Nuclear Development

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Reduction of Capital Costs of Nuclear Power Plants

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REDUCTION OF CAPITAL COSTS OF NUCLEAR POWER PLANTS

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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

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

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

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of 27 OECD Member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

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

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

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

FOREWORD

In order for nuclear power to remain a viable option in the next millennium, the cost of electricity from nuclear power plants must be competitive with alternative sources. Of the three major components of nuclear generation cost – capital, fuel and operation and maintenance – the capital cost component makes up approximately 60% of the total. Therefore, identification of the means and their effectiveness to reduce the capital cost of nuclear plants are very useful for keeping nuclear power competitive. This report represents a synthesis of experience and views of a group of experts from fourteen OECD Member countries, the International Atomic Energy Agency, and the European Commission.

The study was undertaken under the auspices of the Nuclear Energy Agency's Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC). The report reflects the collective view of the participating experts, though not necessarily those of their countries or their parent organisations.

Acknowledgements

The study Secretariat acknowledges the significant contributions of the Expert group assembled for the study. While the Secretariat provided the background papers and recent OECD projections of nuclear installations and electricity generation in OECD countries, members of the Expert group provided all the cost data and reviewed successive drafts of the report. Mr. Andy Yu, of Atomic Energy of Canada Ltd., was the chairman of the group.

TABLE OF CONTENTS

ANNEXES

TABLES

FIGURES

EXECUTIVE SUMMARY

The short-term prospect of nuclear power in the OECD countries is stagnant. However, an economic, environmentally benign, and publicly acceptable option such as nuclear power must be available in the near future, if commitments by many countries of the world for climate change mitigation and to a sustainable future development path is to be materialised. In order to keep nuclear power as a viable alternative in the future energy market, it is important that nuclear power should be competitive with alternative energy sources.

Today's capital investment to construct a nuclear power plant is typically some 60% of generation costs, with fuel costs at 20% and operation and maintenance (O&M) costs the remaining 20%. Since capital investment costs constitute the largest share of the generation cost, identification of the means and assessment of their potential to reduce the capital costs of nuclear plants would be useful for electric utilities to keep nuclear power competitive.

This study was undertaken under the auspices of the Nuclear Energy Agency's Committee for Technical and Economic Studies on Nuclear Energy Development and Fuel Cycle. The report represents a synthesis of experiences and views of experts from OECD countries, identifying the means that have been conceived and demonstrated for the reduction of nuclear power plant capital costs and assessing their potential to achieve the cost reduction goal. The most significant means are:

Increased plant size

In general, as the unit size of a nuclear plant increases, the specific overnight capital cost (US$/kWe) of constructing the plant reduces due to economy of scale. However, it should be noted that the economy of scale could be limited due to the physical limitation to increase dimensions of some systems or components (e.g. reactor core, fuel rods, turbine blades). In addition, the maximum unit size in an electric power grid may also be limited in consideration of grid stability, power demand patterns, spinning reserve, or other specific characteristics of the power system. About 12-13% costs savings are reported by Canada and France as a result of increasing plant size. More detailed information is shown in the table below.

Canada	Plant capacity – MWe	1 × 670	1 × 881	2 × 670	2 × 881
	Specific overnight cost ratio	100	88	86	75
France	Plant capacity – MWe	1 × 300	1 × 650	1 × 1 000	1 × 1 350
	Specific overnight cost ratio	100	67	55	48
	Plant capacity – MWe	2 × 300	2 × 650	2 × 1 000	2 × 1 350
	Specific overnight cost ratio	79	55	46	41
United States	Plant capacity – MWe	1 × 600	1 × 900	1 × 1 300	
	Specific overnight cost ratio	100	79	65	

Source: Cost data from the Expert group members in response to the NEA questionnaire.

Improved construction methods

The construction ease, efficiency and cost effectiveness of a nuclear power plant are key factors in improving quality and reducing the construction period and costs. The OECD Member countries have developed various techniques to enhance the construction quality and to reduce the construction period. The following table summarises potential cost savings arising from important improved construction methods.

Construction method	Potential cost saving % of total cost	Reactor Type/Origin	Comments
Open top access	2.4	CANDU – Canada	15% reduction in construction schedule.
Modularization	1.4 – 4.0	BWR – Sweden CANDU – Canada	Potential reduction in construction schedule.
Slip-forming	Undefined	BWR – Sweden	5% reduction in construction schedule.
Parallel construction	Undefined	N/A	Potential reduction in construction schedule.
Improved cabling, instrumentation and control	1.0	CANDU – Canada	–
Formed pipe elbows and reduction in weld inspection	0.4	CANDU – Canada	Potential reduction in construction schedule due to less disruption and inspection requirements.
Sequencing of contractors	6.0 – 8.0	BWR – Mexico	Potential reduction in construction schedule.

Source: Cost data from the Expert group members in response to the NEA questionnaire.

Reduced construction schedule

Numerous methodologies have been applied to reduce the overall schedule. The following measures have been identified as offering potential for improved programme scheduling:

- Advanced engineering methods.
- Simplified reactor base construction.
- Modularization techniques.
- Prefabrication (reactor liner, primary and secondary shield walls).
- Use of heavy lift cranes.
- Up-front engineering and licensing.
- Effective control of changes, project planning, monitoring, feedback and control.
- Improved manpower development and training.
- Maximise working hours by multiple shift work.
- Strong industrial relations policy.
- Optimised access around site and contractors compound.
- Improving construction interfaces and integration.
- Computerised project management scheduling.
- Contingent procurement.
- Inspection services.
- Streamlining and reduction of documentation including quality assurance and quality control.

Design improvement

Design of a nuclear power plant accounts for about 10% of the total capital costs. Design deficiencies would have significant consequences in the construction and subsequent operation of the plant. Systematic studies on structural and functional design improvements have progressed in OECD countries leading to design improvements facilitating construction. Design improvements have been achieved in the following major areas:

- Plant arrangements.
- Accessibility.
- Simplification of design.
- Simulation and modelling using advanced computers.

Currently there is a great deal of activity by plant designers to create new plants that are less complex and dependent more on passively safe systems. Reliance upon natural phenomena such as natural recirculation of cooling water, radiant heat rejection, and negative temperature coefficients of reactor reactivity is allowing for simpler designs that require less mechanical and electrical hardware. Enhanced computer aided design and engineering also contribute to lowering costs.

The examples of next generation reactors that have been developed in OECD countries are: ABWR, Advanced CANDU, AP600, BWR 90+, EPR, ESBWR, KNGR, SIR, SWR1000, and System 80+.

Improved procurement, organisation and contractual aspects

A key element in project management is the contracting strategy applied in procurement of the plant that depends on the owner’s skills and experience. One strategy is the Turnkey Approach. The owner purchases his facility under a turnkey contract with a single vendor who will supply all the equipment and co-ordinate overall construction work. In this option the bulk of the cost and programme risk is placed with a single contractor or consortium, and interfaces between owner and responsible suppliers are minimised. To cover the cost and programme risk, the contractor or consortium may ask for a higher price for the facility under a turnkey contract, depending on the competitive environment at the time of the bidding process.

The other is Multiple Package Contract Approach (Component Approach). The owner conducts a comprehensive multiple-contract procedure for the supply and installation of several hundred items of equipment. In this option the owner may have to pay more on technical co-ordination, interfaces control and supervision of construction works. However, it could enable the owner to perform a less costly design, to do a direct cost control and to minimise paying contingency margins to the main contractor.

Split Package Contract (Island Approach) is between these two extremes, in which the number of packages may vary from a handful to several dozen, aimed at reducing certain interfaces without substantially increasing the contractors’ cost premium. Utilities’ engineering resources is an important factor to separate the packages in this option.

It is impossible to assert that one particular solution is always preferable to the others and will in all cases result in lower cost than the other solutions. The optimal balance for the cost reduction and project management has to be found and may vary depending on the country’s nuclear infrastructure and engineering resources of owners. What can be said is that by the very fact of there being several solutions, these can compete with each other and in this way lead to capital cost reduction according to how many plants will be built in series.

Standardisation and construction in series

Perhaps the greatest potential for capital cost reduction lies in utilising standardised plant designs and constructing similarly designed plants in series. The benefits that derive from standardisation relate mainly to the consolidation of plant safety and the avoidance of much first-of-a-kind effort. The safety impact arises in the main from the adoption of proven approaches and the wider applicability of operational feedback. The expenditure of first-of-a-kind effort is avoided by standardising the design, manufacturing, construction, licensing and operation approaches developed for the first project.

The construction of standardised units in series lowers the average investment costs:

- By the breakdown of fixed costs over all the units of the programme (programme effect).
- By productivity gains, made possible both in the shop for the fabrication of equipment and in the design office for the processing of documents specific to each site, as well as for the construction of buildings, erection and tests (productivity effect).

Costs savings obtained by standardisation and construction in series are reported to range from 15% to 40% depending on country and number of series. The first-of-a-kind (FOAK) cost which is a fixed cost of the programme, corresponds to the costs of the following items:

- Functional studies.
- Drawing up of technical specifications for ordering of equipment.
- General layout of the power-block.
- Detailed design of civil engineering of standard buildings.
- Detailed design of equipment.
- Detailed design for piping and cabling.
- Drawing up of testing and commissioning procedures.
- Drawing up of operating documents.
- Safety studies.
- Qualification of equipment and facilities.

Multiple unit construction

Construction of several units on the same site provides opportunities for capital cost reduction, e.g. in:

- Siting.
- Licensing costs.
- Site labour.
- Common facilities.

In addition to the obvious sharing of the site land cost, site-licensing costs can also be shared among multiple units. During the construction phase, considerable efficiencies and associated savings can be gained from phased construction and rolling the various craft teams from one unit to the next.

In addition, by construction repetition, there is craft labour learning that reduces the time to perform a given task and correspondingly reduces both construction labour cost and schedule.

Multiple-unit plants can obtain significant cost reduction by using common facilities such as: access roads, temporary work site buildings, administration and maintenance buildings, warehouses, auxiliary systems (demineralised water, auxiliary steam, compressed air, emergency power supply, gas storage, etc.), guardhouse, radwaste building and water structures.

Nearly 90% of the world's nuclear power plants are constructed as multiple-unit plants. Multiple unit construction is reported to lead to a reduction of some 15% of capital costs.

Regulation and policy measures

The US experiences after the TMI accident provide us with a useful illustration of the impacts of regulatory requirements on the plant design, on the duration of construction, and finally, on the capital costs.

During the last decade, the US nuclear industry has undergone major managerial and operational process transformations, including various regulatory aspects. There is a broad support within the US industry and the NRC to move toward a risk-informed, performance-based regulatory process for the current power plants. In a risk-informed, performance-based approach, the regulator would establish basic requirements and set overall performance goals. Plant management would then decide how best to meet the stated goals. "Performance based regulations" have potential to reduce costs in the in-service inspection and maintenance works for the power plants in operation.

Today's nuclear power plants in the United States were licensed under a two step system that dates back to the 1950s. The licensing process for the future nuclear power plants ensures that all major issues – design, safety, siting and public concerns – will be settled before starting to build a nuclear power plant. Under the new process, a combined construction permit/operating license can be issued if all applicable regulations are met. In many cases, longer construction times resulted from changing regulatory requirements; specifically, the plants constructed in 1980s had to make extensive and costly design and equipment changes during construction. The reforms in nuclear plant licensing will reduce the likelihood of that situation being repeated in the future by creating a stable, predictable process that ensures meaningful public participation at every step.

