a Organic Rankine Cycle 
power conversion system.

4.2.2 Water-cooled and moderated nuclear power plants (NPPs)

Table 4.2 shows the main features of the NPPs of this type under discussion.

Common to most SMR developments is the pursuit of passive safety systems based on the premise 
that such systems are easier to implement in plants smaller than the current 1 000-1 300 MWe units. The 
prime objective is to prolong the grace period before active measures are required for long-term cooling. For 
example in the initial stage of a small break LOCA, see Table 4.3, some of the concepts rely on gravity 
(AP600) and others on passive steam driven injectors (GE-SBWR, SIR 300, HSBWR) for replenishing coolant 
lost by the RPV from in-containment tanks. For large breaks accumulators are provided. Also, after 
controlled depressurisation most AP600, GE-SBWR, HSBWR concepts envisage gravity injection of water. 
The design grace period ranges between several hours to a few days, depending upon the design. 
Admittedly, actuation of all these "passive" systems requires opening a valve (battery driven or check valve) 
but this is more reliable than the emergency diesels deployed in current large water reactors.

The Siemens SBWR and the SECURE-P eliminate safety-grade make-up systems altogether through 
large water inventories in the RPVs that can sustain full blow-downs without uncovering the core.

With the objective of increasing design margins and enhancing operating flexibility in comparison with 
larger reactors, the SMR designs envisage larger specific pressuriser volumes and water inventories above 
the core (in terms of m³/MW). Contributions to these ends are also expected from the lower power densities 
of the SMR cores that are by 10 to 60 per cent lower than those of their larger counterparts (see Table 4.2).

Significant simplification of the systems throughout the plant as indicated in Table 4.4 and increased 
application of modularised and prefabricated construction are key design features of the advanced SMR 
technologies. There is no new design which does not lay emphasis on simplification and its benefits.

Generally, with the term plant simplification is considered simplification of the arrangement of systems 
and equipment, of operations, inspections, maintenance and quality assurance requirements, resulting in 
significant reductions in equipment and bulk material quantities. Some examples will show the desired 
consequences of plant simplifications.

The simplified reactor coolant loop configuration with canned motor pumps as provided in the AP600 
design offers various benefits including an improvement of plant safety by eliminating the possibility of a shaft 
seal LOCA as well as a simplification of the pump lubricating and cooling systems. Furthermore the compact 
symmetrical reactor coolant loop configuration with application of leak-before-break criteria (that has been 
successfully applied in currently operating large power plants, e.g. German Konvoi Plants) makes possible 
an extremely simple, effective and inexpensive support system. The simplicity of the supports in turn permits 
excellent access to the steam generators and pumps for inspection and maintenance.

Substantial simplification of BWR-design is obtained by the elimination of the recirculation loops, 
pumps and controls needed for forced circulation (as already demonstrated in newer full size BWR designs). 
The simplification provides a number of benefits, e.g. a reduced number of operational transients and 
increased thermal margin for the margins which are expected to occur. Designs which have selected natural 
circulation for providing coolant flow through the reactor core are GE-SBWR, Siemens SBWR, HSBWR 
(Hitachi) and ISER (Japan).
Table 4.2. **Main features of small and medium-sized nuclear power plant concepts based upon water reactor technology**

<table>
<thead>
<tr>
<th>Concept</th>
<th>Boiling Water Reactors</th>
<th>Pressurized Water Reactors</th>
<th>D₂O Reactors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HSBWR</td>
<td>SBWR-200</td>
<td>SBWR-600</td>
</tr>
<tr>
<td>Systems design</td>
<td>Hitachi</td>
<td>Siemens</td>
<td>GE</td>
</tr>
<tr>
<td>Project status</td>
<td>C</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Power, MWe</td>
<td>600</td>
<td>200</td>
<td>600</td>
</tr>
<tr>
<td>Primary pressure, bar</td>
<td>70.7</td>
<td>70.6</td>
<td>72</td>
</tr>
<tr>
<td>Power density, kWt</td>
<td>34</td>
<td>20</td>
<td>37</td>
</tr>
<tr>
<td>Primary circuit configuration</td>
<td>integr.</td>
<td>integr.</td>
<td>integr.</td>
</tr>
<tr>
<td>Normal operation core cooling mode</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Reactor pressure boundary</td>
<td>PV</td>
<td>PV</td>
<td>PV</td>
</tr>
<tr>
<td>-diameter, m</td>
<td>6.3</td>
<td>5.6</td>
<td>5.9</td>
</tr>
<tr>
<td>-height, m</td>
<td>25.0</td>
<td>17.0</td>
<td>22.0</td>
</tr>
<tr>
<td>-material</td>
<td>steel</td>
<td>steel</td>
<td>steel</td>
</tr>
</tbody>
</table>

**Abbreviations:**
- C: conceptual design
- F: forced circulation
- PV: Pressure vessel
- PT: Pressure tube
- PV: Pressure vessel
- PT: Pressure tube
- NU: natural uranium

**Status:** Spring 1990
<table>
<thead>
<tr>
<th>Concept</th>
<th>BWR</th>
<th>PWR</th>
<th>D_{2}O</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>HSSWR</td>
<td>SWWR 200</td>
<td>SWWR 400</td>
</tr>
<tr>
<td><strong>High pressure water injection for small LOCA</strong>s**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- In containment reservoirs</td>
<td>-</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>- Ex containment reservoirs</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Gravity driven</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Steam driven</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>- Emergency battery actuation of injection system</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td><strong>Low pressure water injection for large LOCA</strong>s**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Accumulators</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Active depressurization</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>- In containment steam dump</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>- In containment reservoir</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>- Gravity driven</td>
<td>-</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>- Steam driven injector</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Pumped/emergency diesel</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Emergency battery actuation of injection system</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>- Grace period for operator action in days 1)</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Heat removal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Large in vessel heat storage capacity</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>- Containment wall cooling via heat conduction and natural circulation</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- In vessel/in containment heat exchanger/steam generator to ex containment air cooler or condensing pool</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
</tbody>
</table>

1) No core protection regulatory limits exceeded in this period assuming no operator action for LDB events including loss of all AC power
2) several

Status: Spring 1990
Table 4.4. Features leading to plant simplification in the OECD small and medium-sized water reactors

<table>
<thead>
<tr>
<th>Feature</th>
<th>BWR HSBWR 200</th>
<th>BWR SBWR 600</th>
<th>BWR SIR 300</th>
<th>AP 600</th>
<th>MS 300</th>
<th>SPWR</th>
<th>PIUS- P</th>
<th>D_{2}O CAN DU 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elimination of primary system recirculation loops (integrated design)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Elimination of primary system recirculation loops (integrated design) with pumps</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Reduction of RPV external large bore primary piping</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Reduction of number of welds</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Elimination of safety grade coolant make-up systems</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Increased in vessel heat storage capacity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Application of passive emergency cooling</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X^{1}</td>
</tr>
<tr>
<td>Application of passive residual heat removal system</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X^{2}</td>
</tr>
<tr>
<td>Location of PRV penetrations in the upper part of the vessel</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Incorporation of relatively large pressurizers (PWR)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Minimization of the number of seismic structures, simplification of builders' concept</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ease of component replacement</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Elimination of emergency diesels</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
</tbody>
</table>

1) Accumulator type design
2) Moderator system will remove decay heat in case of a LOCA coincident with ECC failure

Status: Spring 1990
A further plant simplification is the gravity driven emergency core cooling system. It is a passive safety system eliminating the need for pumps or safety grade diesels. All designs described in this chapter have chosen passive measures for emergency core cooling or residual heat removal.

Factory prefabrication, modularisation and ease of decommissioning (small components, prestressed cast iron vessels, boron tanks) are further key claims of the advanced SMR technologies. All principal components are to be built in a factory where full quality control and production line techniques can be used. They are completed as modules which are then simply assembled on site.

The benefits obtained are very much reduced on site requirements for nuclear grade welding, substantially reduced construction schedule and thus significant economic advantages. This implies, however, implementation of a number of identical plants in series. Such techniques are by no means totally novel. 1 300 MWe plants built recently in Japan, France and Germany have deployed them with great success.

Short descriptions

- **HSBWR**

The 600 MWe Hitachi Small BWR is a conceptual design of a BWR with natural circulation. The RPV with the reactor core and with simplified internals is located in a free standing steel pressure containment vessel (PCV) which also contains the suppression pool. The space between the PCV and the reactor building is filled with water and forms the outer pool. For short term emergency core cooling a steam driven pump and accumulators with emergency coolant at low pressure are provided. The core cooling after normal reactor shutdown and the long-term cooling are performed by residual heat removal (RHR) systems with injection pumps and heat exchangers. If the RHR systems are not available because of pump failure, coolant can be fed into the RPV by manually refilling the accumulators with attachable pumps. Heat removal from the PCV can be achieved by natural circulation in the suppression pool and heat conduction through the steel PCV wall to the outer pool between the PCV and reactor building walls. This heat removal from the PCV to the outer pool does not require any movable components. It suppresses the PCV pressure to within the design pressure for 3 days without water supply to the outer pool.

The simplification of systems and components and the arrangement of the spent fuel pool and control room in another building results in a reduction of the reactor building volume to 50 per cent of the current BWR building for the same rated capacity. All water pools are in the basement of the reactor building improving its seismic resistance. Simplification of the components and systems and the adoption of steel structures in the PCV shortens the construction period to 32 months (i.e. to commercial operation).

- **SBWR 200**

The Small Boiling Water Reactor of 200 MWe is under investigation at Siemens to serve potential customers who cannot accommodate large standard nuclear power plants. The major development task is attainment of specific capital cost that is close to that for a large station while maintaining a comparable level of safety. Based on standard BWR technology, there are several features that are used to achieve this goal:

- Natural circulation-cooled, low power density core with low steam void reactivity;
- Natural steam separation and thus elimination of related internal equipment;
- New hydraulic control rod drives without drive extensions below or above the RPV;
- RPV-internal emergency heat exchangers with heat removal path to ultimate heat sink for all accident conditions;
- Reactor isolation valves directly attached to RPV, no steam release for normal transients;
- Reduced redundancy in nuclear auxiliaries;
- Reactor, auxiliaries and turbogenerator located in a single, large containment building.
The safety target for the SBWR is to meet the same stringent level that is realised in KWU big Konvoi stations (PWR of 1 300 MWe). With the proposed concept this target is achieved, especially since all RPV penetrations are located in the upper part of the RPV and reliable shutdown and passive emergency heat removal are ensured under all design basis accident and ATWS conditions.

- **SBWR-600**

The GE 600 MWe SBWR is an advanced BWR (conceptual design). The natural circulation scheme demands a larger vessel than a forced-circulation BWR of comparable size. An isolation condenser submerged in a suppression pool above the reactor vessel allows depressurisation without fluid removal when the reactor is isolated from the turbine condenser. This also insures the low pressure needed for gravity driven water injection from the suppression pool during emergency core cooling. The SBWR design includes a non safety steam injector system which provides high pressure make-up water to the reactor for loss-of-feedwater transients and small break accidents. The heat transferred to the suppression pool during a loss of coolant accident can be removed automatically and passively for three days without operator action by the natural circulation water flow of the Passive Containment Cooling System (PCCS). The PCCS design includes a water filled annulus that is built into the side of the suppression pool wall (also the containment wall). The heat of the pool is transferred to this "water wall" which in turn is cooled by natural circulation of the water inside the annulus. Beyond 3 days, water make-up is all that is needed to continue the passive cooling functions.

- **SIR 300**

The 320 MWe Safe Integral Reactor is a small passive light water reactor developed by an USA-UK venture consisting of Combustion Engineering, Stone and Webster, Rolls Royce and UKAEA. SIR is an integral PWR in which core, steam generators, pumps and pressuriser are all contained within a single pressure vessel. The core is low down in the vessel. Apart from the control rod drives and guides, the space above the core is left free for refuelling operations. Outside the core barrel is a ring of 12 modular steam generators. Above the steam generators are arranged six mixed flow pumps. The upper part of the vessel forms a pressuriser with electrical heaters to maintain the design pressure. Decay heat can be removed through the steam generators via natural convection or using the safety relief valve lines and containment pressure suppression tanks. Because it does not include any large-bore piping, there cannot be a large-break LOCA.

High pressure injection is provided by a passive steam injector which uses primary side steam and obtains its water supply from the containment pressure suppression pools located above the vessel.

- **AP600**

The AP 600 stands for "Advanced Passive" PWR of 600 MWe designed by Westinghouse Electric Company. The main design objective was the simplification of plant systems. The reactor coolant system employs hermetically sealed canned motor pumps. The steam generators bottom channel heads permit direct attachment of two pumps per steam generator. The containment is a vertical cylindrical steel shell surrounded by an air baffle shell. The residual heat removal is performed by one RHR heat exchanger (HX) located in a natural circulation loop. The HX is located in the in containment refuelling water storage tank, which serves as the heat sink.

To accommodate leaks, a passive safety injection system comprising a set of tanks is provided. The steam released from the RCS is condensed on the containment wall. The condensate drains back down and is available for recirculation into the RCS. These passive RHR and safety injection systems are to eliminate the need for high and low head safety injection pumps as well as the need for safety grade diesel generators and cooling water systems. The passive containment cooling system transfers the heat from the containment structure to the environment utilising the natural circulation of air between the reactor containment structure.
and the shield building surrounding the containment aided by the drain of water via gravity onto the containment shell if required.

- **MS-300/600 (MSPWR)**

  The Mitsubishi Simplified PWR (MSPWR) is a new type PWR conceptual design incorporating advanced safety system to improve economy, safety and reliability.

  The major features of MSPWR are the introduction of a combination of passive safety systems and active safety systems and application of steam generators for long term decay heat removal.

  The passive safety systems, which actuate during a LOCA, terminate the accident and maintain core and container vessel cooling with a grace period of 3 days. The active safety systems which actuate in NON-LOCA situation and very small LOCA situations, are powerful and capable of restoring a safety state with minimum damage of plant. The combination of passive safety systems and active safety systems ensures both plant safety and availability.

  The steam generators of MSPWR are also used as safety grade passive residual heat removal system. For this purpose, a horizontal type steam generator is adopted to maintain natural circulation in the primary loop after an accident.

- **SPWR**

  A design study has been carried out in order to realise a reliable and economical reactor for the next generation of medium-sized power plants (Ref. 19).

  Two basic types (hot vessel and cold vessel types) of SPWR are available. Furthermore, there are many options for the location of the main circulating pump (hot leg and cold leg).

  All these reactors dispense with control rod drive systems, and their operation is controlled by means of negative temperature and void coefficients of the reactor core and the concentration of boron in the primary water. Reactivity changes due to fuel burn-up are also compensated by adjusting the boron concentration.

  In the event of an abnormality such as a drop of main circulating pump delivery pressure, the hydraulic pressure valves at the upper interface between the primary water and borated water are automatically opened and the borated water is injected into the reactor core to cause shutdown.

  Among the wide options of SPWR, SPWR-H/H (hot vessel/hot leg type) has been selected as the reference concept, since it seems to be the most realistic one to realise in the near future. 700 MWe power plant with twin 1 100 MWth reactors has been studied by using the reference concept.

- **PIUS**

  As representative for the PIUS-type reactors, only the Secure-P will be described.

  The 640 MWe SECURE-P unit is an ABB developmental design, according to the PIUS design philosophy that aims at protecting the core against overheating and subsequent fuel damage in accident situations using safety systems that are based on process functions which rely on natural laws (e.g. gravity, thermohydraulics). The reactor core is a low-rated PWR core. Each fuel assembly comprises gadolinium rods to suppress excess reactivity at the beginning of a fuel cycle and to keep the boron content in the primary coolant low. All primary components - the reactor core, the primary recirculation pumps, the steam generators, the piping (riser and downcomer) as well as the pressuriser are surrounded by a pool of cold
(50°C) and high boron content (2 200 ppm) water. The primary system and the pool water are located in a common prestressed concrete vessel separated from one another through an upper and a lower hydraulic interface element. Should the core tend to approach dryout conditions, e.g. through loss of the secondary side heat sink (feedwater) or overpower, the primary circuit first heats up and may reach the boiling point. The resulting decrease in density (bubbles) increases the flow through the core. The pumps speed increases; after having attained their maximum flow rate they cannot prevent inflow of borating water from the pool through the lower interface region. As a result of this inflow the reactor is shutdown or its power is limited to a safe value. Thus the thermohydraulics of the system provide self-protection against unsafe conditions.

Heavy water reactor

- CANDU 3

As shown in Figure 4.1 the CANDU 3 is the only SMR being based on heavy water reactor technology and being developed within the OECD. With a net electrical power output of 450 MW the CANDU 3 represents the smallest and latest version of the successful CANDU-reactor line. It makes full use of the proven technology of the established 665 MW mid-size CANDU 6 being updated with relevant features resulting from the ongoing Canadian research and development programme.

The CANDU 3 is fuelled by natural uranium and permits on-power refuelling as well as low excess reactivity. The fuel bundles are situated in zirconium-niobium horizontal pressure tubes being surrounded by a zircalloy calandria tube with CO₂ as thermal isolator in the annulus. Except the pressure tubes all other components of the reactor assembly operate under low temperature and low stress. The fuel bundles are cooled by pressurised heavy water and the secondary heat transport system consists of one loop with two steam generators and two pumps. The arrangement allows natural coolant circulation in case of loss of power in the heat transport pumps.

The additional cooling circuit for the heavy water moderator can also be used for decay heat removal in the unlikely event of loss of coolant coincident with failure of the light water emergency core cooling system.

Main design goals are aiming to:

- Enhanced safety;
- Low man-rem exposure (50 per cent reduction from CANDU 6 to design);
- High lifetime capacity factor;
- Maximisation of component/plant life (up to about 100 years);
- Easy replacement of any component;
- Short and manageable construction schedule (30 months from first concrete).

The reactor is designed for an envelope of different site conditions and foresees standardized key components as being used in the operating CANDU power stations.

Maintenance and inspection outages are reduced to 21 days on a more than two-year-period or less than 90 days for major equipment replacements with a frequency of more than 15 years.
4.2.3 Technical characteristics of gas cooled reactors

Graphite moderated Gas Cooled Reactors (GCR) have been operated since 1956 for commercial power generation in unit sizes up to 670 MWe. More than 500 operation years represent the technological and operational background of this reactor line, thus contributing significantly to the worldwide SMR-experience.

Magnox Reactors and the Advanced Gas-Cooled Reactors are based on metallic cladding of the fuel and CO₂ as coolant. System design and component reliability have been improved throughout the years so that good availabilities and an excellent thermal efficiency of more than 40 per cent have been achieved. Steam temperatures up to 540°C are identical to conventional power plants. The radioactive impact on the personnel has been remarkably low.

The further development of GCR in the USA, Germany, Switzerland and Japan has concentrated on the High Temperature Gas Cooled Reactor (HTGR) type using helium as coolant and a ceramic cladding of the fuel that is capable of retaining the fission products up to temperatures of more than 1600°C. This cladding is built up of very dense pyrolytic carbon and silicon carbide layers surrounding a small uranium oxide or uranium carbide kernel with a diameter of about 0.5 mm, forming a small "pressure vessel" able to withstand reliably up to about 800 bar of internal pressure. The so called "coated-particle" is a common feature of all HTGRs no matter whether the coated particles are embedded in a block-type or a spherical (pebble) graphite matrix.

The operation temperatures of HTGRs can be adapted to the specific needs of industrial cogeneration applications to the extent that the metallic material for the heat exchanging components are qualified. As a result of extensive material research heat transfer components can already be build up to 900-950°C with lifetimes exceeding 150 000 h.

The specific safety features of HTGRs are mainly based on:

- The high temperature resistance of the all ceramic core structure,
- The large difference between operation temperatures and failure limits of the coated particles,
- Self-stabilisation due to the negative reactivity temperature coefficient and large margin for allowable temperature-rise,
- The low power density of the core (less than 7MW/m³),
- The large heat capacity of the graphite moderator and structures,
- The inert, phase-stable helium coolant.