The Utility Requirements Document (URD) provides the first level of standardisation of future families of ALWRs and specifies the technical and economic requirements (for both a simplified evolutionary plant and a midsize plant) incorporating passive safety features. The URD contains more than 20 000 detailed requirements for ALWR designs.

All the major Western Europe utilities are involved to produce a joint utility requirement document (EUR) aimed at the LWR nuclear power plants to be built in Western Europe beyond the turn of the next century [1]. The safety approaches, targets and criteria of the future plants, their design conditions, their performance targets, their systems and equipment specifications as well, are being harmonised under the leadership of the electricity producers. Benefits are expected in two fields: strengthening of nuclear energy competitiveness and improvement of public and authorities acceptance.

In conclusion, the report states that there are a number of potential means to reduce the capital costs of nuclear power plants. Capital cost reductions will be significant if the programmes combine several of the cost reduction measures identified in this report. It should be noted that many of these measures are already applied by some countries, but in most cases not all.

INTRODUCTION

Overview of the study

Objectives and scope

This study was recommended by the Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) as part of its 1997-1998 programme of work, and was endorsed by the NEA Steering Committee. The aims are both to identify means used or conceived for the reduction of nuclear power plant capital costs and to assess their efficiency when feasible. The present report builds upon findings from a previous study carried out in 1988-1990.

The main objectives of the study are:

- To analyse in-depth capital costs of nuclear power plants in NEA Member countries.
- To identify, in as much detail as possible, the various means to reduce capital costs.
- To estimate the capital cost reductions obtained by the different means identified.

This study provides an overview of different elements constituting capital costs and an in-depth analysis of these features. It focuses on identifying various cost reduction means and analysing their effects on capital costs. The study also investigates technical means used in advanced reactor concepts to reduce capital costs.

The study covers:

- Review of nuclear power plant capital costs in NEA Member countries, covering units in operation, under construction and advanced reactors under development.
- Analysis of the main elements that constitute capital costs of nuclear power plants.
- Quantitative analysis of the various cost reduction means identified in the 1988 study.
- Identification of enhanced engineering, design, procurement and construction methods employed to reduce nuclear power plant capital costs.
- Identification of technical means used in advanced reactor concepts (e.g. AP600 in the United States, EPR and SIR in Europe, ABWR in Japan, advanced CANDU in Canada, KNGR in the Republic of Korea) to reduce capital costs.
- Identification of policy measures (e.g. nuclear power programme management, mature regulation, streamlined licensing procedures) that could contribute to the reduction of capital costs.

The scope of the project does not cover fuel cycle or O&M costs since its objective is to analyse capital costs. However, it is acknowledged that capital cost reduction methods should not ignore potential increases in O&M costs that would jeopardise the overall benefits in terms of electricity generation costs. Capital cost reduction methods should not only maintain but also enhance the technical and safety performance of nuclear units.

Working method

This study was carried out by an Ad Hoc Expert group including representatives from governments, utilities, research institutes, architect engineers, and nuclear reactor vendors. Belgium, Canada, the Czech Republic, Finland, France, Germany, Hungary, Japan, Mexico, the Netherlands, the Republic of Korea, Sweden, Turkey and the United Kingdom were represented in the group as well as the International Atomic Energy Agency (IAEA) and the European Commission (EC). The members of the Expert group are listed in Annex 1.

A questionnaire, using a cost breakdown structure, was circulated to Member countries in order to collect the following information:

- Capital cost data of nuclear power plants.
- Experience in reducing capital costs.
- Economics of next generation reactors.
- Regulatory and policy measures to reduce capital costs.

Responses to the questionnaire were received from the Expert group members and from the United States (not represented in the group). They provided capital cost data and capital cost reduction information. Germany, the Republic of Korea, Canada, the United Kingdom and the IAEA provided information regarding the economics of the next generation reactors. Mexico provided financial information on an advanced boiling water reactor (ABWR). Moreover, a number of participants presented information on capital costs in their respective countries at the Expert group meetings. The tables and figures included in the report are based on this information, except where otherwise specified.

Previous study

In 1988, the Nuclear Energy Agency set up an Expert group under the auspices of the NDC to carry out a study on the "Means to Reduce the Capital Cost of Nuclear Power Stations" [2]. The main objective of the study was to investigate to what extent capital costs of nuclear power could be reduced to allow further assessments on whether nuclear power could keep its competitive margin as compared with fossil fuels in spite of the significant drop in fossil fuel prices.

Eleven Member countries, the EU and the IAEA participated in that study and shared their experiences, views and knowledge regarding various approaches to the reduction of capital costs of nuclear power plants. A number of cost reduction measures were identified and described in a report issued in 1990 as a working document made available to experts. The most significant means to reduce nuclear power plant capital costs identified by the study were: increasing plant size, constructing multiple unit plants, standardisation and replication, design improvements, construction method improvements, reducing construction schedule, and performance improvements. However, the report fell short of providing quantitative analysis on the efficiency of the various measures identified.

Recent developments

In OECD Member countries there have been very few orders for new nuclear power plants since the early 1990s, but nuclear power is still a major energy source. At present, nuclear generation covers 25% of total electricity consumption in OECD countries and 17% of the world's electricity. Increasingly, the fast-growing countries in Asia are expected to turn to nuclear generation in order to meet their high electricity demand.

A revival of nuclear power programmes in a number of OECD countries may be expected in view of environmental protection and sustainable development goals. Nuclear electricity generation is a carbon-free energy source and has been identified as a cost-effective means to reduce greenhouse gas emissions from the energy sector. Current nuclear electricity generation avoids the emission of some 2.3 billion tonnes of carbon dioxide, equivalent to approximately 7 to 8% of global CO_2 emission.

Electricity market liberalisation is already an established fact in several countries and there is a trend to adopt it in many other countries. Liberalisation of the electricity sector might have significant impact on the future of nuclear power, which is traditionally centralised and under state supervision. The essential aim of market liberalisation is to improve overall economic efficiency. Consequently, the competitiveness of nuclear power within a deregulated power industry would be of great interest.

The economics of nuclear power have already been demonstrated in several countries and further efforts are under way. Over the last decade progress has been made on reactor concepts and designs, i.e. next generation reactors such as AP600, System80+, EPR, ABWR, BWR90, SIR, Advanced CANDU, and KNGR. The primary aim of these next generation reactors is to reduce generation cost. To achieve this purpose they must have lower investment cost which accounts for the largest fraction of the generation cost. To date it is not clear to what extent this has been achieved.

In most OECD Member countries except Japan, the Republic of Korea, Hungary and Turkey, there is no definite programme on further construction of nuclear power plants. Even though in some cases, decisions not to invest in nuclear power plants were made for reasons other than economic, it is clear that there will be incentive for more nuclear generation if the economics can be demonstrated unequivocally. Consequently, in most Member countries where decisions on further construction of nuclear power are pending, there is strong competition from alternative sources. It is therefore important to be assured that the capital cost of a nuclear power plant (the main cost component of nuclear electricity generation) can be reduced considerably.

Other relevant studies

In addition to the study on the "Means to Reduce the Capital Costs of Nuclear Power Plants in 1988-1990" [2], the NEA has recently completed and published a number of reports on the economics of nuclear power, including reports covering topics such as: the projected costs of generating electricity [3], the economics of the nuclear fuel cycle [4], the costs of high-level waste disposal [5], the costs of low-level waste repositories [6], and the costs of decommissioning nuclear facilities [7].

Nuclear power status and economics

Status of nuclear power plants

At the end of 1997, 358 reactors were connected to the grid in sixteen OECD countries, representing an installed nuclear capacity of 300.9 GWe (see Table 1). These nuclear power plants generated 2 006.6 TWh in 1997, corresponding to about 24.3% of the total electricity production in OECD countries. In recent years, nuclear power programmes are stagnant in most OECD countries. Several countries have even decided to exclude, temporarily or indefinitely, new nuclear power plants in their power system expansion plans. In 1997, ten reactors with the capacity of 9.4 GWe were under construction in four OECD countries – the Czech Republic, France, Japan and the Republic of Korea – and only six new nuclear units, four BWRs (4.7 GWe) in Japan and two PWRs (2.0 GWe) in the Republic of Korea, were firmly committed.

Tables 2 and 3 show NEA's latest published statistics concerning actual and estimated nuclear electricity generation and capacity respectively, up to 2010 [8]. The nuclear generating capacity in OECD countries is expected to grow from 300.9 GWe in 1997 to 325.9 GWe in 2010. However, the nuclear share of total electricity capacity and generation from 1997 to 2010 is expected to decrease from 16.0 to 14.3 and from 24.3 to 22.0% respectively.

Table 1. **Status of nuclear power plants (as of 31 December 1997)**

COUNTRY	Connected to the grid		Under construction		Firmly committed		Planned	
	Units	Capacity	Units	Capacity	Units	Capacity	Units	Capacity
Belgium	7	5.7	0	0.0	0	0.0	0	0.0
Canada	21	15.5	0	0.0	0	0.0	0	0.0
Czech Republic	4	1.6	2	1.8	0	0.0	0	0.0
Finland	4	2.4	0	0.0	0	0.0	0	0.0
France	59	62.9	1	1.4	0	0.0	0	0.0
Germany	19	21.1	0	0.0	0	0.0	0	0.0
Hungary	4	1.8	0	0.0	0	0.0	1	0.6
Japan (a)	54	43.6	1	0.8	4	4.7	17 (b)	18.4 (b)
Korea (Rep. of)	12	10.3	6	5.4	2	2.0	8	9.2
Mexico	2	1.3	0	0.0	0	0.0	0	0.0
Netherlands	1	0.5	0	0.0	0	0.0	0	0.0
Spain	9	7.3	0	0.0	0	0.0	0	0.0
Sweden	12	10.1	0	0.0	0	0.0	0	0.0
Switzerland	5	3.1	0	0.0	0	0.0	0	0.0
Turkey	0	0.0	0	0.0	0	0.0	10 (c)	6.5 (c)
United Kingdom	35	12.7	0	0.0	0	0.0	0	0.0
United States	110	101.0	0	0.0	0	0.0	0	0.0
TOTAL	**358**	**300.9**	**10**	**9.4**	**6**	**6.7**	**36**	**34.7**

(a) Gross data converted to net by the Secretariat.

(b) Balancing item for consistency between Secretariat's capacity projections and other columns of this table.

(c) Turkey is planning to build 10 HWR or 5 PWR with a total capacity of 6.5 GWe.