Small power sizes and/or low operation temperatures such as required for district heating enhance the safety margins further so that even an unstaffed operation seems to be possible for such a purpose (Ref. 20) (see GHR 10 under Chapter 4.2.1).

Based on construction and operation experiences with the OECD Dragon Project, Peach-Bottom No. 1, Fort St. Vrain, AVR and THTR together with the results of broad R&D programmes there are two main development lines of HTGR cogeneration power plants represented by a 550 MWe integrated design with a prestressed concrete pressure vessel (PCRV) and modular designs with steel pressure vessels of LWR-type and quality. Table 4.5 shows the major characteristics of the reactors described.
Table 4.5. **MAIN FEATURES OF SMALL AND MEDIUM SIZED HIGH TEMPERATURE REACTORS**

<table>
<thead>
<tr>
<th>Concept System Design</th>
<th>High Temperature Reactors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HTR-Module</td>
</tr>
<tr>
<td>Project Status</td>
<td>HTR-GmbH</td>
</tr>
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<td>Power, MWe</td>
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<td>Primary circuit</td>
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<td>Normal operation core</td>
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<td>cooling mode</td>
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</tr>
<tr>
<td>-material</td>
<td>steel</td>
</tr>
</tbody>
</table>

**HTR-500 (Germany)**

The reactor design is close to the THTR-300 concept with primary circuit and steam generators integrated into a PCRV. Modifications have been focused on standardization and simplification of improved components and systems such as:

- Once-Through Then-Out on-load refuelling pebble-bed core,
- Compact PCRV by high strength, temperature resistant concrete, improved prestressing methods and component arrangements,
- Separate decay heat removal systems also operable under natural convection,
- Liner cooling system as ultimate heat sink in hypothetical accidents,
- Filtered, vented, aircraft-crash resistant confinement,
- Vertical shaft magnetic blower bearings.

The assumed accident conditions can only develop slowly providing enough time for countermeasures. A risk analysis has shown that no dangerous radioactive release will occur under all accident conditions with a pressurised reactor. Even in case of depressurisation and total loss of heat sinks, the PCRV is capable of absorbing the decay heat in a passive way. Long term radioactive releases would be strongly reduced mainly by the graphite structures acting as an "internal filter" and by the passive confinement filter. No immediate measures for sheltering or evacuation of the population would be required even in this case.
Construction time is estimated to be under 60 months and power generation costs are claimed to be equal to large LWR.

- **Modular HTGR**

The modular reactor concept has been developed since 1979 in contrast to the established tendency at that time to enhance the unit sizes of power plants for further improvements of economics. The specific power demand can be matched by multiple arrangement of reactor modules. The design of modular HTGRs is governed by the aim to keep, solely by passive heat transfer, the fuel temperatures so low under all accident conditions that no significant fission product release can take place even including the depressurisation accident combined with loss of all active cooling. This leads to limitations in power size and power density as well as to a larger surface/volume ratio because the decay heat has to be transported to coolers or structures outside of the reactor vessel only by heat radiation and heat conduction via the surface of the core and the pressure vessel. This leads to a relative large height of the core for a small diameter to reduce the temperature gradients in the core itself.

A typical time/temperature relation for a depressurised reactor under loss of active cooling is shown in Figure 4.2. The maximum temperatures of about 1600°C are reached after approximately 30 hours in a small part in the centre of the core and slowly drop after 30-50 hours without exceeding the fuel design temperatures that have been qualified by extensive investigations in this temperature range on irradiated fuel. These accident simulation tests show that no coated particle failure or enhanced diffusion can be expected within this temperature limit (Ref. 21). The system and fuel behaviour have been successfully demonstrated also in the 50 MWth AVR plant.

![Figure 4.2. TEMPERATURE EVOLUTION DURING A LOSS OF COOLING ACCIDENT OF A SMALL HTR; AND IN THE HEATING TESTS WITH IRRADIATED FUEL ELEMENTS](image-url)
This clear and easily understandable design principle reduces the need for active safety systems to a very high degree and limits the safety grade equipment such that the "cost" for power limitation and large vessel dimensions can almost be compensated. The plants are also capable of withstanding a complete station blackout over a long time period, thus needing no multiple redundant emergency power supplies. Safety relevant actions are mainly reduced to shutting off the blowers and activating the absorbers for cold and long term subcriticality.

- **MHTGR (USA)**

  The American Modular High-Temperature Gas-Cooled Reactor (MHTGR) has a unit power size of 450 MWth. The block type fuel is arranged as an annular cylinder to keep the central temperatures under the above mentioned limits. The power density can be raised to 6 MW/m³ due to this geometrical form.

  The side-by-side vessel arrangement is identical to the German HTR-Module to prevent ingress of water as well as overheating of metallic components and to permit hot stand-by operation with subsequent smooth restarting. Decay heat removal of the MHTGR is normally done by an additional cooling circuit.

  The reactor is embedded underground, thus reducing the need for further sheltering against airplane crash or sabotage. The reactor cavity cooling is done by natural air convection. In hypothetical accidents the decay heat can also be absorbed by the surrounding earth.

  The US-NRC has already performed a preliminary safety assessment and endorses the main safety characteristics and design principles (Ref. 22). Investigations for improved economics and power output are underway.

- **HTR-Module (Germany)**

  The German 200 MWe HTR-Module is based on the pebble bed principle with on load refuelling and multiple reshuffling of the pebbles to get a homogenous power distribution at an average power density of 3 MW/m³. The reactor concept is mainly based on the AVR test reactor which has been operated successfully over 23 years up to 950°C and demonstrated the system behaviour also under selected hypothetic or design accident conditions. The emphasis in the application is cogeneration of power and either industrial process heat or district heat. Concepts for high temperature process heat and a barge mounted version have also been developed.

  As an alternative to the steel-vessel reference design, a Prestressed Cast Iron Vessel (PCIV) is being qualified that excludes sudden burst and eases transport, construction and decommissioning (Ref. 23). (This vessel type is also applicable to some other reactor systems.)

  All components are designed for full plant service life of 40 years. Replacement of sub-units including the total core assembly is nevertheless possible to ensure a high degree of capital security.

  Due to the low excess reactivity of the on-load refuelled core and an adjusted moderation ratio by limitation of the heavy metal inventory in the fuel elements, the effects of reactivity accidents are strongly reduced. Water ingress or even sudden ejection of all absorber rods can easily be controlled by the negative temperature coefficient and simple shut down of the blower. The safety properties were confirmed by the German Reactor Safety Commission in April 1990 (Ref. 24) and by a detailed concept assessment of the "Technischer Überwachungsverein, Hannover" (Ref. 25).

  New concept features have been qualified by R&D programmes and large scale testing so that the reactor is available for commercial application in short time.
4.2.4 Technical characteristics of liquid metal reactors (LMRs)

In a fast neutron spectrum it is possible to produce more fissile material than is being used for the fission process itself. The conversion of U-238 to fissionable Pu-239 multiplies the energy derived from the mined uranium some 60 times. As moderating, light material has to be avoided in fast reactor cores, liquid metal -- generally sodium -- is used as coolant.

Fifteen LMR prototype reactors and power plants have been built in OECD countries since 1946 and have accumulated many years of operating experience. The breeding capability has also been demonstrated in large scale plants. LMR base technology is available today for the design and construction of improved new reactor generations up to 1 500 MWe.

LMR development work has been directed to find configurations that will produce electricity with cost competitive to LWR power cost. The value of fuel being produced is incorporated in the economic evaluations to help compensate the higher specific LMR capital costs. This aim can be reached in two ways, either enhancing the power (e.g. Joint European Fast Breeder Project) or taking full use of simplification and modularisation in the SMR power frame. In both cases the developments aim to enhanced use of passive safety features mainly by the excellent heat capacity and natural convection capability of the sodium coolant for decay heat removal.

There are three modular small or medium-sized liquid metal reactor concepts under consideration in the US and Japan, namely:

- The "Advanced Liquid Metal Reactor (ALMR)" by General Electric et al. (former PRISM project) with 155 MWe/module and 465 MWe per power block;
- The Sodium Advanced Fast Reactor (SAFR) by Rockwell International et al. with 450 MWe per "Power Pak Module"; and
- The 200 MWe -- "Advanced Double Pool Reactor (ADP)" being designed by the Japanese Central Research Institute of Electric Power Industry (CRIEPI).

Main design data of these reactor concepts are listed in Table 4.6.
<table>
<thead>
<tr>
<th>Concepts</th>
<th>System design</th>
<th>Project status</th>
<th>Power MWe</th>
<th>Pressure, bar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ALMR</td>
<td>GE et al.</td>
<td>p</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rockwell et al.</td>
<td>C</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CRIEPI</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Primary circuit configuration</td>
<td>pool</td>
<td>pool</td>
<td>pool</td>
<td></td>
</tr>
<tr>
<td>Reactor pressure boundary</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- diameter</td>
<td>6</td>
<td>13</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>- height</td>
<td>19</td>
<td>14.50</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>- material</td>
<td>stainless steel</td>
<td>stainless steel</td>
<td>stainless steel</td>
<td></td>
</tr>
<tr>
<td>Operation temp. (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- core inlet</td>
<td>336</td>
<td>357</td>
<td>385</td>
<td></td>
</tr>
<tr>
<td>- core outlet</td>
<td>485</td>
<td>510</td>
<td>540</td>
<td></td>
</tr>
<tr>
<td>- steam temperature</td>
<td>282</td>
<td>457</td>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>

In addition to general LMR design goals there are specific aspects for Small or Medium-sized LMRs:

- The enhancement and utilisation of the inherent passive safety characteristics of liquid metal reactor systems which may be more easily achieved in smaller units;
- Increased utilisation of the characteristics of liquid metal fast reactors to consume actinides and thereby reduce the toxicity level of spent fuel to less than the level of natural uranium ore in a few hundred years instead of hundreds of thousands of years (actinide burning);
- Significantly reducing the plant's construction time by factory construction of small reactors;
- Significantly reducing the capital commitment for each of the LMR plants (prototype, initial, and final).

In addition the development of an integrated fuel cycle facility with the potential of being located on the reactor site is being considered for LMRs.

These aims should be matched in an economic way by:

- Selection of a reactor size and shape that will enhance the removal of decay heat with natural circulation of sodium in the primary system and ambient air circulation around the vessels, piping and other hardware;
- Selection of fuel, a reactor size and shape that will enhance the negative reactivity feedback characteristics of the core;
- Selection of fuel and cladding materials that will also enhance the negative reactivity feedback characteristics. The demonstrated ability of metal fuel to perform well with extended radiation is permitting its other features to be used without the economical penalty that was of concern in the 1960s;
• Selection of a core size and shape that provides enhanced actinide burning characteristics;
• Selection of a plant size that limits required capital commitment and construction time.
• Development of buildings, vessels and internal support structure that enhance:
  - The ability to change the core configuration from primarily power generation to breeding or actinide burning core;
  - The plant’s ability to be seismically isolated;
  - The plant’s ability to incorporate modular components, instruments and controls that utilise advanced and changing technologies;
  - The plant’s ability to be economically dismantled after decommissioning.

Currently there is only one small size LMR project in the world which has governmental and utility support: the American Advanced Liquid Metal Reactor (ALMR).

Two different concepts have been put together under this project: the modular reactor PRISM of General Electric Co. (Ref. 28) and the integrated metal fuel cycle, which is developed by Argonne National Laboratory (Ref. 29).

It should be kept in mind that PRISM could work with mixed oxide fuel (MOX) too and a large monolithic reactor could be operated with metal fuel also. The combination chosen for ALMR is well suited for the U.S. market. The European or Japanese market could come to another combination of reactor size and fuel cycle.

In any case European and Japanese programmes will examine the merits and benefits of small-sized FBRs (Refs. 30 and 31).

Some years ago there was competition between PRISM and SAFR of Rockwell, but recently the US Department of Energy (DOE) selected PRISM for further development (Ref. 32).

Before going into details of the reactor, another important fact must be underlined: LMRs are more economic when operated as large plants with about 1 000 MW electrical output. This is due to the very expensive fuel and component handling equipment and large sodium auxiliaries, which could be jointly used for several reactor modules in a large plant. Therefore the ALMR is planned with nine PRISM reactors in a plant of 1 245 MW net electrical power, with common auxiliaries and handling equipment and with an integrated fuel cycle facility -- as final or optimum installation.

The main goals of the LMR have not been changed with PRISM: electricity and fuel production as a breeder. PRISM is an integrated or pool-type reactor, designed for a saturated low pressure steam cycle, with low primary and secondary circuit temperatures.

The intermediate heat exchangers (IHX) and the electromagnetic primary pump (EMP) design is innovative but based on well known LMR technology, as are also the remaining reactor components. Therefore good continuity in R&D is assured and the operational experience of running LMRs can be fully used.

Lessons learned from the TMI and Chernobyl accidents show that human errors played a dominant role. PRISM has been designed in a way that operator actions should not be required to keep the reactor in a safe state and that the operator should not be able to interrupt, or defeat, automatic or passive safety actions. Similar requirements are now common for advanced reactors all over the world.

PRISM terminates anticipated transients, such as Loss of Flow (LOF), Loss of Heat Sink (LOHS) and Transient Over Power (TOP) without scram in a safe but floating state, using inherent reactivity feedbacks.
and the fully passive cooling capacity. Therefore the second reactor protection and shut down system could be economised and replaced by a very simple ultimate shut down device.

The safety graded decay heat removal system RVACS is completely passive. It needs neither operator action, nor control or energy. A permanent air flow around the containment vessel removes the heat by natural convection. The heat losses during power operation are negligible.

The reactor containment consists of a steel guard vessel around the primary vessel and a steel dome above the primary vessel closure head. This steel containment is surrounded by concrete structures.

The guard or containment vessel design, the inherent reactivity feedbacks and the passive decay heat removal capacity should exclude all accident sequence leading to a Core Disruptive or Loss of Coolant Accident.

The safety issues of PRISM have been analyzed in a preapplication design review made by the US NRC with support of the Brookhaven National Laboratory (Ref. 33).

The fuel bum up target value, the core subassembly design and the fuel management of ALMR are similar to other LMR projects. In certain operating modes, the ALMR could reduce radioactive waste by "Actinide burning" easier than large liquid metal reactors.

The small size and design innovations of the PRISM concept are expected to compensate for losses in economy of scale by reducing the extent of safety grades systems and components, by increasing the extent of factory fabrication of all safety related components and the standardization that is possible with such manufacturing activities, and by shortening construction schedules. Additionally, further benefits are expected because the use of multiple reactor modules and two or more turbine generators leads to higher availability factors and reduced system reserve margin requirements (Ref. 34).

Today utilities require construction times not longer than four to five years. The modular plant design offers considerable possibilities of schedule reduction by assembling prefabricated modules and by simultaneous work on several well separated reactors (Ref. 35).

During a fuel handling campaign or in case of a failure on a primary or secondary circuit component, only the affected module is shut down, the others continue electricity production without interruption so that a high availability factor is achieved.

The small and slim reactor size allows exchange of all primary components -- reactor vessel included -- with a shielded flask, which is a proven technique in sodium technology. The same technique could ease the decommissioning at the end of life or in exchanging certain components in order to extend the life of the plant.

The long-term advantage of using fast reactors to effectively multiply the usable nuclear fuel reserves is recognised and being pursued by most OECD countries. LMFBRs also have the potential of effectively burning actinides and thereby reducing the radioactive life of the resulting waste products. Liquid metal systems are preferred for fast breeders on the basis of their generic characteristics:

i) the ability of the coolant to absorb heat without excessively moderating the speed of neutrons, thereby enhancing breeding;

ii) the reactor can operate at a low pressure due to the high boiling temperature of liquid metals,

iii) the operators' radiation doses can be lowered because of the non-corrosive nature of sodium in stainless steel systems (this is the result of the dual effect of reducing the required maintenance and reducing the radiation levels in and around the reactor and its cooling system hardware);

iv) the high conductivity of the liquid metal coolant.
The long-term potential of increasing the available fuel supply and reducing the long term radiation level of nuclear waste are fundamental reasons for development of this type reactor. Therefore the time-scale for its development provides an opportunity to expand international co-operation on the R&D required for this technology. Joint programmes could significantly reduce future expenditures and effectively use technology that have been developed in all countries during the past 40 years.

4.2.5 Fuel Cycle

The fuel cycle characteristics of SMRs are fundamentally similar to the fuel cycles of large power reactors. It should be taken into account, however, that for some of the SMR types, especially for the "revolutionary" new concepts, the fuel elements are also of a new type.
5. MARKET AND ECONOMIC ASPECTS

General background

This chapter addresses the potential for SMRs to penetrate existing and future energy markets and analyses the economic feasibility of them doing so. Given current patterns of energy supply/consumption (Ref. 36), there is scope for substantial expansion of the nuclear component of energy supply in most countries. Admittedly, in countries where nuclear penetration of electricity production is already high, this expansion would have to be in markets other than the traditional electricity one -- unless electricity itself expands into non-traditional markets.

The pattern of consumption gives some guidance on the specific sectors of the energy market that might be most open to nuclear power. For example, there is little prospect of nuclear penetrating the transport market in the near future -- even allowing for some increase in electrification of railways and road vehicles. The industrial, commercial and domestic sectors offer the best prospects, with the electricity markets offering scope for substantial expansion of the nuclear component. Domestic and industrial heat markets also offer scope for substantial penetration of cost competitive nuclear plants. However, public acceptance of the close proximity of such plants to centres of high population could prove a major obstacle in expanding penetration into district heating markets in many countries.

The growing energy demands of the OECD countries are brought out in Chapter 2 (additional data is included in Appendix C) and it is expected that this growth will continue. Indeed numerous forecasts of world energy demand by OECD and other international organisations have indicated that it is expected to continue to rise at a significant rate -- although in many industrialised countries energy demand is beginning to saturate as energy is used more efficiently relative to growth in GNP. These OECD and other forecasts have been used as the base for this study; no attempt has been made to make new demand predictions.

5.1 Electricity

Electricity markets

Electricity demand has continued to grow steadily over the past few decades, experiencing a setback in the early 1980s. Indeed, in the industrialised countries of the OECD over recent years the share of electricity in the energy market has increased significantly (Figure 5.1 shows the increase of electricity consumption versus the increase of primary energy). This growth in electricity demand is demonstrated particularly well in West Germany (see Figure 5.2) where, since 1975, it has been growing even faster than GNP despite a decline in the overall energy intensity (primary energy consumption per unit GNP). Even if GNP (or even total energy consumption) were to stagnate, electricity demand could continue to grow.

Over the past 15 years nuclear power has steadily increased its contribution to the electricity sector of the energy market as new stations were brought on line: part of the increase is probably due to more effective operation of the stations. However, many of the reactors that are currently being brought on line were ordered many years ago. In recent years there have been fewer orders for new nuclear or fossil stations because the economic recessions which followed the oil price rises left many countries with surplus operating capacity. Nuclear orders were particularly affected, largely because of anti-nuclear sentiment. However, in some countries delays or cancellations have resulted from cost increases due to licensing delays and increased safety requirements; in others (France and Belgium) because the market was saturated. This is well brought out in the pattern of introduction of nuclear power plant in the European Community from its beginnings to that expected by the end of the century (see Figure 5.3 from Ref. 37). Many reactors are now approaching the end of their lives and will have to be replaced. On the basis that public acceptability issues and perceptions of costs can be resolved, a joint NEA/IAEA Expert Group has estimated that the world
nuclear market could require at least 800 GWe of new and replacement capacity by the year 2030, allowing for extrapolation of non-WCCA estimates from 2005 to 2030 (see Refs. 38, 39).

Most of this forecast (at least 600 GWe) is for advanced industrialised countries, such as those of the OECD, where large integrated grids and high electricity demand growth allow for the incorporation of large power stations that give the traditionally-assumed benefits of "economies of scale". Under these circumstances it is expected that SMRs will only be considered if they can compete economically with the larger plant or have some other advantages which make them more acceptable and more attractive under specific circumstances.

There are factors such as limitation of cooling water supplies, fragmented utility structure, small size of electricity grid, and dispersed populations, that might favour SMR-sized reactors. However, in many cases these factors could be overcome by additional cooling provisions, plant sharing, improved transmission networks and so on. Consequently, overall cost is likely to remain the key element of comparison. Nevertheless a potential market is there for a suitable product. Indeed, many utilities that have experienced delays and cost increases during plant construction would be attracted to economically comparable SMRs, and might even be prepared to pay slightly more for small reactors if they could be shown to reduce capital outlays and to minimise the uncertainties during construction and licensing.

It has to be concluded, however, that within the OECD Member countries SMRs are only likely to penetrate electricity markets if they can be shown to be cost-competitive with large (GWe-sized) plants. In this context it should be noted that the consensus of views in Belgium, France, Japan and Switzerland is that SMRs are unlikely to have any economic advantage over large reactors for electricity generation. In the UK and West Germany views are mixed with some sections of their nuclear industry expressing support for SMRs. In the US there is established support for the large plants on the basis of cost and economies of scale; however, there is a significant growing preference for plants in the 600 MWe range due to their low cost and shorter construction time both of which reduce the financial risk.

Economics of electricity supply

The nuclear electricity industry has, in general, moved in the direction of increasing plant size to benefit from "economies of scale". The proponents of this approach argue that the capital cost of a plant increases less rapidly than its capacity according to a relationship of the type:

\[
\frac{\text{Capital cost of large unit}}{\text{Capital cost of small unit}} = \left(\frac{\text{Capacity of large unit}}{\text{Capacity of small unit}}\right)^p
\]

The overall scaling exponent \(p\) is derived from a number of similar expressions for different plant items, such as the nuclear steam supply system, the turbine plant, the electrical plant, etc. These individual exponents can only be determined by experience. When they are combined, the effective exponent for the whole plant (\(p\) in the expression above) is normally less than one, and generally in a range of about 0.5 to 0.9 depending on the relative sizes of the units. For this range the specific capital cost (i.e. per kW) would reduce to 0.7-0.9 with a doubling of the plant size.

To compete, SMRs must be seen to have advantages that would offset these "economies of scale" relative to larger plants. There are a number of ways in which such advantages might be achieved: these are discussed below.
Figure 5.1. PRIMARY ENERGY AND ELECTRICITY CONSUMPTION IN OECD COUNTRIES

Figure 5.2. GROSS NATIONAL PRODUCT, CONSUMPTION OF PRIMARY ENERGY AND ELECTRICITY IN WEST GERMANY (INDEX:1960=100)

Source: Statistik der Energiewirtschaft Hrsg. VK, und BMW Elektrizitätswirtschaft Jg. 67, Hefte 5

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Increased factory fabrication: Many of the components of a modern nuclear power station (e.g. a PWR or CANDU) can be fabricated in a factory and then assembled on site. Greater factory fabrication gives a number of potential advantages, notably:

- Reductions in site training and supervision requirements;
- Less dependency on good weather conditions;
- Fewer site support facilities and site allowances;
- Improvements in quality control and standardization.

A standardised small reactor should offer greater scope than a large reactor for increased factory fabrication -- and a corresponding reduction in on-site costs. Indeed, for small reactors up to 300 MWe it may be possible depending on the design to construct the entire reactor module in the factory and thus minimise the site work required at the expense of a small increase in transportation costs.

It is difficult to quantify these advantages but, taking the US as an example, there is some evidence that factory wage rates are only 70 per cent of site rates while factory productivity is 25 per cent better than on-site productivity. A West German analysis of a modular HTGR also indicated some cost savings (of about 10 per cent) in factory fabrication of a range of plant components.

Passive safety and simplification: At smaller plant sizes there is likely to be scope for technological changes leading to simpler designs that could include enhanced passive safety characteristics. This is well brought out in Table 4.4. While continuing to maintain current high safety levels, these simpler designs could lead to cost savings; for example, the engineered safety systems currently represent about 10 per cent of the capital costs of large reactors giving clear opportunities to make savings.
There may however be some cost penalties associated with the simplified systems; as a result, for example, of reduced power densities leading to increased reactor size and hence cost, or of the additional cost of passive safety systems which could offset some of the reductions in engineered safety systems.

**Reduced construction time:** High capital costs of nuclear stations, long construction periods can add substantially to reactor costs through high interest charges. Moreover, long timescales provide scope for costs to escalate and for regulations to change during the construction phase. Many countries have suffered from such expensive delays during construction, notably the UK and the US, whereas others such as Japan, Korea and France have experienced fewer problems.

In general, SMRs should offer shorter construction periods as a direct consequence of increased factory fabrication, greater replication of standard units, and faster commissioning due to simpler designs. The site programme should also be easier to manage and less subject to delays. These advantages have led to quoted construction times of 2-4 years for small reactors compared with 5-6 years for larger reactors in a number of countries.

The interest paid on capital expended during the construction phase is compounded and added to the "overnight" plant cost as "interest during construction" (IDC) or "allowance for funds used during construction" (AFUDC). Shorter construction periods will save on these additions, especially important if interest rates are high. Short construction times also allow less opportunity for things to go wrong and so require smaller contingency allowances. Finally, short construction periods enable plants to earn revenue from electricity sales at an earlier date.

**Matching demand:** Smaller units can provide a better match of supply to demand, allowing expenditure on new plant to be delayed nearer to the time that the new capacity is required. The interest saved (by not having to commit capital at an earlier date) can be regarded as an effective saving in capital investment. This benefit is more likely to apply to small grid systems or to those cases where only modest increases in demand arise. Large grid systems with significant demands for new plant (that will include also replacements for old plants) are unlikely to save much from a better match of supply to demand.

**Learning:** It has been observed in industrial operations of many kinds that unit costs often decrease at a constant rate each time cumulative production doubles. This is known as the Learning Curve Effect, which can be expressed, in its simplest form, as

\[
\text{cost of nth unit} = (\text{cost of 1st unit}) \times n^C
\]

where the exponent \( C = \ln L/\ln 2 \). \( L \) is the Learning Coefficient which is determined by the rate of cost reduction. For example, if the unit cost reduces by 10 per cent for each doubling of cumulative production, \( L = 0.9 \); in other words we have a 90 per cent learning curve.

Learning effects are likely to be greatest for items with a high labour content which can be manufactured in a factory environment to a standard design. This should give significant benefits to small reactors because:

- Progress along the learning curve should be quicker for several small reactors than for one large one;
- More factory fabrication leads to more rapid cost reductions by learning;
- More frequent construction should help to keep skilled teams together, especially on multi-unit sites.

The learning process should also impact on licensing and commissioning time, showing benefits to SMRs by virtue of a greater number of units. But of course, these benefits cannot be claimed for the first-of-a-kind SMR.
These arguments have been used to justify learning curves as low as 80 per cent for small reactors relative to 95 per cent for reactors of 600 MWe or more. However, it is difficult to accept that such rapid learning effects could continue for more than a few modules, and a 90 per cent learning curve may be more realistic overall.

Also, learning effects may not continue indefinitely and may cease altogether if there is a significant break in the construction programme.

Other costs: All the above factors impact on the plant capital cost. For costs other than capital, the effect of SMRs is likely to be less significant. Most fuel cycle activities such as uranium purchase, enrichment, fabrication, storage or reprocessing, and waste management are usually carried out centrally and are little affected by reactor size. Some SMRs may have lower thermal efficiencies and small cores may require relatively larger quantities of fuel than larger versions so that more fuel will be required. However, this is dependent on reactor design and is not a necessary consequence of reactor size.

Operating and maintenance costs might be expected to respond to economies of scale like capital costs and so be higher for smaller reactors. However, such increases may be partially offset by savings due to the simpler system, more automation, more plant standardization and reduced safety surveillance (because of the higher degree of passive safety). Moreover, if several small reactors were to be built on one site they would then be able to share the costs of common facilities and services, such as the fire brigade, canteen, maintenance staff, etc.

Decommissioning costs are likely to be reduced for SMRs because smaller components should be easier to deal with. Indeed, some small reactor proponents have even suggested that it might be possible to transport the entire reactor vessel for reactors of up to 300 MWe to some central site for dismantling or direct disposal, and so save on costs. However, when discounted over the timescales involved in decommissioning such savings are likely to have a negligible effect on overall generating costs.

Lifetime: There is no evidence that reduced reactor size will extend the lifetimes of individual plant components, although it could be argued that specific aspects of some SMR designs could do so -- because of reduced neutron fluence on the reactor vessel for example. However, small reactors may offer greater opportunities for refurbishment due to simpler designs and smaller components. Indeed, it has been argued that reactors of less than about 300 MWe could probably be designed to allow the entire reactor module to be replaced, thus extending the life of the plant almost indefinitely. However, because of the effect of discounting, life extensions after the first few decades will have only a small effect on levelised generating costs.

Availability: Small reactors are claimed to have potentially higher availabilities than larger units. These claims are based on a number of factors, including:

- Simplicity of design making the plant less likely to go wrong;
- Ease and speed of repair of modular designs and more readily available spare parts;
- Reduced refuelling times or increased periods between refuelling depending on the mass rating of the fuel;
- Increased component reliability due to the higher quality control available under factory conditions.

For several small interconnected units on the same site, there is also the increased flexibility to operate different combinations of reactors and turbines if units fail. This could offer significant operational advantages, such as a better part load behaviour of the total plant, improved reliability and continuity of energy supply. However, this may be offset by the additional complexities of controlling an interlinked system.
Although these advantages are not necessarily confined to small reactors, there is some historical evidence that SMRs have performed more reliably than larger reactors of the same type. (Nevertheless, one should take into account the reasons for shutdowns, analyses done by Finland and their experience does not support this data.) Thus, for General Electric and Westinghouse reactors, the evidence points to smaller reactors having been more reliable over a significant period (see Table 5.1).

**Table 5.1. REACTOR PERFORMANCE**

**Performance of Westinghouse PWRs**

<table>
<thead>
<tr>
<th>Size Range (MWe)</th>
<th>No. of Units Produced</th>
<th>Cumulative Operating Experience (Reactor Years)</th>
<th>Cumulative Average Load Factor (%)</th>
<th>Annual Load Factor for 1987 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;600</td>
<td>16</td>
<td>270</td>
<td>68.8</td>
<td>77.8</td>
</tr>
<tr>
<td>600-999</td>
<td>32</td>
<td>257</td>
<td>61.2</td>
<td>67.1</td>
</tr>
<tr>
<td>&gt;999</td>
<td>25</td>
<td>177</td>
<td>58.2</td>
<td>60.8</td>
</tr>
</tbody>
</table>

**Performance of General Electric BWRS**

<table>
<thead>
<tr>
<th>Size Range (MWe)</th>
<th>No. of Units Produced</th>
<th>Cumulative Operating Experience (Reactor Years)</th>
<th>Cumulative Average Load Factor (%)</th>
<th>Annual Load Factor for 1987 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;600</td>
<td>9</td>
<td>151</td>
<td>60.2</td>
<td>67.2</td>
</tr>
<tr>
<td>600-999</td>
<td>23</td>
<td>278</td>
<td>58.3</td>
<td>63.6</td>
</tr>
<tr>
<td>&gt;999</td>
<td>17</td>
<td>119</td>
<td>51.8</td>
<td>46.4</td>
</tr>
</tbody>
</table>

**Insurance:** The consequences of accidents in small reactors should be less than in larger plants because each unit has a smaller radioactive inventory and there is a smaller asset at risk in the case of serious plant damage. This should be reflected in a reduced allowance to cover activity releases and loss of facilities. However, the issue needs detailed consideration to assess, in particular, the counter argument that there are more small reactors at risk per unit of power (or capacity).

**SMR economics:** In the last few years, the decline in fossil fuel prices has reduced the economic benefit of nuclear power stations relative to fossil stations. However, recent NEA analyses have confirmed that large PWRs should remain competitive with coal stations in almost all OECD countries provided that coal prices rise by modest amounts and the reactors achieve a reasonable standard of performance (Table 5.2).

Nevertheless, in some countries such as the UK, the US, Belgium and Italy the publics' concerns over the safety, reliability and costs of large reactors have effectively eliminated any prospects of new orders for such plants in the next few years. SMRs may be less affected by such concerns and could be preferred if their overall costs are comparable.
Table 5.2. **Generation costs in OECD countries**

January 1987 US mills./kWh

5% rate of return, 30 year plant life, 72% load factor

<table>
<thead>
<tr>
<th>Country</th>
<th>Nuclear (PWR)</th>
<th>Coal</th>
<th>Ratio coal/nuclear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I.</td>
<td>O.M.</td>
<td>F.</td>
</tr>
<tr>
<td>Belgium</td>
<td>15.6</td>
<td>5.4</td>
<td>8.1</td>
</tr>
<tr>
<td>Central Canada</td>
<td>13.21</td>
<td>2.4</td>
<td>4.0</td>
</tr>
<tr>
<td>(CANDU)</td>
<td>16.4</td>
<td>4.6</td>
<td>6.5</td>
</tr>
<tr>
<td>Finland</td>
<td>12.9</td>
<td>5.4</td>
<td>9.1</td>
</tr>
<tr>
<td>France</td>
<td>21.4</td>
<td>7.4</td>
<td>11.1</td>
</tr>
<tr>
<td>Germany</td>
<td>21.4</td>
<td>8.7</td>
<td>13.2</td>
</tr>
<tr>
<td>(domestic coal)</td>
<td>17.6</td>
<td>6.4</td>
<td>10.6</td>
</tr>
<tr>
<td>Japan</td>
<td>25.4</td>
<td>8.7</td>
<td>8.5</td>
</tr>
<tr>
<td>Netherlands</td>
<td>22.5</td>
<td>3.7</td>
<td>6.0</td>
</tr>
<tr>
<td>Spain</td>
<td>22.6</td>
<td>6.6</td>
<td>6.6</td>
</tr>
<tr>
<td>(imported coal)</td>
<td>21.7</td>
<td>11.4</td>
<td>5.6</td>
</tr>
</tbody>
</table>

I. Investment  
O.M. Operation and Maintenance  
F. Fuel  


Complete cost comparisons will depend on the availability of detailed costed designs and will probably not be finalised until experience has been obtained with the construction and operation of the initial reactors. However, preliminary analyses based on the potential benefits outlined above have indicated that SMRs could be cheaper than large reactors, although the uncertainties are still large relative to the likely savings.

The UKAEA has carried out a generalised assessment of the prospects of SMRs competing with a 1 200 MWe reactor for electricity generation. Table 5.3 gives details of the calculations for single reactor stations at 5 per cent discount rate and a 40-year reactor lifetime. The single reactor station generating costs (normalised to a large 1 200 MWe station) are plotted in Figure 5.4 along with comparable data for a small reactor station of installed capacity 1 200 MWe comprising multiple interconnected units. It can be concluded that SMRs of 600 MWe down to about, say, 300 MWe show promise of competing with large reactors; below that range they are likely to become decreasingly attractive.
Table 5.3. Single reactor station (UKAEA example) relative specific costs

<table>
<thead>
<tr>
<th></th>
<th>1 200 MWe</th>
<th>600 MWe</th>
<th>300 MWe</th>
<th>150 MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital (from scaling laws)</td>
<td>0.66</td>
<td>0.82-0.94</td>
<td>1.04-1.38</td>
<td>1.37-2.07</td>
</tr>
<tr>
<td>% Saving for:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factory fabrication</td>
<td>-</td>
<td>(0.5)</td>
<td>(5-15)</td>
<td>(5-15)</td>
</tr>
<tr>
<td>Safety/simplicity</td>
<td>-</td>
<td>(0-5)</td>
<td>(5-10)</td>
<td>(5-10)</td>
</tr>
<tr>
<td>Faster construction</td>
<td>-</td>
<td>(0-5)</td>
<td>(5-10)</td>
<td>(5-10)</td>
</tr>
<tr>
<td>Assumed station availability (%)</td>
<td>(75)</td>
<td>(80)</td>
<td>(80)</td>
<td>(80)</td>
</tr>
<tr>
<td>Capital (revised)</td>
<td>0.66</td>
<td>0.82-0.94</td>
<td>0.63-1.11</td>
<td>0.74-1.66</td>
</tr>
<tr>
<td>Fuel cycle *)</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Operations (inc. maintenance *)</td>
<td>0.11</td>
<td>0.14-0.17</td>
<td>0.19-0.25</td>
<td>0.25-0.39</td>
</tr>
<tr>
<td>Decommissioning (3% of capital)</td>
<td>0.02</td>
<td>0.02-0.03</td>
<td>0.02-0.05</td>
<td>0.02-0.05</td>
</tr>
<tr>
<td>Generating cost</td>
<td>1.0</td>
<td>1.0-1.3</td>
<td>1.1-1.6</td>
<td>1.2-2.3</td>
</tr>
<tr>
<td>Savings from additional factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(% of capital only *)</td>
<td>-</td>
<td>(5-10)</td>
<td>(15-25)</td>
<td>(20-30)</td>
</tr>
<tr>
<td>Potential overall generating cost</td>
<td>1.0</td>
<td>0.9-1.2</td>
<td>0.9-1.4</td>
<td>1.0-2.0</td>
</tr>
</tbody>
</table>

1. For the large (1 200 MWe) reactor the generating cost is normalised to unity and the breakdown into its components of capital, fuel cycle, operations (including maintenance) and decommissioning is based on that of a typical PWR in the UK. All specific costs for the smaller reactors are relative to the 1 200 MWe normalised generating cost.

2. Because most fuel cycle activities such as enrichment, fabrication, storage, reprocessing and waste management are likely to be carried out in centrally-located facilities they should be effectively independent of reactor size; consequently a fixed unit cost has been assumed.

3. Operating and maintenance unit costs would be expected to be significantly higher than those of a large plant, particularly for single reactor stations where each plant is on its own unique site; the attributed costs are those from a qualitative assessment of the various factors involved.

4. Additional factors comprise reactor lifetime, matching supply to demand, planning margin, learning effects, siting and transmission and licensing.

A similar type of exercise was carried out by the Japanese Institute of Applied Energy in 1987 with comparable results. This exercise demonstrated benefits arising from plant simplification, reduced construction time, improved availability, better match of supply to demand especially in meeting a low demand growth, and from the use of modular units. The main factors offsetting these vis-à-vis large reactors were, of course, economies of scale and lower O&M costs. The relative effects of each of these parameters for a 600 MWe reactor expressed as a change in the capital cost of a 1 200 MWe reactor are shown in Figure 5.5. Negative values indicate cost reduction (in percentage terms), the cases refer to interest and growth rates in MW/year. It was concluded that benefits should accrue to SMRs unless there is a very disadvantageous scale factor associated with a low demand growth.

In another economic analysis in 1989 by the Japanese Institute for Future Technology, the SPWR concept (two units giving 700 MWe total power output) was compared with a large PWR. The results of this analysis are reproduced in Figure 5.6 which shows separately the reductions achieved from the base SPWR case as a result of modularisation and as a result of using the same size turbine as a large reactor. It was concluded that the SPWR could cost about 10 per cent less than a large current PWR although admittedly there is significant uncertainty in the data.
Figure 5.4. COMPETITIVENESS OF SMRS AGAINST LARGE NPPs
(based on UK-data)

LEGEND
- - Single Unit high
- - Single Unit low
- - Multiple Units high
- - Multiple Units low

Reactor Size (MW_{e})

Figure 5.5. CAPITAL COST REDUCTION

- 6% /600 MWe GROWTH
- 8% /300 MWe GROWTH
- 10% /100 MWe GROWTH
A West German investigation of the economic effects of modularisation concluded that the benefits could even be greater than those tabulated above. An analysis based on the HTR module showed that doubling of the power size by increasing from 2 to 4 modules and from 4 to 8 modules led to a cost reduction of about 16 per cent in each case. The benefits arising from modularisation have clearly been assumed to offset the complexities of controlling an interlinked system to a greater extent than in the UK exercise.