Table 2. **Estimates of total and nuclear electricity generation**

Net TWh

COUNTRY	1997 (Actual)			2000		
	Total	Nuclear	%	Total	Nuclear	%
Australia (b)	172.6 (f)	0.0	0.0	190.9	0.0	0.0
Austria	55.2 (f)	0.0	0.0	55.9	0.0	0.0
Belgium	75.0 (f)	45.1 (f)	60.1	71.6	45.2	63.1
Canada	550.0 (f)	77.9 (f)	14.2	557.0	100.0	18.0
Czech Republic	60.0	11.7	19.5	65.3 (a)	21.6 (a)	33.1
Denmark	50.4 (a)	0.0	0.0	34.7 (a)	0.0	0.0
Finland	65.8	20.0	30.4	72.6	21.0	28.9
France	481.0 (f)	376.0 (f)	78.2	485.0	380.0	78.4
Germany	450.3 (f)	160.1 (f)	35.6	467.0	160.0	34.3
Greece	40.1 (f)	0.0	0.0	46.8	0.0	0.0
Hungary	35.1	14.0	39.9	38.5	14.2	36.9
Iceland	5.6	0.0	0.0	7.7	0.0	0.0
Ireland	18.9 (f)	0.0	0.0	22.3	0.0	0.0
Italy	240.4	0.0	0.0	271.2	0.0	0.0
Japan (b,c,e)	879.6 (a)	288.4 (a)	32.8	917.6	292.6	31.9
Korea (Rep. of)	219.0 (f)	77.1 (f)	35.2	267.8	100.5	37.5
Luxembourg	1.2	0.0	0.0	1.9 (a)	0.0	0.0
Mexico	161.4	10.5	6.5	173.0	11.0	6.3
Netherlands	83.3	2.4	2.9	88.4	3.4	3.8
New Zealand	35.2 (f)	0.0	0.0	36.2	0.0	0.0
Norway	111.6	0.0	0.0	115.1	0.0	0.0
Portugal	33.6	0.0	0.0	38.2	0.0	0.0
Spain	181.2 (f)	53.1 (f)	29.3	164.9 (a)	53.1 (a)	32.2
Sweden	144.9 (f)	67.0 (f)	46.2	145.1 (a)	67.7 (a)	46.7
Switzerland	60.5	23.9	39.5	60.0	24.0	40.0
Turkey	111.2	0.0	0.0	147.8	0.0	0.0
United Kingdom	325.1 (f)	89.4 (f)	27.5	340.0 (a)	87.0 (a)	25.6
United States	3 597.0 (f)	690.0 (f)	19.2	3 711.0	690.0	18.6
TOTAL	**8 245.1**	**2 006.6**	**24.3**	**8 593.5**	**2 071.3**	**24.1**
OECD America	4 308.4	778.4	18.1	4 441.0	801.0	18.0
OECD Europe	2 630.4	862.7	32.8	2 740.0	877.2	32.0
OECD Pacific	1 306.4	365.5	28.0	1 412.5	393.1	27.8

(a) Secretariat estimate.
(b) For fiscal year (July-June for Australia, April-March for Japan).
(c) Gross data converted to net by Secretariat.
(d) Including electricity generated by the user (auto production) unless otherwise stated.
(e) Excluding electricity generated by the user (auto production).
(f) Provisional data.

Table 2. **Estimates of total and nuclear electricity generation (cont'd)**

Net TWh

COUNTRY	2005			2010		
	Total	Nuclear	%	Total	Nuclear	%
Australia (b)	210.6	0.0	0.0	223.8	0.0	0.0
Austria	60.4	0.0	0.0	66.8	0.0	0.0
Belgium	75.2	45.2	60.1	80.4	45.2	56.2
Canada	583.0	101.0	17.3	600.0	97.0	16.2
Czech Republic	76.3 (a)	24.0 (a)	31.5	83.9 (a)	24.0 (a)	28.6
Denmark	35.6 (a)	0.0	0.0	35.6 (a)	0.0	0.0
Finland	77.0	21.0	27.3	85.0	21.0	24.7
France	515.0	400.0	77.7	540.0	410.0	75.9
Germany	483.0	160.0	33.1	485.0	160.0	33.0
Greece	54.0	0.0	0.0	63.3	0.0	0.0
Hungary	41.0	14.2	34.6	43.0	16.2	37.7
Iceland	8.0	0.0	0.0	8.3	0.0	0.0
Ireland	27.5	0.0	0.0	32.9	0.0	0.0
Italy	311.0	0.0	0.0	341.0	0.0	0.0
Japan (b,c,e)	1 008.3 (a)	373.4 (a)	37.0	1 099.0	454.1	41.3
Korea (Rep. of)	341.7	133.0	38.9	408.1	186.0	45.6
Luxembourg	1.9 (a)	0.0	0.0	1.9 (a)	0.0	0.0
Mexico	198.5	11.0	5.5	242.9	11.0	4.5
Netherlands	97.2	0.0	0.0	106.8	0.0	0.0
New Zealand	39.7	0.0	0.0	43.3	0.0	0.0
Norway	119.2	0.0	0.0	128.0	0.0	0.0
Portugal	43.5	0.0	0.0	50.8	0.0	0.0
Spain	167.0 (a)	53.1 (a)	31.8	169.4 (a)	53.1 (a)	31.3
Sweden	144.5	63.5	43.9	148.3	63.5	42.8
Switzerland	61.0	24.0	39.3	61.8	24.0	38.8
Turkey	251.9	9.1	3.6	351.5	18.2	5.2
United Kingdom	372.0 (a)	69.0 (a)	18.5	389.0 (a)	51.0 (a)	13.1
United States	4 030.0	652.0	16.2	4 329.0	610.0	14.1
TOTAL	**9 434.0**	**2 153.5**	**22.8**	**10 218.8**	**2 244.3**	**22.0**
OECD America	4 811.5	764.0	15.9	5 171.9	718.0	13.9
OECD Europe	3 022.2	883.1	29.2	3 272.7	886.2	27.1
OECD Pacific	1 600.3	506.4	31.6	1 774.2	640.1	36.1

(a) Secretariat estimate.
(b) For fiscal year (July-June for Australia, April-March for Japan).
(c) Gross data converted to net by Secretariat.
(d) Including electricity generated by the user (auto production) unless stated otherwise.
(e) Excluding electricity generated by the user (auto production).
(f) Provisional data.

Table 3. **Estimates of total and nuclear electricity capacity**

Net GWe

COUNTRY	1997 (Actual)			2000		
	Total	Nuclear	%	Total	Nuclear	%
Australia (b)	38.5 (f)	0.0	0.0	41.5	0.0	0.0
Austria	17.5 (f)	0.0	0.0	18.1	0.0	0.0
Belgium	15.2 (a)	5.7	37.5	15.4	5.7	37.0
Canada	111.9 (f)	15.5 (f)	13.9	117.0	16.0	13.7
Czech Republic	14.9	1.6	10.7	15.3	2.5	16.4
Denmark	9.0 (a)	0.0	0.0	9.6 (a)	0.0	0.0
Finland	15.5	2.4	15.5	16.7	2.7	15.6
France	114.5 (f)	62.9 (f)	54.9	112.8	63.1	55.9
Germany	101.2 (f)	21.1 (f)	20.8	103.1	21.1	20.5
Greece	9.9 (f)	0.0	0.0	11.3	0.0	0.0
Hungary	7.5	1.8	24.5	8.0	1.8	23.0
Iceland	1.0	0.0	0.0	1.3	0.0	0.0
Ireland	4.3 (f)	0.0	0.0	4.7	0.0	0.0
Italy	70.5	0.0	0.0	73.9	0.0	0.0
Japan	213.5 (a)	43.6 (f)	20.4	234.5	43.7	18.6
Korea (Rep. of)	41.5 (f)	10.3 (f)	24.8	52.7	13.7	26.0
Luxembourg	1.3	0.0	0.0	1.4 (a)	0.0	0.0
Mexico	34.8	1.3	3.8	38.1	1.4	3.6
Netherlands	19.9	0.5	2.4	20.5	0.5	2.3
New Zealand	7.6 (f)	0.0	0.0	7.8	0.0	0.0
Norway	27.8	0.0	0.0	27.9	0.0	0.0
Portugal	9.4	0.0	0.0	10.6	0.0	0.0
Spain	48.5 (f)	7.3 (f)	15.1	47.8 (a)	7.3	15.3
Sweden	33.7	10.1	30.0	34.8 (a)	9.5	27.3
Switzerland	15.8	3.1	19.4	16.0	3.2	20.0
Turkey	22.0	0.0	0.0	28.1	0.0	0.0
United Kingdom	73.6	12.7	17.3	81.0 (a)	12.1 (a)	14.9
United States	799.0 (f)	101.0 (f)	12.6	843.0	99.0	11.7
TOTAL	**1 879.7**	**300.9**	**16.0**	**1 993.0**	**303.2**	**15.2**
OECD America	945.7	117.8	12.5	998.1	116.4	11.7
OECD Europe	632.9	129.2	20.4	658.3	129.4	19.7
OECD Pacific	301.1	53.9	17.9	336.5	57.4	17.1

(a) Secretariat estimate.
(b) For fiscal year (July-June for Australia, April-March for Japan).
(c) Gross data converted to net by Secretariat.
(d) Including electricity generated by the user (auto production) unless otherwise stated.
(e) Excluding electricity generated by the user (auto production).
(f) Provisional data.

Table 3. **Estimates of total and nuclear electricity capacity (cont'd)**

Net GWe

COUNTRY	2005			2010		
	Total	Nuclear	%	Total	Nuclear	%
Australia (b)	46.0	0.0	0.0	48.4	0.0	0.0
Austria	18.4	0.0	0.0	18.7	0.0	0.0
Belgium	15.7	5.7	36.3	17.8 (a)	5.7	32.0
Canada	118.0	16.0	13.6	119.0	15.0	12.6
Czech Republic	17.2	3.4	19.9	17.9	3.4	19.1
Denmark	8.5 (a)	0.0	0.0	8.5 (a)	0.0	0.0
Finland	16.9	2.7	15.4	17.0	2.7	15.3
France	117.0	62.9	53.8	119.0	62.9	52.9
Germany	105.0	21.0	20.0	106.0	21.0	19.8
Greece	13.0	0.0	0.0	15.2	0.0	0.0
Hungary	8.4	1.8	21.9	9.1	2.4	26.8
Iceland	1.3	0.0	0.0	1.3	0.0	0.0
Ireland	5.7	0.0	0.0	6.8	0.0	0.0
Italy	77.4	0.0	0.0	81.3	0.0	0.0
Japan	257.0 (a)	55.2 (a)	21.5	279.4	67.2	24.1
Korea (Rep. of)	67.9	18.7	27.5	79.5	26.3	33.1
Luxembourg	0.5	0.0	0.0	1.4 (a)	0.0	0.0
Mexico	45.4	1.4	3.0	58.8	1.4	2.3
Netherlands	21.8	0.0	0.0	23.2	0.0	0.0
New Zealand	8.2	0.0	0.0	8.6	0.0	0.0
Norway	30.3	0.0	0.0	33.1	0.0	0.0
Portugal	11.3	0.0	0.0	12.5	0.0	0.0
Spain	48.2 (a)	7.3	15.1	48.7 (a)	7.3	15.0
Sweden	30.5 (a)	8.9	29.2	30.5 (a)	8.9	29.2
Switzerland	17.0	3.2	18.8	17.7	3.2	18.1
Turkey	46.9	1.3	2.8	65.7	2.6	4.0
United Kingdom	85.0 (a)	9.3 (a)	10.9	85.0 (a)	7.0 (a)	8.2
United States	909.0	95.0	10.5	955.0	89.0	9.3
TOTAL	**2 147.5**	**313.7**	**14.6**	**2 285.1**	**325.9**	**14.3**
OECD America	1 072.4	112.4	10.5	1 132.8	105.4	9.3
OECD Europe	696.0	127.5	18.3	736.4	127.1	17.3
OECD Pacific	379.1	73.9	19.5	415.9	93.5	22.5

(a) Secretariat estimate.

(b) For fiscal year (July-June for Australia, April-March for Japan).

(c) Gross data converted to net by Secretariat.

(d) Including electricity generated by the user (auto production) unless stated otherwise.

(e) Excluding electricity generated by the user (auto production).

(f) Provisional data.

Nuclear power economics

Since 1983, the OECD has published a series of reports on projected costs of generating electricity [2]. The 1989, 1992 and 1998 updates have been jointly undertaken by the NEA and the IEA in co-operation with the IAEA and UNIPEDE. These three reports include data from non-OECD countries (Brazil, China, India, Romania and Russia in the 1998 update). The 1992 and 1998 updates provide cost estimates for nuclear, coal and gas power plants and some plants based on renewable energy sources as well as combined heat and power (CHP) units, while earlier studies dealt only with nuclear and coal power plants. The main objective of these studies is to compare generating costs for different options in each country.