It is important now to acquire data that are more design-specific, particularly from individual countries. Some such preliminary information is available for specific reactor designs:

- The future generating costs of a 300 MWe Safe Integral Reactor (SIR) have been assessed by the UKAEA at 3.0-3.2 p/kWh in 1989 money values, reducing to 2.6 p/kWh for a 600 MWe twin unit plant; this compares with 3.3 p/kWh for the large PWR proposed for Hinkley C -- and has provided sufficient incentive to encourage continuing development of the system. Whilst privatisation of the electricity supply industry in the UK has affected nuclear costs, the relativities should remain broadly the same; indeed any changes could benefit SMRs because of the demand for higher rates of return for example.

- In Germany the costs for a future series plant of electricity from the HTR modules range from 7 to 11 pf/kWh (1988) depending on station size (Figure 5.7). At these costs modular HTRs could not compete with large PWRs but would compete with coal at 120-180 DM/te, a price range below that of domestic coal at current (1990) prices (Figure 5.8). The corresponding oil price range is 160-250 DM/te. HTRs of medium size (550 MWe) are believed to be cost competitive to large PWRs.

- Also in West Germany, the SBWR-200 has been developed for overseas markets where small-sized grids and low availability of capital precludes the use of large reactors. It is believed that the SBWR-200 design could be competitive against small fossil stations.
Figure 5.7. POWER GENERATION COSTS: COAL-FIRED PLANT - HTR MODULE

Figure 5.8. PRICE DEVELOPMENT OF FOSSIL FUELS IN WEST GERMANY

- The levellised generating costs of the 600 MWe Westinghouse PWR (AP600) have been quoted recently (Ref. 40) at 4.3 cents/kWh (1990 money values) -- based on the reactor being built to a firm price and firm schedule. This compares well with the levellised generating cost of a large PWR commissioned in the period 1995-2000 of 4.0 cents/kWh but in 1987 money values (Ref. 41).

5.2 Heat

The primary energy requirements in the world amounted to roughly 12 TW-year for the year 1989 (in the order of 100 000 TWh (Ref. 14); 4.9 TW year/year or about 45 per cent of it correspond to heat consumption. Explicit figures for heat consumption are not available for the OECD countries; from the available data for primary energy requirements and final energy consumption in the OECD (Appendix C), it can nevertheless be estimated that final heat and electricity consumption are approximately equal. This supposition is confirmed by data available for specific countries (West Germany and Switzerland), where in 1987 heat for domestic use and for supplying industrial processes reached respectively 63 per cent and 59 per cent of the final energy consumption. Heat represents thus the dominant sector in the OECD's final energy requirements. While the contribution of "clean" electricity (mainly hydroelectric and nuclear but also others) averages over 41 per cent of that generated in the OECD countries (reaching even 98 per cent in Switzerland), both heat application sectors are based on extensive use of fossil fuels and contribute to heavy local environmental problems as the sites are normally close to densely populated areas. Again based on German and Swiss figures, it is estimated that roughly 80-90 per cent of the final OECD heat consumption relies on fossil fuels.

This indicates that the theoretical potential for substitution of fossil fuels is far greater in heat generation that in electricity generation. Here again the worldwide statistics for 1989 (Ref. 14) clearly shows the impact of heat consumption on the environment:

Table 5.4

<table>
<thead>
<tr>
<th></th>
<th>Primary Energy Requirements TW-year/year</th>
<th>CO₂ Production GT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>4.0</td>
<td>7</td>
</tr>
<tr>
<td>Heat</td>
<td>4.9</td>
<td>11</td>
</tr>
<tr>
<td>Transport</td>
<td>2.1</td>
<td>5</td>
</tr>
</tbody>
</table>

Potential non-fossil heat sources are electricity, heat from nuclear reactors and renewable energy sources. According to realistic estimates, solar and geothermal power are now expected to be limited to 10 per cent of the heat market at most in the short to medium-term; consequently nuclear heat could play an important role.

A large part of the total heat market is dedicated to low temperature applications (see as an example Figure 5.9 for Germany) mostly for space heating (domestic heat); this large market is partially supplied by district heating networks which are fed either by dedicated heating plants, by waste heat extracted from industrial processes or by co-generation of electric power and heat (CHP). This, along with the production of industrial process heat, represents a market potential for nuclear CHP plants.
5.2.1 District heat markets

The substitution of fossil fuels for heating purposes by means other than solar collectors necessitates a centralised energy generation system with an adequate distribution network. This centralised heating system can supply either electricity (for direct electric heating or operation of heat pumps) or warm water at temperatures around 100-150°C. Clearly, increased penetration of electricity into the heating market would create an additional demand which could be met by nuclear power, and its potential competitiveness would be as discussed in the earlier (electricity) section. In this section, therefore, only provision of district heating by means of warm water distribution networks will be addressed.

The technology and the economics of district heating have been broadly evaluated in an OECD/IEA study and recommendations made for a rational deployment of this energy supply system (Ref. 42). Heat for district heating supply systems can be generated from a number of sources that include:

- Heat only plants;
- Combined heat and power plant;
- Utilisation of industrial waste heat;
- Waste incineration;
- Low grade heat from geothermal sources.

From the fuel point of view, any kind of fossil fuel (coal, oil, natural gas), refuse and nuclear fuel can be used. The energy carrier is usually hot water; in some older district heating networks (mainly in Germany) steam is also used.

The shares of district heating in OECD countries which provide this energy supply system are shown in Figure 5.10 for 1987 (Ref. 43). In recent years there has been a steady increase in the provision of district heating in all these nations (Figure 5.11). The annual growth rates in subscribed capacity are about 3-5 per
cent reaching a maximum of 12 per cent in Italy. Germany has by far the largest demand but it is considerably below other countries such as Denmark, Sweden and Finland in its share of district heating in the total heat market and in its supply per capita (Figure 5.12). Whilst some of this difference is attributable to the colder, northerly locations of the other countries, there is a strongly held view within Germany that there is potential for substantial increases. Many of the other countries also expect to increase the share of district heating in their heat supply systems.

Apart from climatic factors other boundary conditions, namely:

- The degree of dependence on imports of primary energy,
- The degree of deployment of "clean" power plants (nuclear and hydro),
- The existence of domestic coal,
- The degree of deployment of natural gas distribution networks,
- The strength of environment protection laws,
- The existence of financial promotion measures;

can influence in a positive or negative way the deployment of district heating. In fact, quite a strong correlation between these factors and the degree of district heating share has been identified for the most European countries (Ref. 44).

The existing European district heating networks are generally relatively small, with installed capacities in the range of 600-1 200 MWth in large cities, 100-300 MWth in smaller ones and around 10-50 MWth in towns and small communities. Despite expansion of the existing networks, the size of the individual heat sources in the networks will remain only a fraction of the installed capacity because of parallel operation of several sources for reasons of redundancy.

Figure 5.10. SHARE OF DISTRICT HEATING
Figure 5.11. DEVELOPMENT OF DISTRICT HEATING IN OECD COUNTRIES

Figure 5.12. SUPPLY PER CAPITA OF DISTRICT HEATING
In many countries there are regions where significant increases of the district heat share and thus of the heating networks could be achieved (Figure 5.13). Two recent studies performed in Germany (Ref. 45) and Switzerland (Ref. 46) show large theoretical potentials for nuclear heat. The estimates based upon the heat demand of the communities and the technical feasibility of supplying them with nuclear heat showed a theoretical capacity potential around 8,500 MWth for Germany and about 1,500-2,000 MWth for Switzerland.

It is against this background, that the potential utilisation of nuclear power in district heating applications has to be examined. For the deployment of nuclear district heating two ways have to be considered:

- The substitution of older, conventional heat sources in existing heating networks; and
- The more difficult installation of new networks with nuclear heat sources.

However, in general the prospects do not appear promising in the short term. Even in Germany, where opportunities appear greatest, most of the boilers on existing networks have recently been refurbished so that there is little incentive to replace them by small reactors, especially when economic aspects and public concern about the safety of nuclear power are considered.

Figure 5.13. HEAT DEMAND POTENTIAL IN WEST GERMANY

Source: FWI 1985, 6 and FWI 1989, 1
5.2.2 Economics of district heating

Small reactors have been developed specifically to meet demands for district heating where utilisation of heat from large reactors (built either as electricity generation or CHP plant) would be much greater than required. This is clearly illustrated when the size of a heat source is compared to the load curve of the grid to be fed by it. A typical load curve for industrialised countries of the northern hemisphere is shown in Figure 5.14. The theoretical annual utilisation factor of the heat source as a function of the relationship between reactor power size and connected load of the grid is shown in Figure 5.15. In other words, a heat source capable of covering 100 per cent of the connected capacity will practically never operate on full load, while a source covering only 10 per cent of the peak load of the grid will have a utilisation factor of almost 100 per cent, i.e. it will practically work continuously in base load mode.

As well as the beneficial effects of a high utilisation factor on specific capital costs, operation close to base load mode and thus without excessive requirements for frequent load following, allows for some design simplifications as compared to plants designed for extended load following.

Such considerations, along with the need for standardisation and the objective of covering as many grids as possible, were the main incentives for the choice of the power range of the German NHP-200 reactor. Its size corresponds to the maximum number of potential applications as a base load supplier in existing large district heating grids in Germany. On the other hand, the size of the heating reactors considered in Switzerland (10-50 MWth) has been determined by the objective of a large series of identical reactors, along with the special demographic conditions of the country where some 50 per cent of the population live in communities of less than 5 000 inhabitants.

The competitiveness of dedicated heating reactors has to be measured not only against large nuclear plants but also against fossil fuels as energy carriers in both centralised and individual heating installations.

The competition between centralised and individual heating systems is dominated by the heat transmission costs (capital investment and operation costs of the grid). A major disadvantage is that the investment for the grid has to be made long before all potential customers are connected to it, which leads to a considerable loss of interest on capital invested.

This is most critical for new district heating networks. Once the initial capital investment has been paid off, the economic benefits inherent in centralised energy supply systems usually balance the additional operation and maintenance costs of the network. The problem of additionally burdening the total heat costs with transmission costs is common to all countries and is independent of the kind of heat source; it is also one of the reasons why district heating is less widely deployed than individual heating in countries with a free heat market. The above considerations indicate that a highly probable use of dedicated heating reactors will be in the replacement of older, conventional boilers as heat sources in existing grids.

As far as the competitiveness of dedicated heating reactors against fossil fuels is concerned, a recent study performed in Switzerland for Swiss conditions has shown that the specific heat generation costs of the heating reactor concepts examined (at power ranges between 10 and 50 MWth) could become competitive against gas-fired heating plants around the turn of the century depending on the reactor concept and size, as well as on the evolution of the gas prices (Figure 5.16). However, at the level of fossil fuel prices in effect in early 1990, such reactors cannot compete with fossil district heating plants or individual boilers. This situation is also reflected in some typical examples from countries with different boundary conditions:
Figure 5.14. TYPICAL HEAT LOAD CURVE

Figure 5.15. RATIO REACTOR POWER: CONNECTED LOAD (%)
• In West Germany the district heat as a whole, no matter whether fossil or nuclear, has to contend with individual oil or gas-fired domestic heating. Within the district heat sector the NHP has to compete with coal-fired cogeneration plants with heat production cost that may range from 15 to 45 DM/MWth (Ref. 47) depending upon the extraction process and the cost of electricity. The heat generation cost of the Siemens 200 MWth plant has been estimated at 40 DM/MWth(th) during its first year of operation at 5000 h/a equivalent full power operation. The competitive position is especially evident if lifetime levelised costs are considered.

• The cost of district heat in Switzerland is today comparable to the cost of electrical heating and almost twice as high as the cost of individual oil or gas-fired heating calculated on the base of today's fossil fuel prices (Figure 5.17). The only existing nuclear district heating in Switzerland (REFUNA) operates with energy prices to the consumer of around 80-100 SFr/MWth. On the other hand the forecasts for the development of the oil prices (Ref. 48) are quite optimistic, predicting at most a very slow and smooth increase. In the natural gas sector the resources are so large that the actual prices are likely to be kept at the same level for a long time in order to preserve the market share (Ref. 49).

• In Japan, average energy prices in 1988 were 9.0 and 6.4 ¥/Mcal in the domestic and commercial sectors respectively. This could provide a good opportunity for nuclear heating in the domestic sector if the necessary distribution networks were provided, but this is considered unlikely unless environmental restrictions prevent the use of fossil fuels.

There is a clear need for a strategy to be evolved as to how nuclear power could meet these heat demands. The chosen strategy could have to take into consideration the evolution of the costs of alternative strategies, a key input of which would be the evolution of the current low cost of natural gas.

All these heat demands could be met from (currently inexpensive) natural gas. Any potential penetration of nuclear power into this heat market would therefore be faced with competition from this widely perceived "clean" source of inexpensive energy.

As for all nuclear installations though, the costs for decommissioning and final storage of the radwaste are included in the energy costs calculated for small heating reactors. If the comparison between fossil and nuclear fuels is to be meaningful, then the same rules have to be applied to fossil fuels as far as the reduction and final storage of fossil wastes is concerned. The reduction of SO$_2$ and NO$_x$ emissions is, according to some studies performed in Switzerland (Ref. 50), not very expensive: In the heating sector, a 50 per cent reduction of the sulphur content in the fuel (oil extra-light) and therefore of the SO$_2$ emissions is coupled with an increase of 2-3 per cent in the fuel price. A two-thirds reduction of NO$_x$ by means of advanced burners results into an increase of less than 10 SFr/MWth. A more drastic reduction of these pollutants is coupled, however, with considerably higher cost penalties.

The increasing public concern about pollution of the environment and especially about the risks of global warming may well increase pressures to reduce or even eliminate the use of fossil fuels. There is certainly increasing pressure on the industrialised nations in particular to reduce their emissions of carbon dioxide, as was recommended following the World Climate Conference of Toronto in 1988. Since fossil fuels are used to a very great extent in the world's heat markets and even in the district heating market (Figure 5.18), there is clear scope for their substitution by a non-CO$_2$ emitter, such as nuclear power. Such arguments are already being made in the electricity sector but are repeated here because of the particular relevance of the heat sector to SMRs. The measures for energy conservation and/or substitution of fossil fuels by renewable energy sources are coupled with additional costs which, according to some experts, might make the energy prices comparable to or greater than those of nuclear energy sources (Refs. 51, 52).
Figure 5.16. COST OF DISTRICT HEATING

Figure 5.17. COST OF DISTRICT HEATING (SWITZERLAND)
If, on the other hand, one persists in using fossil fuels (including the replacement of coal/oil by natural gas that, while effective in reducing CO₂ emissions, is only about half as effective as nuclear power) and tries to collect and abate the CO₂ produced, heat production will have to be centralised, as CO₂ collection and abatement measures are effective only on a large scale. The heat generated from fossil fuels under such conditions will be dependent on distribution networks and burdened with the aforementioned distribution costs.

The above illustrates the importance of energy distribution systems on the deployment of centralised energy supply systems and in particular of small heating reactors. It seems probable therefore that the introduction of a nuclear heat source in an existing network (for example as a replacement for an older conventional heat source), which is not coupled with prohibitive energy transportation costs, will be the best way to demonstrate the advantages of this mode of energy generation. On the other hand the heating network itself will determine the selection of site, the operation mode (compatible to the other sources of the network) and the optimum size of the nuclear heat source.

5.2.3 Process heat and cogeneration (CHP) markets

Nuclear CHP plants have not yet been introduced on a wide scale, although good experience has been obtained from Canada, Switzerland and the Federal Republic of Germany by feeding process heat from commercial reactors to local industrial complexes (Bruce, Gösgen, Stade).

As industrial process heat is produced predominantly in a combined mode comprising generation of electricity as well as heat, no distinction will be made in the following analysis on whether the heat is extracted by water, steam or some other heat transmission fluid (gases, molten salt, etc.) that is specific to the production processes. Moreover, there is no difference in principle on whether the low or top end temperatures are used for process heat or electricity production respectively.
Unfortunately, no large distribution networks for heat exist -- especially for higher temperature levels where the energy losses would become unacceptably high. This leads to CHP plant sizes that are, in general, significantly below those of large electricity generating plants. Furthermore, if there is no connection to a large heat distribution grid, the heat supply of industrial complexes cannot rely on a single CHP plant; industrial CHP supplies are, therefore, normally divided into several units to avoid a complete breakdown in the production process and to keep the reserve capacity in reasonably sized units. This again limits the maximum size of an industrial CHP plant by at least an additional factor of two/three compared to the power needs of a specific site. That is why only small or medium-sized CHP plants are suitable for such applications -- with a few exceptions.

The current power size distribution of CHP plants is well illustrated by the existing situation in Germany. Figure 5.19 relates the number and size of boiler units to locally-installed total capacity. It can be seen that there are no individual boiler units exceeding 500 MW (thermal) and that there is an increasing number of boilers for smaller unit sizes. On the other hand there is a considerable number of sites with higher capacities. This arises because several smaller units are usually combined to enhance the security of energy supply and to reduce reserve capacities -- as was brought out earlier.

Although the distribution networks for process heat in industry are usually smaller than in the district heating sector, the base load fraction is considerably higher (Ref. 53). Another typical fact in industrial final energy consumption is that only a small proportion is used as electricity and the overwhelming remainder in form of heat (Ref. 10).

Figure 5.20 shows the distribution of process heat requirements as a function of temperature in Germany. This could be taken as typical of most industrialised countries as the comparison with the Japanese position shows (Figure 5.21). The temperature range can be divided into two parts below and above 900°C, because of the temperature limitation for metallic heat exchangers.

It is particularly important to note that the energy needs of the iron/steel industry dominate in the high temperature range and account for most of the demand. However, in this industrial process the fossil fuel (mainly coal/coke) is used primarily as a (chemical) reducing agent. Direct reduction by hydrogen (development work was once done in Japan, for example) offers a potential future process that could substitute for the existing fossil fuel one.

The process heat consumption in both temperature ranges for Germany (Figure 5.22) shows that nearly comparable amounts of energy are needed. However, if the non-energetic use is taken out of consideration the low temperature range is seen to dominate. Units of GW x 8 000 h/y are chosen to give a direct indication of the market potential. For example, in the chemical industry, that takes a considerable share of the energy demand, more than 75 per cent of the process heat is used below 900°C and more than 50 per cent between 300°C and 900°C (see Figure 5.23). Thus most of the energy needed can in principle be supplied by nuclear process heat plants.

Apart from the "classical" CHP applications i.e. electricity plus steam or hot water extraction, that represent a first logical step towards nuclear CHP, the use of nuclear power can also be expanded into other industrial sectors (Refs. 54, 55):

- Oil refineries;
- Seawater desalination;
- Heavy oil production (enhanced oil recovery);
- Oil sand/oil shale retorting;
- Aluminium oxide production;
- Hydrogen production from natural gas or water.
Figure 5.19. CHP - capacity distribution - West Germany

total plant capacity: 41 GW

Source: EST - Report, March '88
KFA - PTH, Feb. '90

Figure 5.20. Segmentation of process heat requirement according to process temperature (1979)

Total Process Heat 73.69 mtce (599 TWh)

Source: A. Buch, VDI-Berichte Nr. 415 (1981), S. 5-18
Figure 5.21. PROCESS HEAT REQUIREMENTS (JAPAN)

Figure 5.22. PROCESS HEAT CONSUMPTION FRG 1982

Temperature regions

Source: H. Schaefer, VDI/VDE/GFPE May 85 KFA - PTH, Feb. '90.

79
The technological basis for the coupling of nuclear power into those processes is already available to a great extent. To move forward would mainly need some component development and testing, and some process matching. While aluminium oxide production requires temperatures of about 900°C, the other processes can be operated at temperatures significantly below 700°C, well in the range of proven material qualification.

A rough impression of the market potential is obtained by taking the actual production or estimates concerning enhanced oil recovery, oil shale/sand retorting, etc. (Refs. 54, 56).