The 1998 update focuses on base load technologies and plant types that could be commissioned in participating countries by 2005-2010 and for which they have developed cost estimates. The data given below refer to the 1998 update. All costs are expressed in US Dollar of 1 July 1996.

The overnight construction costs vary from one country to the other. Some countries provided an average figure for a type of plant while others mentioned several figures related to specific plants. The following are the cost ranges reported, taking into account the average value of each technology whenever a country released several cost estimates for the same technology:

	Overnight construction cost (US$/kWe of 1 July 1996)
Nuclear	1 277 to 2 521
Coal	772 to 2 561
Gas	402 to 1 640

The wide ranges of values may be explained by design changes to match specific regulatory and siting requirements, plant size, single or multiple-unit site, series effect, and exchange rate volatility.

Total capital investment costs including overnight costs, contingencies, interest during construction (IDC) and decommissioning costs are as follows:

	5% discount rate (US$/kWe of 1 July 1996)	**10% discount rate (US$/kWe of 1 July 1996)**
Nuclear	1 718 to 2 848	2 098 to 3 146
Coal	966 to 2 739	1 048 to 2 930
Gas	440 to 1 703	453 to 1 771

Total generation costs calculated using the levelised lifetime cost method, expressed in US$, vary widely from country to country for the same technology, due partly to the impact of exchange rates.

	Total levelised generation cost (US mills*/kWh of 1 July 1996)	
	at 5% discount rate	**at 10% discount rate**
Nuclear	25 to 57	40 to 80
Coal	25 to 56	35 to 76
Gas	24 to 79	24 to 84

*US mill = 1×10^{-3} US$

The main common assumptions are:

Plant commissioning date : 2005
Economic lifetime : 40 years
Load factor : 75% at equilibrium

The respective shares of investment in the total levelised generation costs at 5 and 10% discount rate are indicated below:

Share of investments in total levelised generation costs (%)					
Nuclear (LWR)		**Coal**		**Gas**	
at 5%	at 10%	at 5%	at 10%	at 5%	at 10%
43 to 70	60 to 80	26 to 48	38 to 62	13 to 32	21 to 42

As shown in the above table, investment accounts for the largest share in total levelised generation costs for nuclear power plants. Therefore, reducing capital costs is the key issue in enhancing the competitiveness of nuclear power as compared to fossil-fuelled power plants. The report shows that the nuclear option is more competitive in countries engaged in nuclear programmes that combine the advantages of series, site and productivity effects.

While generation costs have decreased for all technologies since 1986, according to the results of successive studies in the OECD series, nuclear generation costs decreased less significantly than coal and gas generation costs. The drastic drop in generation costs for coal and gas stems from lower fuel costs and technological progress, in particular higher plant efficiency and lower investment costs. In order to maintain the competitiveness of nuclear power as opposed to fossil fuels and, in the longer term, renewable sources, significant technological progress is needed to reduce capital costs and increase efficiency.

The competitive margin of nuclear power has been reduced steadily in most countries over the past decade or so due to technological progress (in particular regarding combined cycle gas turbines) and to lower fossil fuel prices in the international markets. However, it is unlikely that technological progress could continue at the same rate as far as gas and coal fired power plants are concerned, and fossil fuel prices might rise as demand increases. Nevertheless, nuclear power will remain competitive only if significant cost reductions are achieved in investments, through standardisation, series orders, and improved reactor concepts and designs. Cost reductions in nuclear power plant operation and maintenance and fuel cycle will also help; however, such aspects are not addressed in this report.

Capital cost data

Capital cost breakdown structure

Total capital costs are the overall cost of constructing a power plant, leading from initial site investigation to commercial operation. In addition to the base costs, which consist of direct and indirect costs, other costs such as supplementary costs, financial costs, and owner’s costs are also included. Direct costs include those related to equipment, structures, installation and material; indirect costs encompass design, engineering and project management services; supplementary costs include such items as spare parts, contingencies and insurance; financial costs include escalation and interest during construction. Owner's costs include the owner's investment and services, and financial costs where applicable. The overnight costs consist of the direct costs, the indirect costs, the supplementary costs, and the owner's costs, except the financial costs that are time dependent.

For the comparison of capital costs of nuclear power plants, one should be aware that differences in capital costs are not only caused by differences in countries, contract approaches and project management, but also in exchange rates, details of the design, work force productivity as well as market opportunities.

It is observed that the cost breakdown structure of a nuclear power plant varies from country to country. The cost breakdown structure mainly depends on the contract approach as well as on the project management system. It is also affected by the purpose of cost calculation, and sometimes it relates to the computer system that is used for project management. In turnkey contract or island approach, vendors are not willing to provide the customer with the breakdown of their scope of supply, nor do they want to release detailed cost information on their scope. On the other hand, the component base approach is more open than other contract approaches in the context of cost data availability.

International organisations have also developed a cost breakdown structure for the use of cost control and bid evaluation [9]. The IAEA has designed a uniform system of accounts to report plant capital investment costs, fuel costs, and O&M costs for nuclear power plants. The structure of the IAEA "nuclear power plant total capital investment costs account system" is a good example of capital cost breakdown structure.

The Expert group drew up an "overnight cost breakdown structure" for this study, which could be applicable to all types of nuclear reactors and to any type of contractual approach.

The overnight cost breakdown structure is given below in Table 4.

Table 4. **Overnight cost breakdown structure**

Direct costs	1.1	Land and land rights
	1.2	Reactor plant equipment
	1.3	Turbine-generator plant equipment
	1.4	Electrical and I&C plant equipment
	1.5	Water intake, and discharge, and heat rejection
	1.6	Miscellaneous plant equipment
	1.7	Construction at the plant site
Indirect costs	2.1	Design and engineering services
	2.2	Project management services
	2.3	Commissioning
Other costs	3.1	Training and technology transfer
	3.2	Taxes and insurance
	3.3	Transportation
	3.4	Owner's costs
	3.5	Spare parts
	3.6	Contingencies
Overnight costs	**Direct costs + Indirect costs + Other costs**	

Each cost element in Table 4 may be described as follows:

1.1 Land and land rights

Costs of land purchase and all compensation related to land rights.

1.2 Reactor plant equipment

Costs of nuclear steam supply systems, and related systems or auxiliary equipment. This includes the nuclear fuel handling and storage systems. The costs of maintenance and lifting equipment in the reactor plant are included in this account.

1.3 Turbine-generator plant equipment

Costs of turbines, generators and condensers, together with related systems and auxiliary equipment. This includes the feed-water, the main steam systems and other secondary side systems. The costs of maintenance and lifting equipment in the turbine-generator plant are included in this account.

1.4 Electrical and I&C plant equipment

Costs of all electrical power equipment from generator terminals to the main transformer, all electrical equipment required for the distribution of power to the station loads and all equipment associated with conventional and nuclear instrumentation and control. This includes the reactor protection system, the radiation monitoring system, the main control room and the computer system and the lighting system in the plant.

1.5 Water intake, discharge and heat rejection

Costs of the water intake and discharge structures, including conduits. This includes circulating water systems, pump house, intake and discharge structures, common facilities and cooling tower.

1.6 Miscellaneous plant equipment

Costs of HVAC systems, fire protection systems service, air and water service systems, communication equipment, shop and laboratory equipment, dining and cleaning equipment. This covers all equipment and systems not included in other accounts.

1.7 Construction at the plants site

Installation costs of all mechanical, electrical and I&C equipment, which are not included in the equipment supply packages. Costs of civil works for all buildings and structures at the plant site, including the radioactive waste buildings, the service building, the water treatment building and the administration building. This also includes site excavation, construction of the cooling water reservoir, the security installations, sanitary installations, yard drainage and sewer systems, the underground piping and conduits, landscaping and harbour. Costs of labour, construction facilities, tools and materials necessary for construction and installation are included in this account.

2.1 Design and engineering services

Costs of design and engineering activities, for components, systems, buildings and structures performed by the equipment suppliers and A/E at their home offices and field offices. It includes mainly basic design, detailed design, design review, procurement and interface engineering.

2.2 Project management services

Costs of project management services performed by the equipment suppliers and Architect/Engineer (A/E) at their home offices and field offices. The services are mainly cost control, schedule control, quality control, licensing and technical support to the owner. This includes costs for site supervision of construction work.

2.3 Commissioning

Costs of commissioning services performed by the equipment suppliers and A/E, complete with relevant documentation. This includes the costs of maintenance work during commissioning, costs of commissioning labour, commissioning materials, consumables, tools and equipment necessary for the execution of commissioning work not covered in the equipment supply contracts. The costs of electrical energy, fuel, water, gas, and other utilities up to the commercial operation date are also included in this account.

3.1 Training and technology transfer

Costs of staff training and technology transfer provided by the equipment suppliers and A/E.

3.2 Taxes and insurance

Allowance for all taxes and insurance premiums.

3.3 Transportation

Costs for transport of equipment and materials, including transportation insurance.

3.4 Owner’s costs

Costs of installations, services and fees incurred by the owner, which are not included in the other accounts. This includes the costs for the construction of camps, garages, canteens, information centres, workshops, warehouses, etc. This also includes the costs of personnel, including salaries, licensing, storage of equipment, tools and instruments for workshops.

3.5 Spare parts

Costs for spare parts and consumables, at the date of the commercial operation, provided by the equipment suppliers.

3.6 Contingencies

Allowances for all unexpected costs for unexpected events up to the date of commercial operation that are not in the supplier’s scope. This may include costs of repair, reassembling, reinstallation and other reworks.

NB: In many equipment supply contracts, some parts of items 2.1-2.3 are included. If they can not be separated, they must be noted accordingly to avoid redundancy or omission.

Capital cost data collected

The Expert group found that financial costs are so country, time, and project specific that a generic evaluation of financial costs is meaningless. Therefore, the group decided to concentrate only on the overnight cost (excluding escalation and interest during construction, which can be calculated for any specific country, schedule and plant type). The Expert group agreed that there would be concerns about the sensitivity of publishing the detailed cost data and the group understood that it would be difficult and erroneous to restate the actual capital costs of historical projects in today's currency values using price escalators. The project structure and the scope of supplies vary according to the individual case, and sometimes it is not useful to break down the costs in a consistent manner due to the differences in the supply and financing aspects of the contracts for the power plants. Consequently, the group reinforced observations from other published NEA studies that while intra-country cost comparison may be useful to some extent, inter-country cost comparison should not be encouraged. However, for completeness, some cost data are reported for reference only.

In the 1990 NEA report it was noted that the direct cost was the largest portion of the total capital costs, which represented a range between 45 and 90%, dependent on the reactor type and contract approach. In most Member countries, the portion of direct cost is concentrated within the band of 70 to 80% of the total capital costs.

Since the 1990 report, a number of new nuclear power plants have been constructed in several OECD Member countries and it is not useful to compare the change of the composition of capital costs with the previous data. New cost information has been made available by the Expert group members' responses to the NEA questionnaire. Upon examination of the new cost data, the Expert group found a number of contradictions and inconsistencies that support earlier conclusions that inter-country comparison must not be encouraged and that the responses to the NEA questionnaire would not be published in their entirety. For completeness, however, Table 5 shows the compositions of capital costs in several nuclear power plants and the total capital costs of those plants in local currency, drawn from the responses to the NEA questionnaire.

The cost breakdown structure in Europe is less detailed than other countries, probably because of the use of turnkey contracts or the participation of electric utilities in engineering services. In the United States and in Canada, cost management for projects is usually carried out on the basis of their precise cost breakdown structures.

The cost breakdown structure of the French N4 PWR (1 450 MWe) plant is comparatively simple, as most jobs related to the indirect costs are carried out by EdF itself, and installation costs and other supplementary costs such as tax, transportation, spare parts and contingencies, are included in the equipment supply packages. In the cost data for the French N4 plant, indirect costs are included in the owner's costs, and installation costs and other costs like taxes, insurance, transportation, spare parts and contingencies are included in direct costs. For EdF, the training costs are included in the pre-operational costs i.e. the training costs of the future operation team. Costs of "staff training and technology transfer provided by the equipment suppliers" are included in the direct cost and those "provided by A/E" are included in owner's cost. On the other hand, the "owner's costs" provided by EdF include dismantling costs.

For Sizewell-B, it should be noted that design and engineering cost is relatively high, since all the FOAK costs are included in the construction of the first 1 200 MWe PWR in United Kingdom.

Table 5. **Capital costs of nuclear power plants[1] (%)**

COST ITEM	Plant 1	Plant 2	Plant 3	Plant 4[2]	Plant 5	Plant 6
Direct costs						
Land and land rights	0.3	0.1	0.2		0.2	1.8
Reactor plant equipment	21.9	27.6	23.2	29.0	18.6	32.0
Turbine plant equipment	7.2	14.7	5.9	16.0	16.5	22.8
Electrical plant equipment	20.0	13.2	13.5	10.0	5.1	5.9
Heat rejection equipment	2.0	2.2	2.5	7.0	3.8	3.1
Miscellaneous equipment	6.3	15.2	7.1	8.0	3.3	
Construction	19.4	10.1	23.4	10.0	13.4	17.8
Direct costs total	**77.1**	**83.1**	**75.8**	**80.0**	**60.9**	**83.4**
Indirect costs						
Design and engineering	6.7	3.7	11.7		3.5	12.9
Project management	4.0	5.9	0.9		5.8	0.9
Commissioning	0.9	1.7	3.8		18.4	
Indirect costs total	**11.6**	**11.3**	**16.4**		**27.7**	**13.8**
Other costs						
Training	0.3	0.9	2.9	6.0		0.4
Taxes and insurance		0.5	0.4			
Transportation		0.1	0.1			0.6
Owner’s costs	10.4	1.6	2.4	14.0	2.4	1.8
Spare parts	0.3	2.5			2.4	
Contingencies	0.3		2.0		6.6	
Other costs total	**11.3**	**5.6**	**7.8**	**20.0**	**11.4**	**2.8**
Total	**100**	**100**	**100**	**100**	**100**	**100**
Total capital costs (million, national currency 1997)	**73 400**	**16 131**	**3 168**	**13 050**	**2 057**	**4 255**

1) Percentages calculated by the Secretariat based on the provided cost data.

2) Total capital cost of plant 4 (French N4) is an average cost calculated for a series of 10 units, which includes a part of the FOAK costs.

Plant 1:	Czech Temelin (VVER, 1 000 MWe)
Plant 2:	Mexico Laguna Verde (BWR, 650 MWe)
Plant 3:	United Kingdom Sizewell-B (PWR, 1 200 MWe)
Plant 4:	French N4 (PWR, 1 450 MWe)
Plant 5:	American Evolutionary ALWR (1 300 MWe)
Plant 6:	Germany KONVOI (PWR, 1 380 MWe) – historical value of 1990

As previously noted, it was difficult to unify the cost accounting systems of the countries that responded to the NEA Questionnaire because the cost breakdown structures are highly dependent on the contract approach, project management and each country’s accounting system. However, the cost data indicates that the direct costs dominate the capital costs, so it is most important to find the way to reduce direct costs. Thus opportunities for cost reduction in design and project management must be considered. The following chapters will describe the way of reducing these costs.

REDUCTION OF CAPITAL COSTS

As lowering capital costs is very important in improving the competitiveness of nuclear power, various measures that could reduce the capital costs have been developed in the OECD countries. The Expert group identified the following measures for review and analysis:

- Increased plant size.
- Improved construction methods.
- Reduced construction schedule.
- Design improvement.
- Improved procurement, organisation and contractual aspects.
- Standardisation and construction in series.
- Multiple unit construction.
- Regulation and policy measures.

Since the above measures are directly related to the design and construction activities of the nuclear power plants, the measures are often inter-dependent. It should be noted that the combined effects of several cost-reducing measures are not necessarily equal to the sum of the effects of individual measures. In addition, this document examines the impact of “increased plant size” on overnight capital costs; the impact of this measure on total capital cost, that depends on regional and/or national conditions may differ.

The Expert group recognised that there could be some sensitivity in commercial terms if the cost data shown in the report is to be converted to a common currency such as the US Dollar or the EURO. Therefore, there was a limitation to quantify all effects of different cost reduction methods and the specific conditions of the power plants were not fully taken into consideration in analysing the effects. However, it is clear that a better understanding of the proportional cost reductions achieved by the various cost reduction measures would be of great value to decision makers considering future nuclear power programmes.

Increased plant size

Variation of overall and individual economic, technical and safety parameters of nuclear power plants with plant size and capacity has been the subject of many investigations and controversies since the commercialisation of nuclear power plants in the mid-1960s. A better understanding of the size dependence of “scaling” of influential parameters, such as capital costs, can be of significant help to planners of nuclear power plants. This applies to situations where there may be the option of either proceeding with a large unit or with one or several smaller unit plants, as well as to the determination of the best starting point (in time) for nuclear exploitation in an expanding power grid.

Savings from economy of scale

The savings arising from the economy of scale when the unit size of power plants increases in the 300 to 1 300 MWe range have been studied by experts around the world since the early 1960s. In the 1970-1990 period, construction time schedules and costs had increased significantly and the spread between excellent and poor project performance had grown wider. The scarcity of new orders in recent years has made little contribution to alleviate the uncertainties. As a consequence, specific costs (US$/kWe) of large nuclear power plants have been quoted within such a broad range that makes the derivation of scaling factors more difficult. In addition to savings arising from increasing reactor unit and plant sizes, cost reductions due to other factors such as improved construction methods, shortening of construction schedules, construction of multiple-unit plants at the same site, and the effects of replication and series construction have to be investigated as well.

For many years, bigger has been better in the utility industries of industrialised countries. Economies of scale have for some time and in many cases reduced the real cost of power production. As the economies of industrialised countries matured, the expected growth in demand for electric power has stabilised such that many utilities in the industrialised countries are taking a fresh look at the matter of generating unit size. Uncertain load growth, cash constraint, and relatively longer lead-time for larger units define a new planning regime for some utilities. For them, it may be risky to commit scarce capital to build a large unit that must be committed may years in advance of the anticipated need. If that need fails to develop, or develops several years later than expected, it could leave the utility with excess capacity on its hands. Today’s financial climate requires a closer match between installed capacity and demand because a major mismatch in either direction carries substantial costs.

The following scaling function can be used to illustrate the effect of changing from a unit size of P_0 to P_1:

$$\text{Cost}(P_1) = \text{Cost}(P_0) \times (P_1/P_0)^n$$

where Cost (P_1) = Cost of power plant for unit size P_1
Cost (P_0) = Cost of power plant for unit size P_0
and n = Scaling factor, in the range of 0.4 to 0.7 for the entire plant.

In general, a larger nuclear plant will have a lower specific overnight capital cost (US$/kWe) than a smaller one of the same design.

When evaluating the costs of packages, the same exponential law can be used with different values of scaling factors. An example was shown in the 1990 NEA report.

Typical scaling factors

Package	**Scaling factor (*n*)**
Structures	0.2
NSSS	0.3
BOP	0.4
Turbine plant	0.75
Electric plant	0.37
Miscellaneous	0.2

Source: G. Woite, Capital Investment Cost of NPPs. IAEA Bulletin, vol. 20, No.1, February 1978.

The economy of scale may be limited due to the physical limitation to increase dimensions of some systems or components (e.g. reactor core, fuel rods and turbine blades). Adequate industry infrastructure is required to scale up the sizes of different equipment for manufacturing, transportation and erection. The maximum size of units in an electrical grid is limited in consideration of grid stability, demand pattern, spinning reserve or other specific characteristics of the system.

The French experience

In the case of France, the Commissariat à l'Énergie Atomique submitted to the IAEA in 1991 a series of cost estimates for the construction of single and two-unit PWRs in the 300 to 1 350 MWe unit size range. The cost estimates are shown in Tables 6 and 7, and Figures 1 and 2. It must be borne in mind that these cost estimates were based on reactors designed to the same principles, by one vendor/engineering company, with the same safety requirements, to the same site conditions, with the same technical standards, under the same contractual/business arrangements, assuming the same commercial operation date.

Table 6. **Capital investment decomposition (single unit) as percentage of total overnight cost for 1 × 300 MWe plant**

	1 × 300	**1 × 650**	**1 × 1 000**	**1 × 1 350**
20 Land and land rights and site utilities	2.8	2.9	3.0	3.1
21 Buildings and structures	14.8	21.6	26.7	31.0
22 Steam production and discharge processing	23.5	39.4	53.5	66.8
23 Turbines and alternators	10.5	17.7	23.7	29.1
24 Electrical, instrumentation and control	5.6	8.9	11.5	13.8
25 Miscellaneous plant equipment	2.5	3.2	3.7	4.1
26 Water intake and discharge structures	1.9	3.6	5.0	6.4
Sub-total for direct costs	**61.5**	**97.3**	**127.2**	**154.2**
91 Engineering and design	13.3	16.4	18.9	21.1
92 Construction services	6.2	7.1	7.8	8.5
93 Other indirect costs	4.0	4.7	5.4	6.0
Sub-total for indirect costs	**23.4**	**28.2**	**32.1**	**35.6**
Contingencies	2.7	4.1	5.2	6.2
Owner's costs	12.3	15.4	17.5	19.1
Total overnight cost	**100.0**	**145.0**	**182.0**	**215.0**
Specific overnight cost ratio (1 × 300 = 100)	**100**	**67**	**55**	**48**

Source: J. Rouillard and J.L. Rouyer [10].

It can be seen from Table 6 that, for a 350% increase in unit size from 300 MWe to 1 350 MWe, the total direct cost increases by about 151%, while the total indirect cost increases by only 52%. This conclusion is consistent with the expectation that as unit size increases, the savings arising from economy of scale are much higher for such costs as engineering design and construction services than equipment, material and construction labour costs.

Table 7. **Capital investment decomposition (two units) as percentage of total overnight cost for 1 × 300 MWe plant**

	2 × 300	**2 × 650**	**2 × 1 000**	**2 × 1 350**
20 Land and land rights and site utilities	2.9	3.1	3.1	3.2
21 Buildings and structures	20.8	30.4	37.6	43.7
22 Steam production and discharge processing	45.8	77.1	105.0	131.1
23 Turbines and alternators	19.5	33.0	44.3	54.3
24 Electrical, instrumentation and control	11.2	17.8	23.0	27.5
25 Miscellaneous plant equipment	4.4	5.6	6.5	7.1
26 Water intake and discharge structures	3.3	6.2	8.8	11.1
Sub-total for direct costs	**107.9**	**173.2**	**228.3**	**278.1**
91 Engineering and design	17.7	23.5	28.4	32.9
92 Construction services	7.5	9.2	10.8	12.2
93 Other indirect costs	5.1	6.7	8.1	9.3
Sub-total for indirect costs	**30.3**	**39.4**	**47.3**	**54.4**
Contingencies	4.7	7.2	9.1	10.8
Owner's costs	15.1	19.1	21.7	23.9
Total overnight cost	**158.0**	**238.9**	**306.4**	**367.1**
Specific overnight cost ratio (1 × 300 = 100)	**79**	**55**	**46**	**41**

Source: J. Rouillard and J. L. Rouyer [10].