**Refineries**
World oil recovery: 3 billion t/y, heat requirement, 540°C, 550 kWh/t oil
Total market potential -- 200 GW x 8 000 h/y

**Enhanced oil recovery**
Process heat requirement: steam 110-170 bar, 300-500°C, 6t steam/t oil
Total market potential -- 135 GW x 8 000 h/y

**Oil shale/sand retorting**
(e.g. Petrosix Process): heat 600°C
600 kWh/t oil
Total market potential -- 50-100 GW x 8 000 h/y

**Aluminium oxide production**
Process heat requirement: 900°C, 2 700 kWh/t Al-oxide
Total capacity: 41 Mt/y
Total market potential -- 14 GW x 8 000 h/y
Hydrogen production from natural gas
World hydrogen production capacity: 500 billion m³/y
Process heat requirements: 500°C, 0.8 kWh/m³
Total market potential -- 50 GW x 8 000 h/y

Even if only a small part of this potential could be realised for nuclear CHP plants, these applications represent an important motivation for further development of suitable reactor systems. The use of nuclear power in the field of oil recovery and oil refining could give an additional contribution to the stretching of oil reserves and to reducing environmental impacts of those energy consuming processes or "dirty energies" respectively.

Future applications that need either further R&D work, new markets or changed economic conditions could be:

- Petrochemicals;
- Methanol production;
- Ammonia production;
- Hydrogen generation (CO₂-elimination Ref. 57);
- Cement/Coarse Ceramics;
- Iron ore Sintering/Pelletising;
- Coal gasification.

It can be concluded that the use of nuclear energy is not in principle limited to the generation of electricity, but is also well suited to being used as heat in industrial production processes. CHP plants are the norm in this market sector. Plant sizes are governed by the different industrial production processes and by the need for high availability; this latter is usually realised by multiple plant arrangements so that only unit sizes below 500 MW (thermal) show a significant market share. The temperature requirements can also be met by SMRs since, in most cases, the materials for the heat exchanger components are already qualified for the temperature ranges involved.

5.2.4. Economics of CHP

In contrast to dedicated power or dedicated heating plants an economic evaluation of cogeneration plants is more complicated because the economics are determined by two different products -- power and heat. An economic evaluation, based on the generation cost of one product, is only possible if the sales price of the second product is known. It should be kept in mind that the meaning of the term "economic" usually includes only the direct generation cost of a product. Indirect costs, arising for example from environmental pollution, are also an economic factor but are not considered here because they are difficult to define.

An economic evaluation of SMRs for cogeneration of power and heat has to take into account three different competitors, which have to be considered separately:

- Fossil cogeneration plants;
- SMRs for dedicated power or heat generation;
- Large nuclear reactors;

SMRs versus fossil for cogeneration: Cogeneration of power and heat is feasible for both fossil and nuclear plants. There is no difference between the heat generated in a fossil boiler or in a nuclear core. Both plant types can take the same economic advantage from cogeneration if the live steam conditions and the power/heat ratio are suitable. Consequently, if for a certain application one plant type is more economic for dedicated electricity generation, then that plant type will be more economic for cogeneration too.
Therefore, the economic comparisons of SMRs with fossil fuelled plants for cogeneration are the same as those for dedicated plants (electricity and heat) that have been covered in the previous sections of this chapter.

**SMR cogeneration versus dedicated SMR:** Compared with dedicated power or dedicated heating plants, cogeneration offers the potential for considerable economic advantages. This is illustrated in Figures 5.24 and 5.25. Figure 5.24 shows the fuel utilisation of CHP plants versus the amount of heat extracted for a typical modern fossil-fired cogeneration plant. The left-hand side in this Figure without any heat extraction represents operation as a dedicated power plant. The input fuel energy is converted to electricity with an efficiency of about 40 per cent. The major part, about 60 per cent, is removed as waste heat at low temperature. In a dedicated heating plant, however, all of the input fuel energy is extracted and the conversion efficiency, e.g. to district heat, is 100 per cent if losses are neglected (right-hand side of Figure 5.24).

Thus, in a dedicated fossil plant (0 heat extraction in Figure 5.24), one unit of thermal heat energy is equivalent to 0.4 units of electricity (40 per cent efficiency). This electricity could have been generated instead by the same amount of fuel in an almost identical CHP plant. In a cogeneration plant (middle section of Figure 5.24) the waste heat of electricity generation is raised in temperature and extracted. As the capital, fuel and operating costs of the plant remain (almost) the same and as the waste heat is effectively free, the extracted heat has only to pay for the unavoidable reduction in electricity generation. The electricity loss depends on the actual thermodynamic conditions; for example, in the case of district heating (100°C) and a live steam temperature of 530°C, which is usually reached in fossil power plants, the loss is about 0.1 MWe for each MWth of extracted heat (in the region between 0 and the optimum point).

Therefore considering cogeneration plants, one unit of extracted district heat is equivalent to only 0.1 unit of electricity. This relationship is four times less than in the case of dedicated plants, and thus district heat is about four times less expensive -- assuming, as a first estimate, that the investment costs of a dedicated heating plant and a CHP plant are the same. In fact the economics of dedicated heating plants are lower than those of a CHP plant when the cost savings resulting from turbine omission and lower operating temperatures and pressures are taken into account. Two further factors reduce the economic advantages of cogeneration:

- Heat extraction at high temperature (as high temperature process steam) that leads to a lower live steam temperature will increase electricity losses and thus heat extraction cost.
- Power and heat has to be generated simultaneously. For many CHP applications this will not be possible throughout the year.

The favourable low-price heat extraction from CHP plants is limited by the availability of waste heat. If all waste heat is converted (heat extraction about 64 per cent of total thermal plant capacity in our case) the economic optimum is reached. Beyond that point each additional MWth heat extraction has to be paid for by one MW(e) of electricity loss and thus becomes expensive. Figure 5.25 shows relative electricity generation cost versus district heat extraction. Dedicated electricity generation represents 100 per cent electricity generation cost. The electricity generation cost declines with increasing heat extraction more or less rapidly depending on the sales price of extracted district heat. (A sales price range of between 22 and 31 per cent of the sales price of the same amount of electricity seems to be realistic today in most OECD countries.) At the minimum point, i.e. at about 64 per cent heat extraction, the electricity generation cost reaches values of between 60 and 80 per cent of that at zero heat extraction. Beyond the minimum point the electricity cost increases again for the reason explained above. The curves for electricity generation cost have not been drawn to the right-hand axis because electricity generation drops to zero when 100 per cent of the plant heat capacity is extracted, and so it does not make sense to calculate electricity costs in the high heat extraction zone.
Figure 5.24. FUEL UTILIZATION OF CHP PLANTS

Example: - Live Steam Temperature: 530 °C
- Extracted Heat Temperature: 100 °C

1) about 3% general heat losses are neglected

Figure 5.25. ELECTRICITY GENERATION COST, COGENERATION PLANT

Example: - Live Steam Temperature: 530 °C
- Extracted Heat Temperature: 100 °C

4/1990
This example shows that electricity cost reductions of 20 to 40 per cent are achievable by cogeneration of power and heat. Along with environmental benefits (improved fuel utilisation, stretching of fuel resources, for example) cogeneration offers a significant economic advantage, even if the optimum point cannot be reached at all times throughout the year. Thus, if an SMR can be shown to be economic for dedicated power production, it will be considerably more economic for cogeneration of power and heat.

**SMRs versus large nuclear reactors:** There is the same opportunity for large nuclear reactors as for SMRs to reduce electricity generation costs by cogeneration. However, the problem for big reactors would be to reach the optimum point. A heat extraction of 2 400 MWth (64 per cent of 3 800 MWth plant capacity) is very much greater than any heat consumer would require. Even the few district heating grids of large cities only reach capacities of about 1 000 MWth. Thus, with very few exceptions, a large reactor would have to be operated under conditions far removed from the optimum point -- and, indeed, not much different from those of a dedicated power plant. Unlike SMRs, therefore, a significant cost reduction by cogeneration does not seem to be possible for large reactors.

A proper adaptation of power size to each heat market application would allow operation close to the optimum point and so become an important economic factor from which SMRs could profit. Cogeneration of power and heat offers a good opportunity for SMRs to compensate for the economies of scale that benefit larger plant sizes.

### 5.3 Summary of Market & Economic aspects

There is potential for substantial penetration of SMRs into the world's energy markets.

In the electricity sector the scope for penetration may be constrained by the need to be cost-competitive with the well-established large water reactor systems. However, the nuclear industry is not unanimous in accepting the "economies of scale" argument that favours large plant, and there appear to be some SMR designs emerging that show prospects of competing with larger designs.

There are additional factors that could favour a reasonably competitive SMR in electricity markets, notably

- Lower up-front capital investment and correspondingly reduced investment risk that could appeal to utilities and their backers;
- Ability to fill niches or meet demands not open (readily) to large reactors; examples are the plant demands of a small utility, a low growth in electricity demand, site restrictions on space or on cooling water supplies, the needs of the developing countries.

There is extensive scope in the heat sector (both district and industrial) where there has been little penetration of nuclear power to date. Current environmental issues could lend support to arguments for SMR expansion in this sector that is not, in general, open to large reactors. However, current public attitudes to nuclear power could prove to be major obstacles to progress, particularly if the reactor plant has to be sited close to centres of high population.

District heat markets are currently restricted to specific countries that are generally in the north, such as Germany, Switzerland and Finland, where there are heat distribution networks already in existence in certain regions. The obvious immediate market for SMRs is the replacement of existing fossil-fuelled systems. In these countries many of the systems have been recently renewed, thus limiting the short-term scope for SMRs. Further expansion would require a concerted effort within the OECD to install new distribution networks.
Industrial (or process) heat markets lie mainly with large industrial complexes. Furthermore, the economics favour a cogeneration (CHP) system rather than a dedicated plant. Small reactors have a definite advantage over large in this sector where multiple heat units would be required to guarantee supply -- loss of energy supply would mean loss of production. The main competitor for SMRs is thus fossil fuels; at their current low prices, especially of natural gas, it is questionable if SMRs could compete at least in the first few years of operation. However, these low fossil fuel prices can be expected to increase as demand grows, and continuing development should bring reductions in SMR costs.

What therefore is the prospect for SMRs over the next three decades? In the current public climate of public opinion it is unlikely that construction of new stations in close proximity to areas of high population will be readily accepted in many countries -- even with the argument that SMRs are very safe (dilute cores, etc.). Consequently, the first priority of the nuclear industry in those countries will have to be to regain the confidence and support of the public.

In those cases the process will almost certainly be slow and will probably come through construction of new nuclear power plants at sites with similar conditions as those presently in existence. This would suggest that the first market opportunity for SMRs would be, most probably, towards the upper end of the size range. The next (indeed perhaps concurrent) stage could be to tackle the industrial heat market. Installation of SMRs (in cogeneration mode) in large industrial complexes offers not only expansion of the SMR market but also enlarges gradually the number of people familiar with nuclear plants. It is to be hoped that this would lead to an increase in public confidence generally - to the ultimate stage where penetration of SMRs into district heat markets, with their close proximity to urban populations, would become widely accepted.

Complete cost comparisons will depend on the availability of detailed costed designs and will probably not be finalised until experience has been obtained with the construction and operation of the initial reactors. However, preliminary analyses based on the potential benefits outlined above have indicated that SMRs could be cheaper than large reactors, although the uncertainties are still large relative to the likely savings.

The UKAEA has carried out a generalised assessment of the prospects of SMRs competing with a 1 200 MWe reactor for electricity generation. Table 5.3 gives details of the calculations for single reactor stations at 5 per cent discount rate and a 40-year reactor lifetime. The single reactor station generating costs (normalised to a large 1 200 MWe station) are plotted in Figure 5.4 along with comparable data for a small reactor station of installed capacity 1 200 MWe comprising multiple interconnected units. It can be concluded that SMRs of 600 MWe down to about, say, 300 MWe show promise of competing with large reactors; below that range they are likely to become decreasingly attractive.
6. FACTORS IMPEDING DEVELOPMENT AND DEPLOYMENT OF SMRs

The SMR concepts considered above have reached by now, according to their vendors, a stage of technological maturity, which would allow for a rapid realization of any of them - provided a firm order is given. The reality is that most of these concepts have not evolved beyond the stage of paper study, although some test facilities and experimental loops have been successfully operated for specific novel subsystems and components. This chapter will attempt to identify the reasons for this situation and outline instructive approaches where appropriate.

The factors which could influence a decision for or against SMRs during the selection process of the energy source for a new plant have been discussed at an early stage of the R&D efforts for the reactor concepts considered here. Such a list of advantages and disadvantages, taken from an introductory report to the SMR technology published in 1985 by the IAEA (Ref. 1), in a period of relative optimism towards the future of nuclear energy, is given below. Although established for power reactors only, this list of pros and cons is still valid today and it is therefore interesting to reproduce it here:

**For SMRs**

- Lower absolute capital cost, with smaller financial burden;
- Distribution of economic risk through several smaller plants;
- Better controlled construction schedule due to the less on-site work and smaller size of components;
- Earlier introduction of nuclear power will give environmental protection vs. fossil fired units;
- Lower absolute heat rejection permits better adaptation to cooling capacity and extends the number and location of possible sites;
- Better fit to smaller and weaker grids and lower requirements on grid;
- Fit to low load growth rate situations;
- Better past performance records than for larger plants;
- High degree of shop fabrication and potential for series production;
- Earlier introduction of nuclear power with potential for longer term technology transfer early.

**Against SMRs**

- Larger units have lower specific capital cost per kWe and better economic viability;
- In many cases non-standard design, with licensing and commercial availability questions;
- Break in normal technology development for industrialized countries which are used to larger units;
- More limited possibilities for domestic participation due to trends for shop prefabrication; but the smaller size of components vs. larger nuclear power plants can bring an increase in domestic participation;
- Domestic participation targets and seismic design requirements can work against construction time;
- Essentially the same infrastructure requirements as for big plants.

In the meantime some additional arguments became evident:

- The simplicity and ruggedness of the design leads to lower maintenance costs and is believed to improve the degree of safety perception by the public which is an indication of wider public acceptance;
- Passive safety features make the design more tolerant to human errors;

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Due to their better adaptability to local demand SMRs can lead -- if used as independent units -- to a proliferation of sites; SMRs for heat generation purposes are confronted with the lack of competitiveness against the presently low-priced fossil fuels.

The factors in favour of SMRs have been discussed in Chapter 3 "Rationales for the development of SMR". The factors impeding today the deployment of SMRs will be addressed in more depth below. Some of them (especially technological and economical aspects) are specific to this class of nuclear plants; others, like the opposition resulting from sociopolitical considerations, are more general and affect any kind of nuclear installation. Although the relative weight of each individual obstacle is different for each country and for each intended application, there are sufficient common aspects to address them in a general manner. In order to establish the connection between impediment and corresponding counter-measure more clearly, the remedies are given directly adjacent to each impeding factor.

6.1 Technological aspects

Most small and medium-sized reactors considered in this study include to some more or less important extent novel features, mainly in form of integrated systems, advanced fuel and passive components and make use of inherently activated processes. These reactors exist presently only on paper, although some of the aforementioned novel features have been tested experimentally. Though this has occurred either in experimental loops or in the context of older, more conventional reactor systems.

Thus, most reactors considered here suffer from the well-known impediments of the first-of-a-kind system. The potential users (future plant owners as well as the population) are not familiar with the technology involved in these new systems. In addition none of these systems have been submitted for licensing. As a result a certain caution as to the quality of the product is reasonable, until a demonstration of safety, operability and reliability takes place. This demonstration would be most efficiently performed in a prototype or a demonstration plant, which has to be supplied with additional equipment in order to better analyze the plant in all its modes of operation and to efficiently mitigate induced (for the purpose of experimentation) safety related malfunctions (though some vendors claim that no demonstration plant is necessary as the design is evolutionary and based on proven technology). This, being more expensive than the series product plant, must be financed at a higher financial risk, which can hardly be supported by a single utility. In addition, if a demonstration is needed, it inherently creates a time penalty, during which the capital invested does not return any gain.

Potential strategy: it is imperative that the advantages of the chosen SMR concept be demonstrated as soon as possible. The demonstration plants could be installed in the countries with the most favourable boundary conditions and in form of joint ventures, in order to reduce financial risk.

Another technological impediment is connected to the multitude of the new reactor systems actually under consideration, resulting from the spirit of competition between the various vendors and between the various research centres, which has survived from the times of nuclear euphoria: Vendors are forced to find different solutions to the same problem in order to preserve their market positions but the future buyer is confused, as it is not immediately clear, why one system would be better or less good than another one. A larger problem than the confusion generated, is the split of efforts and resources in capital on many, sometimes only insignificantly, different concepts, hindering a smooth and uninterrupted development of the most promising, appealing and valuable projects. This split becomes even more important, due to the aforementioned lack of funds for R&D work.

Potential strategy: Reduction of the number of concepts (for instance one or two representative of each technological line).
It may be noted that the approaches outlined above are applicable directly in a few cases only, namely when concrete economical and technological problems are concerned. In most cases, where non-technological considerations are involved, public perception, the attitude of institutions and the traditional competition spirit of the industry, actions suggested should be understood only as an indicative.

6.2 Economic aspects

It is a fact that all small reactor concepts suffer from the widespread opinion, that their likely higher specific capital costs would cloud their competitiveness. Although the economic impediments can be of a different nature when electricity or heat generating plants are considered, most of them are independent of the form of the energy produced in the plant.

6.2.1 Handicaps vs. large reactors

Many, mostly OECD, countries have large integrated electricity transmission grids. This enabled the construction of large units and encouraged the move to benefit from economies of scale (which were believed to outweigh other economic considerations). In addition in many countries electricity generation has been either directly nationalised (France, Italy) or to a large extent controlled by the state. This enabled a long term view to be taken, which is exemplified by the use of lifetime levelized generating costs and related economic criteria for investment decisions. Therefore utilities have tended to prefer large nuclear power plants.

**Potential strategy:** Focus on the complementary aspects of SMR for deployment in (geographic or energetic) sectors, where large NPPs do not represent the best solution from the economic point of view.

The use of a low discount rate favours capital intensive projects and places less emphasis on many of the economic factors which might favour small reactors, notably smaller up-front capital costs and short construction periods (i.e. lower financial risk per reactor and earlier and more rapid return on investment). However one should keep in mind, that high discount rates would further reduce the competitiveness of small reactors against fossil fuelled plants.

6.2.2 Site related problems

The societal aspects of site proliferation have been already addressed previously. More important are the problems related to the number of sites available and to the site costs, which enter also into the final energy price.

In many countries the number of available sites for the installation of nuclear plants is limited. Often this is due to the relative absence of cooling water (e.g. in Japanese non-coastal regions) or the restrictions imposed to the use of existing cooling resources (e.g. Switzerland). In other cases seismic constraints (e.g. alluvial soils in Japan) further reduce the number of available sites. The use of cooling towers becomes also contested in some countries, because of environmental constraints (protection of the landscape, climatic influences, noise pollution). This pressure on availability of nuclear sites makes it desirable to maximize the generating capacity of the existing sites. This argues for the desirability of large reactors and against the subdivision of capacity into a large number of small, individually sited reactors.

**Potential strategy:** Locating many small units on the same site is one answer to the site proliferation problem. The compensation for the higher specific energy costs could be the improved availability and flexibility of the plant.

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The specific ground demand (m²/MWe) for reactors of the small and medium power range is higher than for usual reactors of the GW range. This is due to the fact, that the surface requirement for plants with powers of the same order of magnitude is in a large extent independent of the physical size of the reactor building itself, but is rather dominated by the non-nuclear and administrative buildings. In addition, given the mostly local energy supply character of the very small reactors, their installation is often foreseen in the vicinity of the customers, i.e. near larger agglomerations, where land prices are more expensive as compared to sites far away from bigger cities. If the reactors are supposed to be used as suppliers of process heat for industrial complexes, the siting problem is not so acute, but the proximity of (normally high) industrial investment leads to either stronger safety measures or higher insurance costs, resulting into a higher end energy price.