When two consecutive units of the same size are constructed on the same site, even more savings in overnight costs can be achieved. These savings in overnight costs decrease with increase in unit sizes, however. For example, in comparing the cost components in Table 7 with those in Table 6, while the overnight cost of a 2 × 1 350 MWe plant is 171% higher than the single 1 350 MWe unit, the overnight cost of a 2 × 300 MWe plant is 158% higher than the single 300 MWe unit.

Figure 1. **Single unit plant cost as percentage of total overnight cost for 1 × 300 MWe plant**

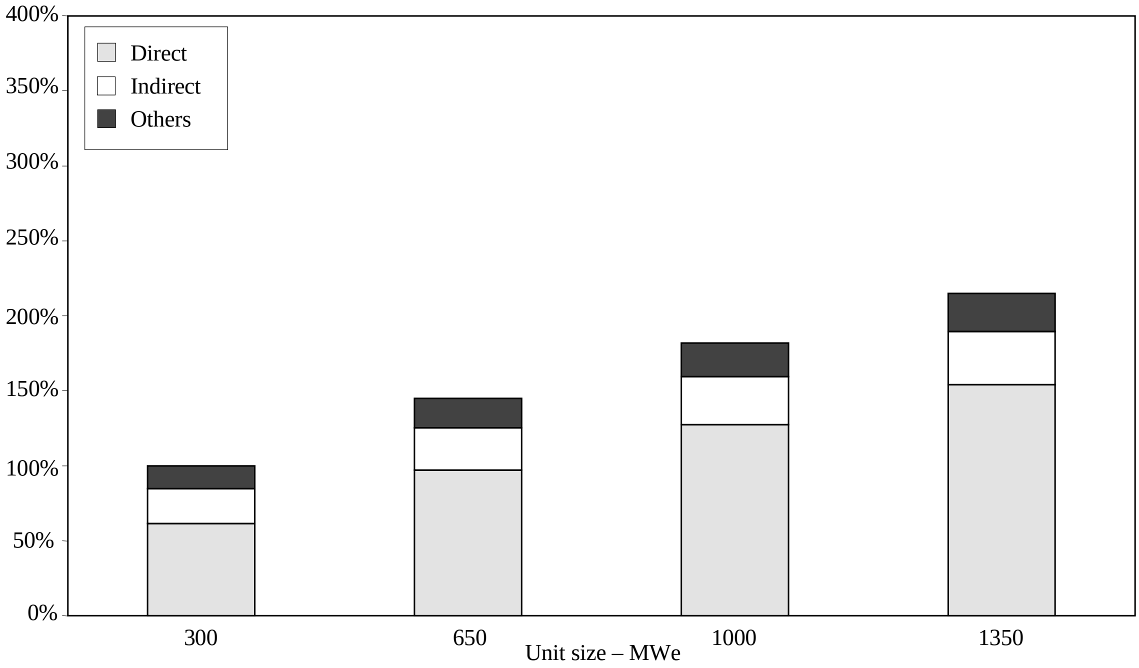


Figure 2. **Two unit plant cost as percentage of total overnight cost for 1 × 300 MWe plant**

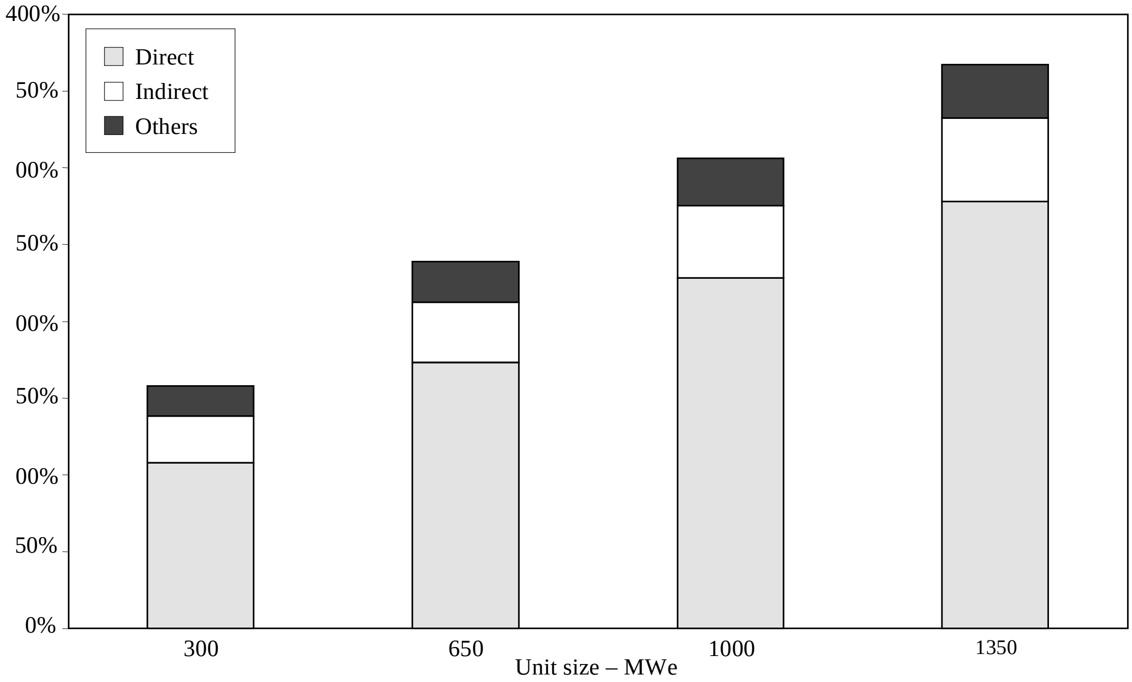
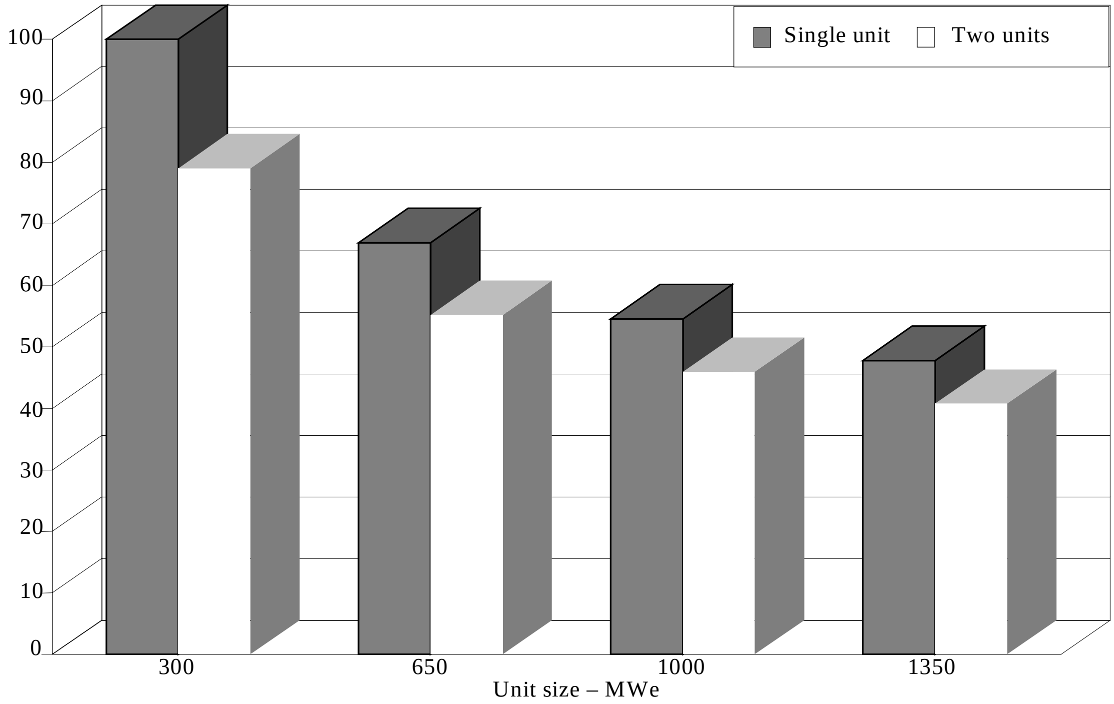


Figure 3. **Specific overnight cost ratio (1 × 300 MWe Plant = 100)**



On the basis of specific overnight costs, i.e. currency unit per kilowatt of net output, it can be observed from Figure 3 that the specific overnight cost of the larger 1 350 MWe plants are estimated to be about 50% lower than the smaller 300 MWe plants.

The Canadian experience

As a second example, recent cost estimates completed in Canada show similar trends in the economy of scale when the costs for the advanced CANDU 9 are compared with the CANDU 6, which began commercial operation in the early 1980s. Tables 8 and 9 and Figures 4 and 5 show the cost components for single and two unit CANDU 6 and CANDU 9 plants as percentages of a single CANDU 6 unit.

It can be seen from Table 8 that, for a 31% increase in unit size from 670 MWe to 881 MWe, the total direct cost increases by about 31%, while the total indirect cost increases by only 3%. It must be borne in mind that this comparison is between an existing design (CANDU 6) that has been commercially available since the early 1980s, with an advanced design (CANDU 9) that has incorporated the state-of-the-art design and construction features. Had the comparison been made using the traditional scaling factors, the savings would have been much higher.

When two consecutive units of the same size are constructed on the same site, even more savings in overnight costs can be achieved. These savings in overnight costs decrease with increase in unit sizes, however, consistent with the French experience. For example, in comparing the cost components in Table 9 with those in Table 8, while the direct cost of the 2 × 881 MWe CANDU 9 plant is 175% higher than the single 881 MWe unit, the indirect cost of a 2 × 881 MWe CANDU plant is only 139% higher that the single 881 MWe unit. This trend is also consistent with that of the French experience.

Table 8. **Capital investment decomposition (single unit) as percentage of total overnight cost for a single CANDU 6**

	CANDU 6 **1 × 670 MWe**	**CANDU 9** **1 × 881 MWe**
21 Buildings and structures	18.3	23.6
22 Steam production and discharge processing	24.0	29.3
23 Turbines and alternators	10.3	11.4
24 Electrical, instrumentation and control	13.2	14.3
25 Miscellaneous plant equipment	7.2	9.2
26 Water intake and discharge structures	1.1	1.5
Sub-total for direct costs	**74.0**	**89.4**
91 Engineering and design	7.5	7.6
92 Construction services	5.2	5.5
93 Other indirect costs	3.0	3.0
Sub-total for indirect costs	**15.7**	**16.1**
Contingencies	5.7	6.9
Owner’s costs	4.6	3.4
Total overnight cost	**100.0**	**115.7**
Specific overnight cost ratio (1 × 670 = 100)	**100**	**88**

Source: Cost data from Canada in response to the NEA questionnaire.