Potential strategy: At least for some applications (namely heat generation) a park of several small units operated partially or totally unmanned could be based on a centralised infrastructure thus reducing the specific ground requirements.

6.2.3 Licensing aspects

Long, costly and burdened licensing procedures have been the rule in the regulatory history of the last decade. Often regulatory authorities have modified the "rules of the game" during the construction of the plant, forcing the plant owners to invest additional capital for technical modifications in order to satisfy the new safety requirements. It seems that Standardisation will be a main concern of the promoters of new reactor systems, but there is no indication, that intensified use of passive safety features, Standardisation, lower power and lower radioactive inventory on the site would lead to a different regulatory approach.

Potential strategy: Even if difficult, Standardisation of plant construction is worth aiming at, as well as up-front licensing. Along with the use of deterministic safety goals and international standards and units it should contribute to a more transparent and safety legislation remaining valid longer and result in a faster licensing procedure in connection with type licensing.

However the deployment of smaller reactors closer to densely populated areas could lead to more stringent safety requirements, which in turn would necessitate additional safety measures, thus resulting into higher capital costs for the plant. This has been the case at least in one country (Switzerland), where the authorities have proposed regulatory statements specific to small heating reactors, setting the dose rate limits for individual persons one order of magnitude lower than limits usually considered for large NPPs.

6.2.4 Limited capital for development

In the light of the low level of acceptance of nuclear energy by the public and of the aforementioned licensing uncertainties, it is understandable that potential investors perceive it as a high risk and that capital invested in development and demonstration work is steadily reduced. Nuclear R&D activities for novel concepts, mostly performed on a non-return financial basis, are thus suffering from this lack of financial support and get lower priority in favour of minor improvements or backfitting for well established technological lines, like large power reactors.

Potential strategy: At least during the present years of uncertain nuclear development international cooperation might be the only way to achieve a reasonable risk sharing and the conservation of know-how.
6.2.5 Heat (co)generation problems

Reactors dedicated to heat generation or used for heat cogeneration are facing in addition to the aforementioned economic considerations the lack of competitiveness against conventional (fossil) heat generation systems due on the one hand to the present low price of fossil fuels and on the other hand to the additional energy cost resulting from the heat transport and distribution costs. These aspects have been extensively discussed in Chapter 5.2.

**Potential strategy**: Comparison of the costs of competing energy sources should be based on the same assumptions, i.e. include in all cases the costs for abating or storage of waste; for fossil fired plants decommissioning and waste storage (including catalysts, filters and ashes) should be taken into account. On the other hand the cost calculations should be performed for the time point of the probable realisation of the SMR and not today, i.e. they should consider the evolution of all relevant factors in time.

Usually the heat demand of individual industries (chemical plants, refineries) are relatively small compared to the capacity of large NPPs. The capacity of a co-generation plant (in both electricity and heat) and the user's demand should match to the maximum possible extent. In addition, the heat supplied should cover wide temperature and pressure ranges which is quite an onerous demand for the supplier. On the other hand the problem of the alternative heat source, which should be available for scheduled and unscheduled shut-downs is not specific to a nuclear CHP-plant.

**Potential strategy**: It would be helpful to concentrate various kinds of industries into an industrial complex around the heat source. Such models have been already studied in Japan.

6.3 Non technical (institutional) aspects

6.3.1 Opposition to nuclear in general and SMRs in particular

During the last decades there had been a growing scepticism towards technical progress in general and a decrease in acceptance of large technical systems in particular. A cross-national comparison of survey data shows that criticism against complex technology has been growing at least in all western industrialised countries (Ref. 58).

Nuclear energy is often mentioned as one of these items of criticism against modern large scale technology. Nuclear power plants are seen as symbols of the "double edged" character of technical progress by critics and by a great part of the population. Nuclear energy is seen as somehow "opaque", not manageable, its risks are "dreadful" even if the probability of a so-called "Maximum Hypothetical Accident" is rather low. The accident at Three Mile Island and, even more, the accident at the Chernobyl nuclear power plant clearly reinforced this feeling of uneasiness.

In this context it must be noted, that the probabilistic considerations actually accepted as a means of quantification of safety among the members of the scientific community are absolutely meaningless to the layman and leave the promoter of nuclear energy completely disarmed, when confronted by the statement: "... But it can happen and it could happen tomorrow!". The nuclear community still does not use a simple logic about reactor safety, which is easily understandable by the public or a deterministic statement of the kind: "No evacuation outside the plant fence will ever be necessary" (though difficult to prove).

**Potential strategy**: Complement probabilistic assessments by deterministic statements, understandable to the public.
Representative surveys conducted in some countries (e.g. Germany, Switzerland) (Refs. 59, 60, 61) at different time points after the Chernobyl accident have shown that the dominant reaction of the population was a feeling of insecurity that manifested itself in an opposition to the future use of nuclear energy. Figure 6.1 shows a compilation of public opinion poll results on nuclear energy in different countries; it must be noted that the questions asked were not always the same and were not asked at the same time. The "don't know" are included with the "against" to avoid an over-optimistic picture of nuclear power. This feeling has been reinforced by the confusion resulting from the differences in safety regulations among different countries. While US data was not included in the Figure 6.1, polls indicate that a majority of Americans think nuclear energy plants are important in meeting energy needs, that nuclear should play an important role and that it is the most realistic source to displace foreign oil.

![Figure 6.1. OPINION POLLS ON NUCLEAR ENERGY](image)

**Potential strategy:** Aim to reinforce the co-ordination of safety approaches in all countries. To intensify these activities in relevant international organisations (IAEA, CEC, OECD).

This uneasiness, which as already mentioned is widely spread among the populations of industrialised countries, has resulted in some of them in concrete political decisions. This occurred mostly in countries where local or national referenda are used (Italy, Sweden, Switzerland, USA). In some countries decisions on a temporary pause (Moratorium) in licensing, constructing and starting of operation of new nuclear plants (Italy, Switzerland) or a definite abandoning of nuclear energy (Sweden) have been imposed by popular decision. In other countries the decision to cease temporarily nuclear activities has been taken by the government as in Belgium and Spain. Finally in some other countries (USA, UK) instead of global legislative measures, opposition to nuclear energy is expressed at public hearings, at which attempts are frequently made to drop or to delay construction and/or licensing of a given nuclear plant.

**Potential strategy:** Develop awareness of unquestionable findings concerning the world wide increase of energy needs, and that the way to satisfy them cannot be based on a "black-and-white" consideration of possible energy sources, but rather on an "energy mix". Provide the necessary arguments for an informed dialogue with the public.
6.3.2 Opposition to SMR In particular

Given this situation - the symbolic role of nuclear power plants for the perceived risks of large technological systems but also the decrease of confidence in organisations to manage this risks - it would scarcely lead to an increase in societal acceptance of nuclear power to substitute large scale NPPs by small scale systems in order to bring up a decentralisation of the (nuclear) energy supply system. In opposition to the installation of many nuclear units on the same site, decentralisation means "more reactor sites", affecting a greater number of the population. From the point of view of a concerned individual the hazards are then coming even closer. Considering that we presently find a widely spread uneasiness, it is likely that the construction of small but more numerous nuclear plants will turn many sceptics into active opponents, because they would then be neighbours of a small scale nuclear plant. Even moderate persons follow the NIMBY(not in my back yard) principle.

**Potential strategy:** Intensify the efforts for informing the population with special attention paid to simplifying explanations of the processes involved and to giving increased weight to the integrity of scientists and engineers working in the nuclear field.

In a climate, in which large reactors are being presented at public inquiries as being acceptable from both a safety and an environmental viewpoint, it is difficult to attribute additional public acceptability to small reactors without apparently challenging the basis of the case for large reactors. Intuitively the public would be expected to be inclined to the belief that small reactors are more acceptable.

**Potential strategy:** As safety is not the only advantage of SMRs, their other merits, which would not harm the good reputation of large reactors should be brought out. On the other hand use the more simple and comprehensible SMRs to promote also the more complicated large NPPs.

These arguments are demonstrated in the Proceedings of the International Scientific Forum on Fuelling the 21st Century, Moscow, October 1987: "...It is not easy to demonstrate public acceptability advantages of small reactors, especially in view of the difficulties of presenting technical arguments that in any case will retain a certain complexity to the public...".
7. INTERNATIONAL COOPERATION

7.1 Present Status

Certain changes are presently occurring which have an impact not only on SMRs but on the nuclear industry as a whole. The driving force has been mostly commercial interests not, as in the past, governmental organisations.

While certain companies have tried to develop new SMRs by themselves the tendency has been to pool resources and share the costs of development. This pooling of resources has been not only for SMRs but for all types of reactors ABWR, APWR as well as SMR. Since technology developed for large reactors will certainly have an impact on SMRs we will not restrict our review of intercompany co-operation to the SMRs previously described.

7.2 International Commercial Cooperation

- **BWR**

  ABWR development began in 1978 with formation of the Advanced Engineering Team (AET). Organised by General Electric, AET consisted of technical specialists from the worldwide BWR suppliers: Ansaldo Mecannic Nuclear SpA (AMN) of Italy, Asea-Atom of Sweden, General Electric (GE), plus Hitachi Ltd. and the Toshiba Corporation of Japan. During 1978-79, referred to as Phase I, AET developed a feasible conceptual design of an improved BWR which made use of the best technology available worldwide. Phase II of ABWR development took place during 1981-83, supported by Tokyo Electric Power Co. (Tepco) and the other Japanese utilities which own BWRs. From start of Phase II, ABWR development was an integral part of the LWR Third Improvement and Standardisation Program undertaken by the Japanese Government, utilities and manufacturers. Phase III, the final phase in the ABWR development came to a close in December 1985, its purpose being to simplify systematically the ABWR and reduce its cost while retaining its major safety and performance characteristics.

  In the USA, the ABWR design is being adapted to the needs of US utilities through the Electric Power Research Institute's Advanced LWR Requirements Program, and is being reviewed by the US Nuclear Regulatory Commission (NRC) for certification as a preapproved US standard BWR under the US Department of Energy’s ALWR Design Verification program.

- **PWR**

  In 1982, five Japanese utilities, Mitsubishi (MHI) and Westinghouse Electric Corporation began a five-year programme to produce a nuclear power plant design that reduces fuel costs by 20 per cent, extends fuel cycles up to 18 months, offers 90 per cent overall plant availability with 98 per cent availability between refuelling outages, provides enhanced safety margins and allows more operating flexibility than existing designs. Armed with data from more than 30 years of nuclear power plant operations and guided by in-depth discussions between the manufacturers and utilities, the programme’s designers created a forward-thinking nuclear plant design: the advanced pressurised water reactor (APWR). Total plant design and extensive verification testing are complete; only detailed site-specific engineering remains.

  The first contacts in the nuclear field between the Siemens Group and the Japanese industry (utilities and manufacturers) date back more than 20 years to when the 300-MW PWR plant Obrigheim was in an advanced stage of construction. Publications, lectures at international conferences and visits to the construction site gave rise to strong Japanese interest, since Obrigheim NPP -- though originally based on the PWR design from Westinghouse, with whom Siemens at that time had a license relationship -- already included many features of Siemens/KWU's modern PWR design.
The increasing Japanese interest in how the Germans had managed to develop an independent, indigenous reactor concept, induced Siemens/KWU to start actively approaching Japanese utilities in the early seventies. It appeared then that The Tokyo Electric Power Company (Tepco) might be the most interested utility.

Certain cooperation deals such as the creation of Nuclear Power International (NPI) by Siemens and Framatome are too new to determine its exact impact on the market. But given that it is dedicated to the coordination of work on pressurised water reactors for the export market, one would assume that one of the major offerings eventually would be an SMR.

- **HTGR**

The basis of the HTGR technology received important inputs in the 1970s through the successful OECD DRAGON Project in the UK with the participation of most European countries, USA and Japan. Active HTGR development programmes within the OECD are being carried out in Germany, Japan, USA and Switzerland. Cooperative efforts between these programmes are performed mainly under governmental umbrella agreements. They cover activities between industries and national laboratories and consist of common R&D work and extensive scientific and technological information exchange.

On the industrial side Siemens and ABB have found a common subsidiary in Germany, the HTR-GmbH, in order to combine their development and marketing efforts. This company is also involved in the deployment of the US-MHTGR.

Additional international cooperation and information exchange efforts are coordinated and initiated by the IAEA, which sustains an active working group for these programmes.

Further support to the programmes is provided by contacts between utility groups in the US, Germany and Switzerland.

- **PHWR**

Note that Siemens via KWU is already cooperating with Argentina in the construction of Atucha 2 and had designed and built Atucha 1. The Argos PHWR was designed based on the Siemens-KWU PHWR technology.

- **CANDU**

AECL has cooperated with Ansaldo on the Cirene plant and has cooperated with certain East European countries in defining the requirements for heating reactors.

There is ongoing collaboration with Japan's EPDC on the CANDU line of reactors. There is also collaboration with KEMA in the Netherlands on safety assessments of CANDU 6 and with Grootint on large scale module construction, the results of which are being included in the CANDU 3 design.

Some of these links are being formalised.

The following Figure 7.1 lists some of the major intercompany links within the OECD which may impact SMR development, though from what has been described above the links are not limited to within the OECD.
Figure 7.1. **COMMERCIAL LINKS WITHIN THE OECD RELATED TO SMR CONCEPTS**
7.3 National Organisations

Information has been or is being exchanged or the exchange fostered by bilateral agreements between national organisations. To cite just a few of the more recent ones:

- The three-year agreement (20th March 1990) on information exchange between the Japan Atomic Energy Research Institute and the UK Atomic Energy Authority on gas-cooled and pressurised water reactors.
- The French-U.S.S.R. accord on safety.
- A Japan UK (JAERI-UKAEA) agreement to exchange information on gas cooled and pressurised-water reactors.
- A complete example from Japan is cited in the following Figure 7.2.
- Utilities from several OECD countries are contributing to EPRI's efforts to develop ALWR requirements (Ref. 7).

One would assume that the commercial links stated previously have at least the tacit agreement of the national bodies and that as those links grow together one would see more extensive bilateral agreements, as a symbiotic relationship grows.

7.4 International Bodies

Apart from the lists of organisations previously presented, three international bodies need to be singled out. International cooperation has been fostered both by the NEA and the IAEA as well as the CEC. The IAEA has certainly taken the major steps especially on the technical side while the NEA has mostly concentrated on the socioeconomic considerations, of which this report is a part. The CEC naturally concentrates on Europe. However, as the reactors move into the commercial sector the international bodies have a lesser role relative to the companies themselves.

NEA

The NEA's main objective is to promote cooperation between the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source. To carry out its mission, the Agency evaluates the technical and economic aspects of nuclear power growth and encourages consultations on its Members' safety and regulatory policies and practices, with a view to their harmonization.

Apart from this report other projects fostering international cooperation on SMRs is the "Projected Costs of Generating Electricity from Nuclear and Coal-Fired Power Stations for Commissioning in the Period 1995-2000" a report on "Advanced Water-Cooled Technologies" as well as a study on "Reduction of Capital Costs for Nuclear Power Plants".

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Figure 7.2. **EXAMPLES OF INTERNATIONAL COOPERATION JAERI & OTHERS (FOR HTR)**

- **FRG**
  - **STATE OF NRW**
  - **INTERATOM**

- **JAPAN**
  - **BMFT**
  - **KFA**
  - **JAERI**

- **USA**
  - **STA**
  - **NRC**

- **PRC**
  - **DOE**
  - **TSINGHUA UNIVERSITY**

- **IAEA**
  - **IWGGCR**
  - **INET**

- Agreements and Exchanges:
  - **Agreement on the Exchange of Information in the Field of R&D of HTR**
    - April 1977
  - **Agreement on Cooperation of Information Exchange on RXY**
    - January 1984
  - **Agreement on Cooperation of Information Exchange on HTGR and VHTR**
    - April 1990
  - **MOU on General Information Exchange on HTGR and VHTR**
    - June 1986, Revised June 1988
The IAEA is not doing work specifically on SMRs but rather includes it within the IAEA’s programme on "nuclear power"; the sub-programmes on "improvement of reactor technologies" and "development of advanced reactor systems" contain the most relevant (to SMRs) activities and specific tasks.

These are commented in more detail. It is to be noted that SMRs (or SMPRs, Small and Medium Power Reactors) as well as nuclear heat applications constituted for many years in the past specific programmatic items or projects for the IAEA, lately however, these have been included within the scope of wider areas of activity and tasks covering a broader scope.

To cite some of the present projects which have relevance are:

- Innovative designs and technology improvements in water-cooled reactors;
- Future design concepts;
- Nuclear heat applications; and
- Application of advanced technologies.

During the past few years, the exchange of information on evolutionary developments and new concepts has been promoted through two IWGs:

- Initiated in 1985, the Agency's activities regarding the development of water-cooled reactors were intensified after the Chernobyl accident with the creation of the IWG on Advanced Technologies for Water-Cooled Reactors (IWGATWR).
- The development of high temperature gas-cooled reactors and their applications has been regularly reviewed through the IWG on gas-cooled reactors and specialists’ meetings.

CEC

The Commission of the European Communities facilitates the coordinated development of the investments in the nuclear field (Euratom Treaty, Art. 40) and to this end sponsors and publishes various studies including illustrative programmes.

The need for new reactors due to the ageing of existing nuclear plants has been identified to occur around 2010. As such the CEC’s analysis of the market is suggesting a three-pronged approach: construction of new reactors in approximately five years, maintenance of present reactors and development of new types of reactors within 20 years.

The Council of Ministers has taken a common position in fostering the opening up of the market in energy. In connection with this there is a concerted effort in standardisation including SMRs, specifically concentrating on Users’ Requirements which would be acceptable to all electricity producers within the CEC.

In more specific areas the Commission is awarding contracts on studies on SMR development and has carried out a series of studies on the potential market for modular high temperature reactors, both for electricity and as a heat source in various CEC countries.
7.5 Future Issues on International Cooperation

Reduction of Concepts

This can be expected to follow as a consequence of the present reorganisations in the industry. One of the rationales for the reorganisations is to reduce waste due to duplication. Certain of the SMR designs are similar and in many cases are aimed at the same market niche. Therefore one would expect the number of products offered to be reduced. Only the most financially promising will be retained, providing a certain standardisation of product lines.

Public Perceptions

As stated before, the public perception is at best mixed about nuclear power and at worst, from the nuclear industry's point of view, totally against it. Since SMRs offer certain advantages from a public perception point of view, it will be the responsibility of credible national and international bodies to present the facts in clear understandable ways. One aspect particular to SMRs is that they should not be seen as scaled-down "old" reactor technology, but that it would be advantageous that SMRs be perceived, as it is in most cases, as a departure from the past in that it uses advanced technological features such as passive safety systems.

Licensing

This is perhaps the key area for fostering SMR. One of the economic advantages stated is the one of series production. This will be true if the market can accept a uniform product.

While licensing philosophies are common to several countries and have in fact been promoted by the IAEA, the detailed licensing requirements are far from uniform and create a multiplicity of markets. This especially has an impact for heating reactors where large production runs are needed.

The intent is not to have a common licensing for multiple countries, but that the reactor be licensable in multiple countries. This can imply recognition of each other's licensing or to rationalise certain aspects of licensing to permit one reactor type to be acceptable in each country, without licensing-related design modifications. Whatever the approach there is a large task to be undertaken. An international body seems well placed to sponsor a feasibility study on this aspect. If this can be accomplished, it will also lead to reductions of "certification" costs as a reactor type need only be licensed once. The licensing costs of a one-off SMR are expected to be proportionately higher than the licensing costs of a one-off large reactor per kW installed.

First Prototype

Assuming that one reactor type is or can be licensed, there will be heavy investment needed to prove both to regulators and to the public the acceptability of the reactor. This will include large scale experiments or a demonstration plant. Since presumably this reactor will be desired by more than one country, financing could be international. The company(ies) and appropriate national and international organisations would have to be involved in the financing and perhaps in defining a standard financial package.

If the project is international, some involvement may also be required to define series co-fabrication between the various countries and potential customers. The first prototype could also serve as a model for potential technology transfer and for a resolution of any fuel cycle issues.

Table 7.1 summarises the tasks and the bodies which would have to cooperate internationally.
Table 7.1. **Summary of Issues and Organisations**

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Organisations/Companies</th>
<th>National Bodies</th>
<th>International Bodies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction of concepts</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public perception</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Licensing</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>First prototype</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Our study has not attempted to define paths for the participants; it has, however, attempted to give visibility to the opportunity for benefits that are available to the decision-makers in the OECD nations, utilities, and reactor manufacturers. It is hoped that this information will help OECD nations achieve the obvious: maximise the benefits and minimise the waste.
8. CONCLUSIONS

8.1 Findings of the Report

There are substantial resources being devoted to development of different SMR concepts throughout the "nuclear" nations of the world. The feature common to all these developments is simplification of the design and the introduction of passive safety features. In this context one of the major advantages of SMRs could be in improving public acceptance of nuclear energy, which must be achieved if nuclear power in general is to play a significant role in the future, including minimising harmful emissions to the world's atmosphere from its energy sector. Another advantage is that SMRs could open up, to nuclear power, markets other than the traditional electricity one, notably the industrial and commercial heat markets -- again important if nuclear power's full potential as an environmentally clean source of energy is to be realised. The SMR characteristics of simplicity, size and passive safety make them particularly suitable for developing countries.

To penetrate electricity markets successfully SMRs would have to be economically competitive with large power plants, and opinions are mixed on whether this can be achieved. In some countries the major reactor manufacturers have developed SMR designs that are claimed to be financially attractive because of the economic benefits that accrue from factors such as simplicity in design, extensive use of factory fabrication, shorter on-site construction times, lower up-front capital and earlier start to revenue earning. This combination of reliability, maintainability and safety should significantly improve owner investments. The proponents of large nuclear plant designs argue that many of these benefits are applicable to their plants, particularly if the installation programme is for a large series of replicate plant.

However, there are additional and more generally accepted claims in favour of SMRs, notably that there are niches in the world's electricity markets where a smaller size of reactor is preferable to that of the current large plants. These special situations arise where the customer utility is small, where the demand growth is low, or where there are restrictions at the available site on, for example, cooling water.

To penetrate the heat market there is a need for small (CHP) reactors that fit into the smaller usually non-interconnected heat distribution networks for heating or industrial process heat as well as providing the process temperatures needed. Using the waste heat from power stations to the maximum degree by optimised matching of heat demand could give considerable economic and environmental advantage. Public aversion to close proximity of nuclear plants to large urban populations will demand even more definitive publicly acceptable proof of the safety of SMRs, before their widespread use in the domestic heat market is accepted.

8.2 Perspectives for the Future

Although good potential for SMRs has been identified, there have been no concrete results achieved so far; no series of commercial SMRs have yet been built by any manufacturer for any customer. The main problem facing promotion of SMRs is how to break this deadlock.

Among the current difficulties are the number of different designs of SMRs available or under development -- and the absence of any operating demonstration plants, or even planned construction projects. Reduction in the number of preferred SMR designs on offer for each market sector (power, district and process heating) would be a major step forward, with a concomitant objective being the achievement of maximum Standardisation. The increasing integration of reactor manufacturers could well lead to this outcome eventually.
Another key issue is the assurance that a licensed design can be built in series and taken into operation (after its first-of-a-kind) without further licensing-related design modifications. Type licences will be even more essential for SMRs than for large reactors because there would be more of them in a programme of fixed capacity, which could be fairly modest in size. Moreover, SMR type licences would help overcome the reluctance of users in the non-traditional nuclear markets and assist in their economies. It is also desirable that a licensed design is acceptable "sans frontières" (i.e. acceptable to all countries).

In this context it is noteworthy that the CEC are already aiming for standardisation of equipment through establishment of common criteria and specifications -- with a view to establishing a common domestic market within Europe. Examples are CEC work directed to LWR safety specifically and fast reactors generally; attention is now being addressed to SMR developments.
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APPENDIX A: ENERGY CONVERSION FACTORS

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<th>PCAL</th>
<th>MTCE</th>
<th>MTOE</th>
<th>TWh</th>
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<td>0.860</td>
<td>0.123</td>
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</table>

ABBREVIATIONS

PCAL  Peta Calorie  $10^{15}$ calories
PC    Peta Joule    $10^{15}$ joules
MTCE  Million Ton Coal Equivalent
MTOE  Million Ton Oil Equivalent
TWh   Tera Watt hours  $10^{12}$ watt-hour
APPENDIX B: LIST OF ABBREVIATIONS AND GLOSSARY OF TERMS
ENGLISH/FRENCH DICTIONARY

ABB Asea Brown Boveri

ADP Advanced Double Pool reactor


AGR Advanced Gas-Cooled Reactor (réacteur avancé refroidi par gaz).

ALMR Advanced Liquid Metal Reactor

AP Advanced Passive pressurised water reactor

ATR Advanced Thermal Reactor (réacteur thermique avancé): A heavy water moderated, light water-cooled reactor.

ATWS Anticipated Transients Without Scram

Availability Factor (Facteur de disponibilité): The availability factor of a nuclear unit or station is the ratio of time when energy can be produced to the total time.

Base Load (charge minimale): The minimum load produced over a given period. A station used for base load is a station that is normally operated when available to provide power to meet the minimum load demands.

BOP Balance Of Plant

Breeding Ratio (rapport de surgénération): The conversion ratio when it is greater than unity. A high breeding ratio results in a short doubling time.

Breeder Reactor (réacteur surgénérateur): A nuclear reactor that produces more fissile material than it consumes. In fast breeder reactors, high-energy (fast) neutrons produce most of the fissions, while in thermal breeder reactors, fissions are principally caused by low-energy (thermal) neutrons. See Fast reactor.

BWR Boiling-Water Reactor (reacteur à eau bouillante): A light-water reactor that employs a direct cycle; the water coolant that passes through the reactor is converted to high pressure steam that flows directly through the turbines.

CANDU CANadian Deuterium Uranium reactor: A type of heavy water reactor.

Capacity Factor (taux d'utilisation en énergie ou facteur de charge): See Load Factor.

CE Combustion Engineering

CEA Commissariat à l'Energie Atomique

CEC (CCE) Commission of the European Communities.
Charge of a reactor (charge d'un réacteur): The fuel placed in a reactor.

CHP Combined Heat and Power

Conversion, chemical (conversion chimique): The operation of altering the chemical form of a nuclear material to a form suitable for its end use.

Conversion as used in reactor technology (conversion, ou régénération): Nuclear transformation of a fertile substance into a fissile substance.

Conversion ratio (rapport de conversion, ou rapport de régénération): The ratio of the number of fissile nuclei produced by conversion to the number of fissile nuclei destroyed. If the ratio for a given reactor is greater than one, it is a breeder reactor; if it is less than one, it is a converter reactor.

Converter reactor (réacteur convertisseur): A reactor that produces some fissile material, but less than it consumes.

Coolant (fluide caloporteur, ou fluide de refroidissement): The medium in a nuclear reactor which absorbs heat from the reactor core where fission occurs and heat is produced, and transfers it to systems which convert the heat into steam.

CPE Countries Centrally Planned Economy countries (les pays à économie planifiée ou PEP).

D.O or heavy water (eau lourde): See Heavy Water.

Decay Heat this is the residual heat in the reactor core after shutdown due to the decay of the radioisotopes in the core

Decommissioning (déclassement): Taking out of service or ending active operations. Can also include making safe or dismantling the plant.

Delivered energy, or end-use energy (énergie fournie): Energy delivered to the final consumer in the form he uses (e.g. heating oil, gasoline, electricity).

Disposition of spent fuel (traitement final du combustible irradié): A generic term for fuel management activities beyond interim storage or transport of spent fuel, i.e. reprocessing or disposal.

DOE Department of Energy: US body studying and promoting various methods of energy production and use.

ECC Emergency Core Cooling

Econometrics (économétrie): The application of mathematical form and statistical techniques to the testing and quantifying of economic theories and the solution of economic problems.

Economics (économie): A social science that studies the production, distribution, and consumption of commodities.

EMP Electromagnetic Primary Pump

End-use energy (énergie fournie): See Delivered Energy.

Enriched fuel (combustible enrichi): See Fuel, enriched.
Enrichment (enrichissement):
   i) the fraction of atoms of a specified isotope in a mixture of isotopes of the same element when
      this fraction exceeds that in the naturally occurring mixture;
   ii) any process by which the content of a specified isotope in an element is increased.

Exogenous (exogène): Originating from outside a system (as from external political, accidental, and
   technological forces).

Fast reactor (réacteur rapide): A nuclear reactor in which no moderator is present in the reactor core or
   reflector. So the majority of fissions are produced by fast neutrons. If a fertile species is present in the fast
   reactor core or in the blanket surrounding the core, it will be converted into fissile material by neutron capture.
   When more fissile material is produced than is used to maintain the fission chain, the reactor is called a
   breeder.

FBR or Fast Breeder Reactor (réacteur surgénératcue à neutrons rapides):
   See Fast Reactor.

Final energy (énergie finale): Refers to the forms in which energy is consumed once it has reached the user:
   the energy in a motor, a stove, a computer or a lightbulb.

Fissile (fissile):
   i) of a nuclide, capable of undergoing fission by interaction with slow neutrons;
   ii) of a material, containing one or more fissile nuclides.

Fission (fission): The physical process whereby the nucleus of a heavy atom is split into two (or, rarely,
   more) nuclei with masses of equal order of magnitude whose total mass is less than that of the original
   nucleus. The lost mass becomes energy according to Einstein's equation \( E = mc^2 \). Fission is initiated by
   the capture of a neutron by the nucleus of a fissionable atom, and is accompanied by the emission of
   between one and three other neutrons (plus gamma radiation, and, rarely, smaller charged nuclear
   fragments). These neutrons in turn can fission adjacent nuclei, producing a self-perpetuating reaction, or
   chain reaction.

Fissionable (fissionable):
   i) of a nuclide: capable of undergoing fission by any process;
   ii) of a material: containing one or more fissionable nuclides.

Fission products (produits de fission): Nuclides produced either by fission or by the subsequent radioactive
   decay of the nuclides thus formed.

Fossil fuel (combustible fossile): A term applied to coal, oil and natural gas.

Fuel cycle (cycle du combustible): The sequence of processing, manufacturing, and transportation steps
   involved in producing fuel for a nuclear reactor, and in processing fuel discharged from the reactor. The
   uranium fuel cycle includes uranium mining and milling, conversion to uranium hexafluoride (UF₆), isotopic
   enrichment, fuel fabrication, reprocessing, recycling to recovered fissile isotopes, and disposal of radioactive
   wastes.

Fuel, enriched (combustible enrichi): Nuclear fuel containing uranium which has been enriched in one or
   more of its fissile isotopes or to which chemically different fissile nuclides have been added.

Fuel, nuclear (combustible nucléaire): Material containing fissile nuclides which when placed in a reactor
   enables a self-sustaining nuclear chain to be achieved.
GA General Atomic.

GCR or Gas-Cooled Reactor (réacteur refroidi par gaz): See GGR.

GDP Gross Domestic Product (PIB ou Produit Intérieur Brut): is equal to the Gross National Product (GNP) minus net factor payments abroad (such as income from foreign investments and wages paid to foreign workers). The GDP is used to distinguish between the product or income of the citizens of a country (the national product) and the product or income produced in that country (the domestic product); it is preferable to GNP as a measure for international comparisons.

GE General Electric.

GGR or Gas-Graphite Reactor (réacteur à gas-graphite): A graphite-moderated, carbon dioxide (CO₂)-cooled reactor.

GHR Gas-cooled Heating Reactor

GmbH: German term signifying "Limited".

GNP Gross National Product (PNB, ou Produit National Brut): The total market value of the goods and services produced by a country's economy during a specific period of time (usually a year), for final consumption, capital investment, and governmental use; by definition, it is equal to the sum of the incomes generated in a country through production. GNP is computed before allowance is made for depreciation and other forms of capital consumption, and it does not include the value of intermediate goods and services sold to producers and used in the production process itself. See GDP.

GWe Gigawatt (10⁹ watts) electric (gigawatt électrique).

Heavy water (eau lourde): Deuterium oxide (D₂O): water containing significantly more than the natural proportion (1 in 6500) of heavy hydrogen (deuterium) atoms to ordinary hydrogen atoms.

HEU Highly-Enriched Uranium (uranium fortement enrichi).

HSBWR Hitachi Small Boiling Water Reactor

HTTR High Temperature Test Reactor

HTR or HTGR High-Temperature Gas-Cooled Reactor (réacteur à haute température refroidi par gaz): A graphite-moderated, helium-cooled advanced reactor that utilises low enriched uranium.

HWR Heavy-Water Reactor (réacteur à eau lourde): Heavy water is used as a moderator in certain reactors because it slows down neutrons effectively and also has a low cross section for absorption of neutrons.

HX Heat Exchange (Echangeur de chaleur).

IAEA International Atomic Energy Agency (AIEA, ou Agence Internationale de l'Energie Atomique).

IEA International Energy Agency (AIE, ou Agence Internationale de l'Energie).


IIASA International Institute for Advanced System Analysis.
**Isotopes (isotopes, ou nucléides isotopes):** Nuclides having the same atomic number (i.e. identical chemical element) but different mass numbers; e.g. 92-uranium-235 and 92-uranium-238. Isotopes have the same chemical properties but slightly different physical properties.

**JAERI** Japan Atomic Energy Research Institute.

**kWh** Kilowatt hour (10³ watt hour).

**lb** Pound (453.592 grams) (Livre).

**LEU** Low Enriched Uranium (uranium faiblement enrichi).

**LMFBR** Liquid Metal Fast Breeder Reactor (réacteur surgénérateur rapide refroidi par métal liquide): A fast reactor that employs liquid metal (sodium) as a coolant. The sodium in the primary loop passes through the reactor and transfers its heat to sodium in a secondary loop. This sodium then heats water in a tertiary loop which produces steam and drives a turbine. See also Fast Reactor.

**Load Factor** (facteur de charge ou taux d'utilisation en énergie): The load factor of a nuclear unit or station for a given period of time is the ratio of the energy that is produced during the period considered to the energy that it could have produced at maximum capacity under continuous operation during the whole of that period. Also called Capacity Factor.

**LOCA** Loss Of Coolant Accident.

**LOF** Loss Of Flow.

**LOHS** Loss Of Heat Sink.

**LWR** Light-Water Reactor (réacteur à eau ordinaire): A nuclear reactor that uses ordinary water as both a moderator and a coolant and utilises slightly enriched uranium-235 fuel. There are two commercial LWR types: the boiling-water reactor (BWR) and the pressurized water-reactor (PWR).

**MHTGR** Modular HTGR see HTR (réacteur à haute température modulaire refroidi au gaz).

**Macroeconomic** (macro-économique): Of, relating to, or based on macroeconomics, i.e. on a study of the economic system as a whole especially with reference to its general level of output and incomes and the inter-relations among sectors of the economy; opposed to microeconomic.

**Microeconomic** (micro-économique): Of, relating to, or based on microeconomics, i.e. on a study of economics in terms of individual areas of activity (as a firm, household, prices); opposed to macroeconomics.

**Moderator** (modérateur, ou ralentisseur): A material, such as ordinary water, heavy water, or graphite, used in a nuclear reactor to slow down fast neutrons so fissile nuclei can more easily and efficiently capture them, thus increasing the likelihood of further fission.

**MOX fuel element** Mixed Oxide fuel element (élément combustible à mélange d’oxides): Fuel element in which fuel is an intimate mixture of uranium and plutonium oxides.

**MW**: Megawatt (10⁶ watts) electric.

**MWh**: Megawatt hour (10⁶ watt hour).

**MWt**: Megawatt (10⁶ watts) thermal.
NEA OECD Nuclear Energy Agency (AEN, ou Agence de l'OCDE pour l'Energie Nucléaire):

**Neutrons, fast** (neutrons rapides): Neutrons of kinetic energy greater than some specified value. This value may vary over a wide range and will be dependent upon the application, such as reactor physics, shielding, or dosimetry. In reactor physics the value is frequently chosen to be 100 000 eV (electron-Volt).

**Neutrons, slow** (neutrons lents): Neutrons of kinetic energy less than some specified value (see neutrons, fast). In reactor physics, the value is frequently chosen to be 1 eV.

**Neutrons, thermal** (neutrons thermiques): Neutrons in thermal equilibrium with the medium in which they exist.

**NHP** Nuclear Heating Plants

**NPP** Nuclear Power Plants

**NRC** (Nuclear Regulatory Commission): U.S. body regulating the use of nuclear energy.

**Nuclear energy** (énergie nucléaire): Energy released in nuclear reactions or transitions.

**Nuclear fuel** (combustible nucléaire): See Fuel, nuclear.

**Nuclear power plant** (NPP) (centrale nucléaire): A reactor or reactors together with all structures, systems and components necessary for the production of power (i.e. heat or electricity).


**PCIV** Prestressed Cast Iron Vessel.

**PCV** Pressure Containment Vessel.

**Peak load** (charge de pointe): The maximum load produced by a unit or group of units in a started period of time. A station used for peak load generation is a station that is normally operated to provide power during maximum load periods only.

**Pebble bed reactor** (réacteur à lit de boulets, ou réacteur à boulets): A gas-cooled reactor, which utilises spherical fuel elements.

**Per capita** Per unit of population (par habitant).

**PIUS** Process Inherent Ultimate Safety Reactor.

**Plutonium** (plutonium): A heavy, radioactive, man-made metallic element with atomic number 94, created by absorption of neutrons in uranium-238. Its most important isotope is plutonium-239, which is fissile.

**Primary energy** (énergie primaire): Energy content of fuels before they are processed and converted into forms used by the consumer. Primary energy refers to energy in the form of natural resources: water flowing over a dam, coal freshly mined, crude oil, natural gas, natural uranium. Only rarely can primary energy be used to supply final energy; one of the few forms of primary energy that can be used as final energy is natural gas.

**PSI** Paul Scherrer Institute.
PWR Pressurized-Water Reactor (REP, réacteur à eau sous pression): A light-water moderated and cooled reactor that employs an indirect cycle; the cooling water that passes through the reactor is kept under high pressure to keep it from boiling, but it heats water in a secondary loop that produces steam that drives the turbine.

Radioactive waste (déchets radioactifs): The unwanted radioactive materials formed by fission and other nuclear processes in a reactor or obtained in the processing or handling of radioactive materials. Most nuclear waste is initially in the form of spent fuel. If this material is reprocessed, new categories of waste result: high-level, transuranic, and low-level wastes (as well as others).

Radioactive waste disposal (évacuation des déchets radioactifs): The disposition of radioactive waste in repositories, after appropriate conditioning, without specific provision for recovery.

Reactor, boiling water (réacteur à eau bouillante): See BWR.

Reactor, breeder (réacteur surgénerateur): See Breeder reactor.

Reactor, Canadian Deuterium Uranium (réacteur canadien à uranium deutérium): See CANDU.


Reactor core (coeur d'un réacteur): The central portion of a nuclear reactor containing the fuel elements and the control rods (and part of the coolant and moderator), where most of the energy is produced.

Reactor, fast (réacteur rapide): See Fast reactor.

Reactor, fast breeder or FBR (réacteur surgénerateur à neutrons rapides): See Fast reactor.

Reactor, gas graphite (réacteur gaz graphite): See GGR.

Reactor, heavy water (réacteur à eau lourde): See HWR.

Reactor, high temperature (réacteur à haute température refroidi par gaz): See HTR.

Reactor, light water (réacteur à eau ordinaire): See LWR.

Reactor, liquid metal, fast breeder (réacteur surgénerateur rapide refroidi par métal liquide): See LMFBR.

Reactor, nuclear (réacteur nucléaire): A device in which a self-sustaining nuclear fission chain reaction can be maintained and controlled.

Reactor, pebble-bed (réacteur à boulets ou réacteur à lit de boulets): See Pebble-bed reactor.