Table 9. **Capital investment decomposition (two units) as percentage of total overnight cost for a single CANDU 6**

	CANDU 6 **2 × 670 MWe**	**CANDU 9** **2 × 881 MWe**
21 Buildings and structures	32.6	41.3
22 Steam production and discharge processing	43.8	53.4
23 Turbines and alternators	18.9	20.4
24 Electrical, instrumentation and control	25.3	25.7
25 Miscellaneous plant equipment	11.5	13.5
26 Intake and discharge structures	2.0	2.5
Sub-total for direct costs	**134.0**	**156.8**
91 Engineering and design	9.0	9.2
92 Construction services	7.5	7.5
93 Other indirect costs	5.7	5.7
Sub-total for indirect costs	**22.2**	**22.4**
Contingencies	8.6	11.5
Owner’s Costs	7.3	5.7
Total overnight cost	**172.1**	**196.4**
Specific overnight cost ratio (1 × 670 = 100)	**86**	**75**

Source: Cost data from Canada in response to the NEA questionnaire.

Figure 4. **Single unit plant cost as percentage of total overnight cost for 1 × 670 MWe CANDU 6**

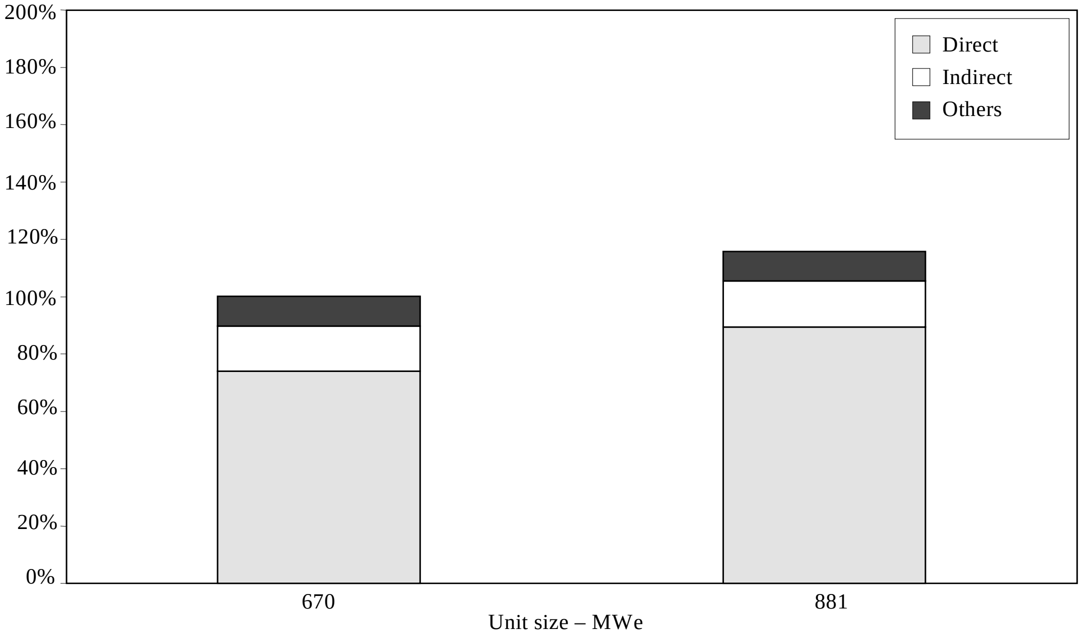


Figure 5. **Two unit plant cost as percentage of total overnight cost for 1 × 670 MWe CANDU 6**

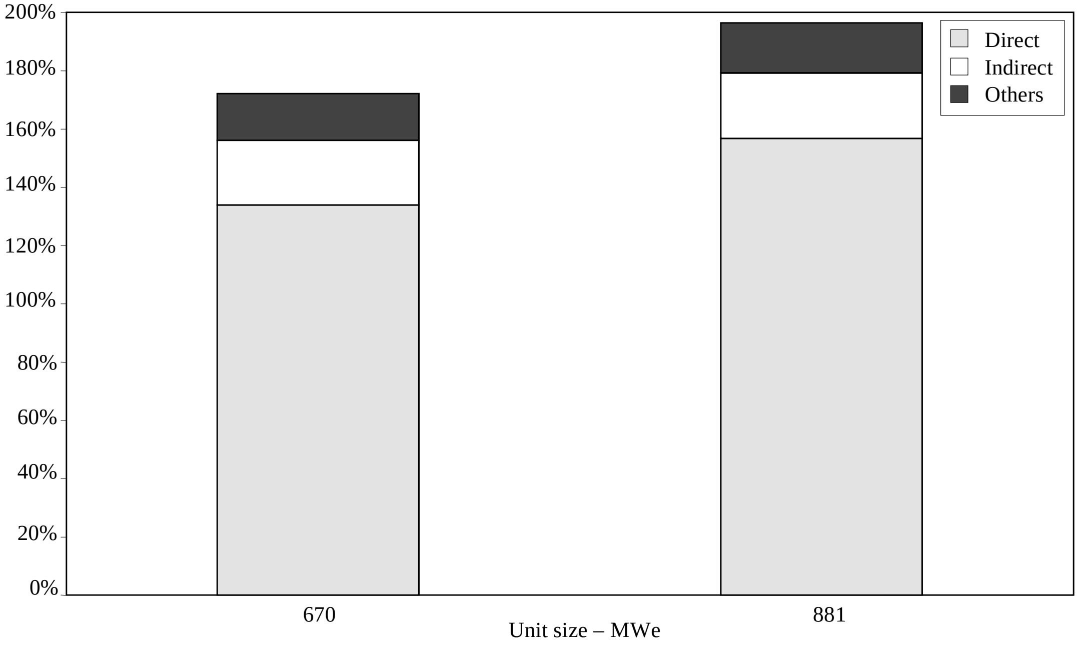
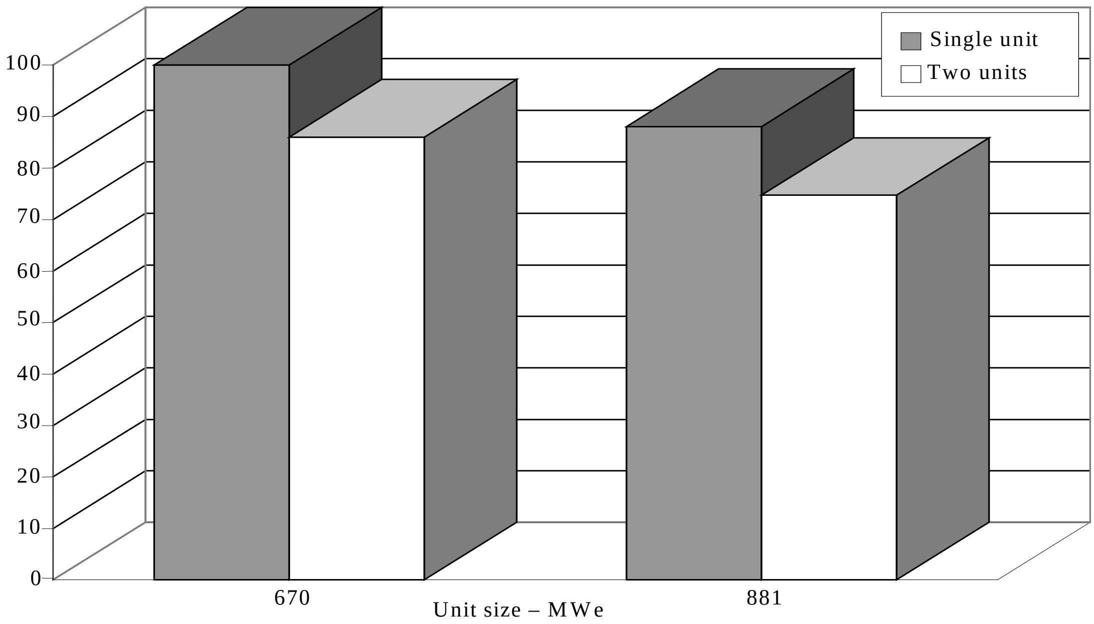


Figure 6. **Specific overnight cost ratio (1 × 670 MWe CANDU 6 = 100)**



On the basis of specific overnight costs, i.e. currency unit per kilowatt of net output, it can be observed from Figure 6 that the specific overnight costs of the larger CANDU 9 plants are estimated to be about 12% lower than those of the smaller CANDU 6 plants.

The American experience

Cost data from the United States in Table 10 shows that capital costs per kWe could be substantially decreased with the increase in plant sizes.

Improved construction methods

The initial construction techniques of nuclear power plants were adopted from fossil power plant construction experience in the industrialised countries; however, considerable development and improvements have been achieved in this area since the first nuclear power plants have been constructed. The development was primarily driven by the need to respond to new regulatory requirements and quality assurance concepts, such as licensing, safety classification, document control, quality assurance, and the preparation of safety analysis reports and other regulatory documents.

The simplified, efficient and cost effective means of designing and constructing nuclear power plants are key factors in improving the quality and reducing the construction schedules and costs of the plants. Many OECD Member countries have developed various techniques to improve the plant design, ensure the quality of the construction, and to reduce the construction period. The most important methods are discussed in the following sections.

Table 10. **Capital investment decomposition of specific overnight costs for evolutionary advanced light water reactors in the United States**

Capital costs	**Reactor capacity**		
	1 300 MWe	**900 MWe**	**600 MWe**
Direct costs (million 1997 US$)			
Land and land rights	4	4	4
Reactor plant equipment	383	307	241
Turbine plant equipment	339	262	197
Electric plant equipment	105	94	83
Main construction heat rejection system	79	63	58
Miscellaneous plant equipment	67	59	43
Construction services	275	225	181
Direct costs total	**1 253**	**1 014**	**807**
Indirect costs (million 1997 US$)			
Design and engineering	72	59	47
Project management	119	98	78
Indirect costs total	**191**	**156**	**126**
Other costs (million 1997 US$)			
Owner's costs	50	40	32
Spare parts	50	40	32
Initial fuel costs	379	379	379
Contingencies	134	109	88
Other costs total	**613**	**568**	**531**
Total capital costs (million 1997 US$)	**2 057**	**1 738**	**1 463**
Specific capital costs (1997 US$/kWe)	**1 582**	**1 931**	**2 439**

Source: Cost data from the United States in response to the NEA questionnaire.

Open top construction

Open top construction methods allow access to the interior of the reactor building from outside the perimeter walls. Equipment is moved through the top of the reactor building using large heavy lift cranes rather than the traditional horizontal techniques. For example, a steam generator can be installed in one to two days as compared with two weeks using traditional methods. A significant reduction in construction schedule may be realised, with elimination of consequential costs.

Full exploitation of the advantages of open top construction is expected to reduce total construction time, but attention must also be focused on the cost of heavy lift equipment and infrastructures necessary for the prefabrication of modular components.

Modularization

The use of standardised plant design provides the opportunity to utilise modular construction. Modules are discrete volumes of the installation that are readily separable for pre-assembly at on-site or off-site locations. Once assembled and tested they can be moved into position for completion of the operations necessary for the integration of the systems. Modules can be pre-fabricated for structural assemblies, piping, tubing, cable trays, reinforcing bar mats, instrumentation, electrical panels, supports, and access platforms, etc.

The factory setting provides a better work environment, as activities tend to have higher quality assurance, with the potential for greater automation and higher productivity. Modular construction reduces site congestion and shortens the construction schedule as production can take place away from and in parallel with site specific activities. Site labour and supervision is reduced although these may be offset by increased transport and factory equipment costs.

Modular construction techniques have proven successful in many countries. The total cost reduction due to modularization is estimated between 1.4 to 4% of the total construction cost. The potential exists for more extensive use of these techniques. Major expected benefits include:

- Improved quality.
- Shortening of the construction schedule.
- Reduction in construction cost.