Reactor, pressurized-water (réacteur à eau sous pression): See PWR.
Reprocessing, fuel (traitement des combustibles irradiés, ou retraitement du combustible): A generic term for the chemical and mechanical processes applied to fuel elements discharged from a nuclear reactor; the purpose is to remove fission products and recover fissile (uranium-233, uranium-235, plutonium-239), fertile (thorium-232, uranium-238) and other valuable material.

RHR Residual Heat Removal.

RPV Reactor Pressure Vessel.

RRA Rolls-Royce and Associates.

RVACS Reactor Vessel Air Cooling System.

Safeguards (garanties): Term used to refer to the total set of international verifications, observations, etc., which together constitute a determination that nuclear materials (or, in some international agreements, facilities or other materials) have not been diverted from nuclear power programmes to the production of nuclear weapons.

SAFR Sodium Advanced Fast Reactor

SBWR Simplified or Small BWR (réacteur à eau bouillante simplifiée): See BWR.

SDR Slowpoke Demonstration Reactor

SECURE Safe Environmentally Clean Urban Reactor

SES Slowpoke Energy System

SIR Safe Integral Reactor.

SMR Small and Medium-sized Reactors (Reacteurs de faible et moyenne puissance)

SPWR (réacteur à eau sous pression simplifié): Simplified PWR. See PWR.

TRIGA Training of personnel, nuclear Research, Isotope production, General Atomic

TWh Terawatt (10^12 watt) hour.

TOP Transient Over Power

Uranium (uranium): A radioactive element of atomic number 92. Naturally occurring uranium is a mixture of 99.28 per cent uranium-238, 0.715 per cent uranium-235, and 0.0058 per cent uranium-234. Uranium-235 is a fissile material and is the primary fuel of nuclear reactors. When bombarded with slow or fast neutrons, it will undergo fission. Uranium-238 is a fertile material that is transmuted to plutonium-239 upon the absorption of a neutron.

W Westinghouse

WEC World Energy Conference (CME, ou Conférence Mondiale de l'Energie).

Woca World Outside CPE Arcas (MEM ou Monde à Economic de Marché).

WRI World Resource Institute
# APPENDIX C: ADDITIONAL ECONOMIC DATA EXTRACTED FROM
# ENERGY BALANCES OF OECD COUNTRIES 1986/87, OECD/IEA 1989

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**Total Primary Energy Requirements / Total des Besoins d'Energie Primaire**

(Mtoe / Mttep)

(Data from OECD Energy Balances 1960-78)
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Per cent of Total

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In Belgium the total installed capacity in 1988 was 14,080 MW, of which 51.3 per cent are fossil-fuelled and 39.2 per cent nuclear power plants. Of the total electricity generation 61,913 GWh, 66 per cent is produced by nuclear, 32.1 per cent by fossil fuels and 1.9 per cent by hydro power. According to the statistics, the electricity consumption rose by 3.9 per cent in 1988 and is thus growing more rapidly than the primary energy consumption. In 1989 production and consumption increased by 3.1 per cent and 2.9 per cent respectively though the share of nuclear dropped to 60.7 per cent and hydro dropped to 1.7 per cent with fossil fuels making up the rest.

In the future the new investment plan foresees a 25 per cent participation in the Chooz B1 and B2 (1390 MW) French nuclear power plants coming on line in 1992 and 1993; four gas turbines (100 MW) and 2 to 4 combined cycle plants (300 MW) coming on line in 1995; and two coal fired plants (600 MW) between 1995 and 1997. The decision to build a new nuclear power plant in Belgium has been postponed. This investment plan is covering the needs within a scenario assuming an electricity growth demand of 2.5 per cent a year. The mean growth rate during 1982-1987 was 3.7 per cent/year.

Tests related to underground storage of nuclear high level waste in a clay layer show very encouraging results. No solution has been adopted yet for the storage of low level wastes.

In Canada energy production and demand in 1988 reached record levels. Total final energy consumption (TFC) and GDP both increased by five per cent. The energy sector represents 7 per cent of the GDP in Canada. In addition to the economic growth, however, the most important single factor impacting upon the continuing upward trend in oil consumption since 1988 was the weather. Changes in thermal coal production and consumption, heavy fuel oil consumption, and electricity production, imports, and exports were all essentially weather-related phenomena. Sharply lower oil and gas prices also contributed to the largest annual increase in Canadian energy consumption since the sixties.

On a year basis (1988), the most prominent production increases were those of natural gas (up 16 per cent), metallurgical coal (up 25 per cent) and oil (up 5 per cent). However, these increases were largely export driven. But electricity exports were slashed by 29 per cent in 1988 due to the drought. In 1989 hydroelectric capacity is estimated to be 57,947 MW, fossil and others 29,090 MW and nuclear 11,867 MW.

In December 1989, Ontario Hydro (the utility in the most heavily populated province in Canada) issued its Demand/Supply Plan Report which recommends a plan for meeting provincial electricity needs over the next 25 years. Under the utilities most probable electricity demand growth scenario Ontario Hydro’s preferred plan calls for the addition of 8.8 GW and the retirement (by the end of the period) up to 2.9 GW of nuclear capacity. These changes would result in an increase in nuclear capacity from 14.2 GW in 1993 to 20.1 GW by 2014. Nuclear energy production would increase to two thirds of the Ontario total in 2014. The projected electricity demand growth forecast for the next 25 years is expected to average 1.6 per cent annually (2.3 per cent annually without extensive demand reduction plans). Projected electricity costs support previous studies which show levelised unit energy costs from new coal-fired capacity about 30 per cent more expensive than from new nuclear capacity.

The first Darlington A reactor is being commissioned. It should be in full commercial service by the summer peak cooling period. Discussions on the proposed CANDU 3 (450 MWe prototype) sale to New Brunswick (Lepreau 2) are continuing. The province of Quebec is studying the possibility of a renewed nuclear programme. The province of Saskatchewan remains interested in CANDU 3, though a decision does not appear imminent. The Newfoundland utility has indicated that it should study a nuclear option though no commitment to such a study has been made yet.
In Finland four nuclear power units were in operation for a total capacity 2300 MWe. The average capacity factor of the units has been of the order of 90 per cent during a couple of years. In 1989 the nuclear share in overall electricity production was 30 per cent.

Backfitting measures, including filtered containment venturing systems, against severe accidents were completed at the end of 1989 at TVO I/II units. Several backfitting measures were also taken at the Loviisa plants directed towards improved safety, but considerable efforts have also been devoted to enhancement of the reliability, and hence also the economics of the plant. Imatrankoima Oy (IVO) and Industrial Power Company (TVO) are projecting new nuclear capacity for Finland in the class of 1000 MWe through their joint venture, Perusvoima Oy (PEVO). The target year is 1998/99 for the first operation.

The construction of the reactor waste final repository at Olkiluoto, the VUI repository, was continued. During 1989 the excavation was completed, its total volume being 90000 m³. The VUI repository will be finished in 1992. Spent fuel is stored in an intermediate store, KPA store, at Olkiluoto. Investigations for final disposal have been carried out at five alternative sites in Finland. At Loviisa, there is no need to build a final repository for reactor waste in the near future. The spent fuel from the Loviisa plant is sent back to the USSR after it has been stored in water pools for about five years.

The amendment to the Liability Act has been approved by Parliament and the new Law on Radiation is under parliamentary consideration. Proposals for the decisions on the safe use of nuclear energy have been prepared for the Finnish Government.

Steady post-Chernobyl positive change in public opinion levelled out at the end of 1988. Opposition to nuclear power as an energy source has generally fallen from 60 per cent, measured immediately after the accident, to 37 per cent. Those with positive attitudes increased over the same period from 18 to 26 per cent.

In France 54 nuclear power units were in operation for a total capacity 51000 MWe. The total production was 285 billion kWh representing an 80 per cent figure for nuclear share in overall electricity production. The average load factor ranges from 62 to 79 per cent. Another eight nuclear power units are under construction accounting for a total capacity of 11000 MWe. Two of them are N4 type nuclear reactors. A third N4 type plant will probably ordered within one year.

Given the national (and European) electrical net configuration (size and connection), the adjunction of 1000 MWe capacity does not represent a great share of the total capacity and small reactors do not represent an actual advantage. Nevertheless the public utility, the NSSS suppliers and, of course, the public research laboratories are strongly interested by improvement in reactor technology used in SMR. The main objectives being greater safety, simplicity and lower investment cost.

No district heating reactors are so far foreseen.

The primary energy consumption in Germany was about 3170 TWh in 1988. Except hard coal, lignite and some natural gas, there are no other large domestic energy resources. Sixty per cent of the primary energy needs has therefore to be imported. The dependency from oil has been reduced from 55 per cent in 1973 to 42 per cent in 1988 mainly by enhancing the contribution of nuclear power and of natural gas. The fraction of OPEC oil has been lowered from 96 per cent to nearly 50 per cent.

Environmental impacts by energy conversion have been reduced remarkably by more efficient use of energy, increased share of natural gas and nuclear power and more restrictive environmental protection laws (desulfurisation, denitrification of flue gas).

The primary energy consumption has only raised by 3 per cent from 1973 to 1988 although the GNP increased by about one third. Electricity consumption growth, on the other hand, has been significantly
higher and raised to 431.5 TWh. The fraction of nuclear power has increased to 12 per cent of total primary energy. The installed power plant capacity in 1988 was 102 GW. Nuclear power contributed 33.7 per cent of this. About 90 per cent of electricity generation is based on domestic energy resources including nuclear power.

Some 30 per cent of the final energy consumption was used by the industry (625 TWh) mainly for process heat applications. Mineral oil and natural gas are the most prevalent fuels in this sector.

District heat has with 51.4 TWh only a 2.5 per cent share of the total final energy consumption. Altogether the F. R. Germany has a district heat network equivalent to 37.6 GW (1987).

Japan energy demand increased in proportion to its economy expansion before the oil embargoes by the OPEC, which meant that energy demand elasticity to GDP was about unity. Since the oil crisis this relationship of energy and economy was destroyed in the industrialised countries. But under the circumstances of low energy price of today, energy demand, especially electricity consumption, has started to grow again. However, sharp drastic increase of energy demand in the industrialised countries will not be foreseen, because their industry has experienced structural reforms of less energy. In 1988, Japanese primary energy supply has increased to 462 mtoe, corresponding to 5.4 per cent increase from the previous year and the elasticity has exceeded unity to 1.1. This kind of consecutive energy consumption increases are basically due to the recent expansion of economy, degradation of energy conservation effort and revival of energy intensive industries such as steel and chemical.

In 1988 the nuclear share of the electricity production made 27 per cent with 28.7 GW of capacity, while the share of fossil-fuelled plants was 60 per cent with 100 GW. In the year 2000 the corresponding figures are expected to be 35 per cent for nuclear and 53 per cent for fossil fuels. 50 GW of nuclear power at 2000 is relatively firm because most of their programmes have started already. However, recent "Long-term Energy Prospects" of 1990 June expects 72 GWe in 2010 to meet the high electricity demand and to cope with greenhouse gas emission reduction issues. Two full-size reactors a year would be needed to be commissioned in order to be equipped with that much of nuclear power. Public acceptance of nuclear is pointed out to be the most difficult problem to achieve that ambitious target. Besides the siting efforts, safe and stable operation of NPP and safety related R&D, waste issues should be clarified to achieve better public understanding of nuclear development.

In Spain 1989 has been a very dry year. This has somewhat displaced electricity production from hydro (decreasing 46 per cent with respect to 1988) to thermal (increasing 37 per cent). The relative nuclear contribution has moved from 36.3 per cent in 1988 to 38.0 per cent in 1989.

Actual increases of 4 per cent to 6 per cent in the last years in the electricity production represent an important departure from the 3.3 per cent figure foreseen in the 1983 National Energy Plan (PEN-83) still current. It is expected that the yearly growth in electricity production will amount to around 4-5 per cent from now to 1995 and 3-4 per cent afterwards.

It is worth mentioning the almost marginal contribution of oil and gas to the electricity production. For oil, because of the current policy of keeping idle the oil fired units (except for eventual peaking or supplementary base load operation in a dry year) due to the oil price situation years ago. For gas, because the natural gas, mostly imported, is devoted only to domestic and industrial uses (including in some cases CHP installations). It may also be added that there are in Spain no centralised urban heating networks.

A new National Energy Plan (PEN) is soon expected, after several years of looking "immediate" and after the recent general elections. The National Energy Plan will be the framework for decisions of the utilities. The big question (or rather the big answer) is what the PEN will say about the nuclear option, with five 1 000 MW units at different stages of construction affected by the "de facto" nuclear moratorium. The October 1989 fire at the Vandellós-I nuclear plant (with a 500 MW natural uranium, gas-cooled reactor) has
given strength to the nuclear opponents. The plant will not be repaired and the process of dismantling will
start; the decision, according to the Government, is based purely on economics (taking into account the cost
of repairs) and on technical obsolescence.

Given the known air pollution problems caused by indigenous coal, it is expected however that one
or two of those stopped units will be granted permission to continue construction and later operation.

At present the electricity sector is studying the possibility of participating in the EPRI programme on
medium power passive reactors (ALWR, Phase 3), providing economic and human resources for the detailed
design of the AP600 and SBWR reactors over the next six years.

The experience accumulated over the years in the construction and operation of light-water reactors
has led to this particular line of technology being the most widely contemplated by the sector, although other
options such as the CANDU type heavy-water reactor are not to be disregarded.

The interest of the electricity generating sector, within the range of SMR possibilities is centred
exclusively on medium power reactors (600 MW) for the production of electrical energy.

Final energy consumption in Switzerland amounted to 212 TWh in 1988. It has been covered to
75.3 per cent by fossil fuels and to 20.8 per cent by electricity. 30.7 per cent of this energy has been
consumed in households, 19.9 per cent in the primary and tertiary sectors, 19.1 per cent by the industry and
the remaining 30.3 per cent have been used in transports. Finally 58.9 per cent of the final energy
consumption was in the form of heat, the remaining being mechanical work, chemistry and light.

With the exception of nuclear energy there was no legal basis for a centralised energy policy in
Switzerland up to September 1990. An attempt to introduce an adequate article in the Constitution has been
defeated by a popular referendum in 1964. A less stringent version has been accepted by the federal votes
of 23rd September 1990. The new legislation is oriented towards energy savings and will enable the central
government to enact standards on energy consumption equipment. It is expected that the development of
conventional district heating networks, which could in the far future lead to a deployment of nuclear district
heating, will be favoured by the new legislation. On the other hand this legislation will favour concentration
of efforts on alternative, renewable energies.

At the same date two so-called "popular initiatives" aiming at a modification of the Swiss federal
legislation have been voted on in accordance with Swiss laws. The first of them postulating a so-called
"10-year moratorium" for any level of licensing has been accepted by 54.6 per cent to 45.4 per cent. The
second one postulating a total abandonment of nuclear energy has been rejected by 53 per cent to 47 per
cent. Although a moratorium seems less rigid than an abandonment, it will certainly lead to a stagnation and
there are fears that the delays resulting from it could correspond to a de facto abandonment of nuclear
energy. The moratorium will certainly impair on R&D efforts in nuclear energy drastically.

The deployment of SMRs has been evaluated in depth especially for district heating purposes in the
past five years. The actual situation is stagnating due to the aforementioned political decisions although the
political impediments are not particular to SMRs but concern nuclear energy in general.

In the United Kingdom inland consumption of primary fuels peaked in 1973, and again in 1979, at
around 2 879 TWh. It fell to around 2 530 TWh over the period 1982-84 but has grown since, reaching
2 757 TWh in 1988. It is currently growing at 0.6 per cent per annum and is expected to rise further, but
more slowly than GDP. The most marked changes in fuel mix have been the growth in the market shares
of gas and electricity. Electricity currently uses 933 TWh of primary energy (34 per cent of the total). The amount of electricity supplied (which includes imports) has been growing in recent years at 2 per cent per annum; the market share is expected to go on increasing.

The new National Grid Company have projected the need for new generating capacity based on demand forecasts by the distribution companies in Spring 1990 for England and Wales. Such projections allow for the expected improvement in the system load factor, for electricity supplied by independent generators, notably the UKAEA, BNFL and industry, and for the potential for load management with some large consumers. Peak demand in England and Wales is forecast to be around 53 GWe in 1995 and 57 GWe in 2000. This implies a need for new and replacement capacity, in addition to the Sizewell B PWR, of 4.5 GWe by 1995 and 15.5 GWe by 2000. Beyond 2000 electricity demand is much more uncertain. However, with much plant reaching the end of its design life in the first two decades of the next century, the need for replacement capacity is likely to be substantial. In Scotland the present excess of capacity implies that new capacity is not needed at least until the end of the century.

More generally, coal demand can be expected to marginally reduce to the year 2000, especially in electricity generation. Oil consumption may grow slightly but production is expected to decline. No significant growth in the market share of gas in traditional industry and domestic areas appears likely in the short-term. However, the introduction of highly-efficient combined-cycle gas turbine plant for electricity generation is a significant growth area following the UK Government’s decision to allow use of this fuel for this purpose based on availability, environmental and cost grounds. Some 7-10 GW of capacity are currently proposed, some of which could displace the use of coal.

The UK Government’s energy policy generally relies on market forces. In addition, policy initiatives are taken, as in the privatisation of British Gas and the forthcoming privatisation of the Electricity Supply Industry (ESI), which will alter the structure of the ESI and the investment criteria it uses, and will introduce new contractual and regulatory procedures that could influence the generation companies’ attitude to risk. Competition in fuel supply is likely to increase with the acceptance of importing low cost foreign coal and the use of natural gas for electricity generation. This could exert downward pressure on the price of UK coal and suggests that the economic goals for nuclear power will become tougher than at present.

In the United States the total electricity generation in 1988 was 2701 TWh, making 44 per cent of total OECD generation. In the same year the nuclear generation was 527 TWh which is 19.5 per cent of the total. By 2000 the total electricity generation is estimated to grow about 33 per cent to 3579 TWh while the nuclear growth rate remains at about 11 per cent during the period, reaching the generation of 565 TWh.

During the 1980’s, no new power plants (coal or nuclear) were ordered in the U.S., however R&D proceeded on LWRs, HTGRs and LMRs. As a result of the R&D efforts many new concepts and designs are currently available to be deployed in the 1990s and/or the first decade of the 21st century. This has put the U.S. in a position to provide improved LWRs in the 1000 MWe range, more LWRs in the 600 MWe range with passive safety features, innovative HTGRs in the small and medium sizes, and advanced LMRs in the small and medium sizes that can be configured to produce electricity, burn high level waste and/or breed new fuel.

The need for additional energy and electricity will continue due to increasing population and human desires for better standards of living. In the U.S. there are three driving forces calling for additional nuclear plant capacity:

1) the reserve electrical power generating capacity will be gone by the mid-1990s if additional capacity is not provided,

2) nuclear power plants provide a safe clean source of electrical power, therefore they are desirable for delivering additional capacity and/or replacement capacity, and
3) the use of nuclear power will reduce the nation's dependence of foreign oil.

It is expected that the need for nuclear power during the late 1990s will provide the initial market for medium-size LWR plants, followed by deployment of medium-size HTGRs and LMRs by the year 2010.
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SMALL AND MEDIUM REACTORS

I. STATUS AND PROSPECTS

Interest is growing, in OECD countries and elsewhere, in smaller reactors than those now generally in service. Small and medium-sized nuclear reactors (SMRs), generating less than 600 MW, are being designed for three purposes: electric power production, heat generation (both for industrial process heat and space heating) and co-generation of both heat and power.

This study by the OECD Nuclear Energy Agency, drawing on the latest information from manufacturers and potential users, explores the design concepts and status of development of these reactors, their economic rationale and markets, safety aspects, and the further steps needed to facilitate their introduction. Aimed at decision-makers in government and industry, it provides an objective review of SMRs in the context of current concerns over fuel sources and technologies capable of providing reliable, low-cost energy with minimal environmental impact.