However, the applications of modularization are not significant at present. The major concerns include:

- Requirement to complete the total design of the plant before module fabrication.
- Necessity to purchase all materials and components before module fabrication.
- Reduction in the flexibility to sequence and overlap tasks during construction and testing.
- Need for expensive heavy life cranes.

Moreover, modularization may increase project risk due to:

- Modules may not fit into the buildings/systems.
- Modular approach reduces the flexibility available during site construction.
- Modularization is more sensitive to the events that could delay the schedule.
- Earlier outlay of funds has to be made because of up-front engineering and early procurement.

Nevertheless, modularization is a very promising technical approach to shorten the construction schedule of nuclear power plants. In order to maximise benefits the plant owner must analyse the impact of modularization on quality, schedules and costs. Efforts should be focused on establishing detailed plans during the design stage for modular construction and the co-ordination of interfaces.

Slip-forming techniques

Large prefabricated modules have included containment walls and liners. In Sweden, the application of slip-forming techniques for these components has reduced the construction schedule by three months, approximately 5% of the total. Slip-forming techniques have also been utilised for large structural buildings including the auxiliary building and turbine hall. They necessitate areas on site for fabrication, transport and installation of the modules.

Parallel construction techniques

Parallel construction techniques involves the integration of the mechanical and civil works. Work progressed in a variety of areas simultaneously. These techniques will significantly reduce the mechanical work required after the civil construction programme is completed. Unfortunately, specific quantitative data is limited and a comparison is not possible.

Instrumentation and control cabling

Installation of cables trays and terminations usually form part of the project's critical path. Remote multiplexing results in a major reduction in the quantity of cable and trays to be installed, and in the number of terminations. The number of cross connections in the control distribution frame is also subject to major reductions, thus alleviating work congestion. The construction cost reduction is estimated at 1% in Canada.

The application of computer technologies has resulted in improvements in cable installation. Examples include:

- Identification of cables with similar routes and pulling them simultaneously to eliminate the repetitive set-up times for instrumentation and control cabling craftsmen.
- Identification of areas where bulk cable pulling could be performed before the start of other electrical installation.

Pipework and welding

Elbow fittings deletion by forming bends within pipe lengths can eliminate associated welds. Cost savings result from deletion of the fittings, welding operations and non-destructive examination of welds. There is potential for schedule reduction due to reduced labour and reductions in the disruption of operation by radiographic examination of welds. However, the cost of forming the pipe bends partially offsets the cost saving. The incorporation of pipe bends is expected to result in an overall construction cost saving of 0.4% in Canada.

Sequencing of contractors

The effective co-ordination of contractors and integration within the construction sequence is vital in order to minimise costs. A variety of improvements have been suggested including:

- Refinement of work packages.
- Practice mock-ups.
- Improvement in prime contractor/sub-contractors communication interface.

Savings in the order of 6 to 8% of the direct capital cost of BWRs have been realised by applying the above practices in Mexico.

Summary of cost savings

The following table summarises potential cost savings resulting from improved construction methods. All figures relate to savings actually achieved.

Construction method	Potential cost saving % of total cost	Reactor Type/Origin	Comments
Open top access	2.4	CANDU – Canada	15% reduction in construction schedule.
Modularization	1.4 – 4.0	BWR – Sweden CANDU – Canada	Potential reduction in construction schedule.
Slip-forming	Undefined	BWR – Sweden	5% reduction in construction schedule.
Parallel construction	Undefined	N/A	Potential reduction in construction schedule.
Improved cabling, instrumentation, and control	1.0	CANDU – Canada	
Formed pipe elbows and reduction in weld inspection	0.4	CANDU – Canada	Potential reduction in construction schedule due to less disruption and inspection requirements.
Sequencing of contractors	6.0 – 8.0	BWR – Mexico	Potential reduction in construction schedule.

Construction management

Although each method outlined above could reduce the construction costs, the reduction effects could not be maximised without competent construction management. It may be particularly applied for the use of modularization technique, since very precise site access sequencing and quality assurance programme are required for the success of this technique. World-wide experience indicates that a strong customer-vendor relationship, based on mutual competence and supported by the desires for both parties to learn from world operating experience is the best basis for the successful management of a major construction project. If the customer lacks the experience, a good architect engineer should be considered.

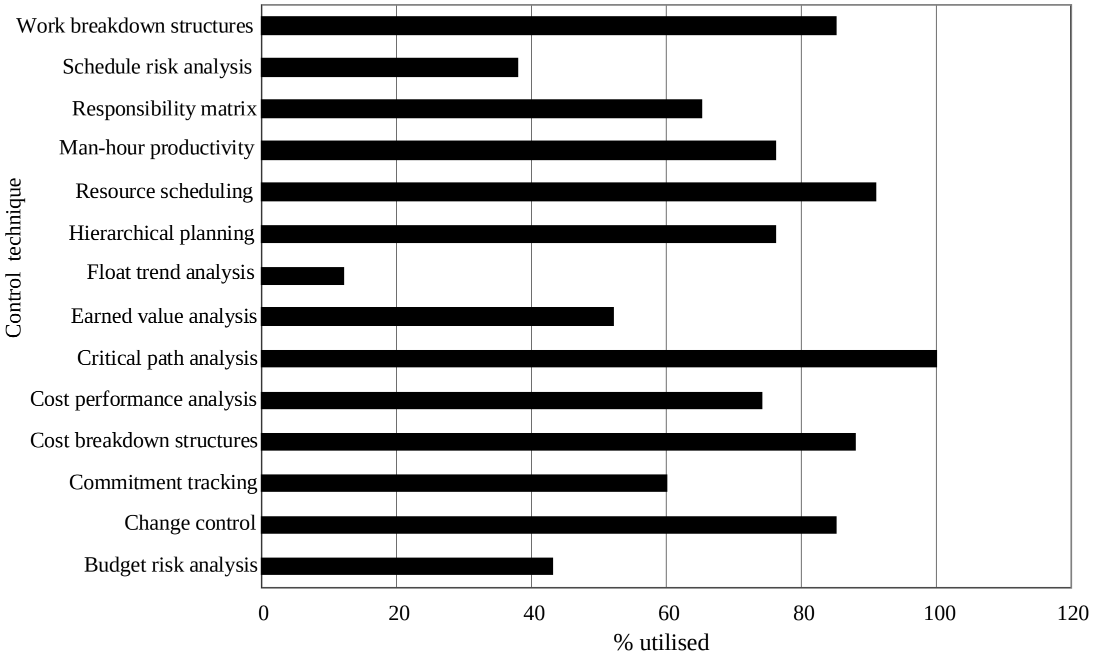
Reduced construction schedule

Project management and cost control

Project management is primarily concerned with the functions of definition, direction, co-ordination and overall control of the project implementation process. Effective project management is essential for achieving project objectives in terms of quality, cost and schedule. Analysis of construction experience has focused efforts on project planning to ensure the achievement of stated objectives through identification, organisation, implementation, feedback, and control.

Scheduling is an essential management tool for establishing expectations and allocating resources. The project master schedule includes the entire duration of the project and is developed with input from all organisational units involved in the project. Construction planning should provide the optimal solution to the sequencing of overall site activities in a logical order to achieve construction objectives. A variety of modern project control techniques have been utilised for power plant construction. Figure 7 highlights the common approaches, and the extent to which such approaches have been utilised.

Figure 7. **Project control techniques commonly utilised**



Source: Information from United Kingdom in response to the NEA questionnaire.

Cost control is an important aspect of project management. Owing to the large capital investment involved nuclear projects are more sensitive to delays in project completion than conventional power projects. The timing of a specific expenditure and its effect on interest during construction can add more than 25% to the capital cost; however, the financing arrangements and their influences on the total cost of building nuclear power plants are beyond the scope of this study.

Factors affecting construction schedule

A lengthy construction schedule exposes a nuclear power project to a variety of risks that are beyond the control of the project management team. Such risks include: increased total interest during construction, escalation in equipment, material and labour costs, out-dated technologies, new licensing requirements, public opposition, labour unrest and strike, and political changes, etc.

Those risks, all of which translate into an economic cost to the plant owner and investor, can be reduced by a shorter construction period. Benefits of a shorter construction period include:

- Reduced administrative costs.
- Reduced skilled personnel turnover.
- Higher personnel morale and dedication.
- Higher work efficiency and better quality of services.

A shorter construction schedule also results in earlier profits from the start of commercial operation, thus improving project economics.

Numerous methodologies have been used to reduce overall construction schedules. The following measures have been highlighted as offering potential for improved programme scheduling:

Construction

- Advanced engineering methods.
- Simplified reactor base construction.
- Modularization techniques.
- Prefabricate reactor liner.
- Prefabricate primary and secondary shield walls.
- Utilisation of heavy lift cranes.
- Reduce the number of embedments.
- Up-front engineering and licensing.
- Effective change control, project planning, monitoring and control.
- Improved manpower development and training.

Others

- Maximise working hours by multiple shift work or around the clock construction scheduling.
- Contract and staff incentives.
- Strong industrial relations policy.
- Optimised access around site and contractors compound.
- Improved construction interfaces, and integration.
- Computerised project management scheduling.
- Improved information management.
- Contingent procurement.
- Co-ordination of inspection services.
- Streamlining and reduction of documentation including quality assurance and quality control.

The selection of applicable examples of good practices should be based on the social and economic conditions prevailing in an individual country and on the capabilities and expertise of the utilities and other organisations.

Factors affecting cost savings

Owing to the large capital investment, nuclear power projects are very sensitive to delays in project completion. Disruptions of the original schedule will lead not only to increased cost overruns and the corresponding increase in interest during construction, but also to postponement in revenues from electricity generation. Thus, the financial commitment of the plant owner and its ability for debt repayment on schedule will be affected.

Cost savings have been maximised by:

- Providing all construction drawings at the contract tender phase.
- Avoiding clashes and delays through better planning, organisation, and interface management.
- Familiarisation of the work to promote better efficiency.

Optimisation of schedule

A wide variety of parameters affect the cost of construction. However, cost minimisation may not necessarily result in the shortening of the construction schedule. For example, in Japan the construction schedule has been shortened to 45 months. However, the cost savings resulting from such a short schedule are compromised by large pre-construction investment in access logistics and site preparation.

Within a short construction period more work is to be carried out in parallel, hence the management costs and risks increase. An optimum balance between risks and the benefits of a short schedule should be established, i.e. low risk of cost over-run, reduced interest during construction, and earlier income from plant operation. Due to the changing nature of macro and micro-economic climates, the correlation and optimisation will be country dependent.

Multiple units, standardisation and phased construction

Analysis has demonstrated that the construction programme would be significantly shortened when benefits in replication are realised. Furthermore, the plant design is already licensed and the interface with the licensing body streamlined.

The benefits may also be realised from building multiple units on a single site. Schedule reductions relate to the building of shared facilities, utilisation of common resource across sites and bulk ordering of materials. The latter may encourage vendors to invest in equipment and processes resulting in improved productivity. Construction of multiple units on one site using phased construction may reduce the overall schedule. Phased construction enables efficient use of:

- Industry for the production of construction materials.
- Manufacturing industry.
- Transport facilities.
- Construction workforce.
- Construction equipment.

Historical information reports labour savings in the order of 50% for construction of a second reactor in comparison to the first. Furthermore, replication of a standardised design has resulted in a 20% reduction in overall construction time.

Comparison of schedule improvements

The following table details a variety of potential savings for the construction of a typical PWR, including the application of modern design principles and parallel working.

Element of construction programme	**Potential savings in construction schedule for each specific element of construction (%)**	**Factors influencing saving**
First concrete pour to reactor base complete	30	Improvements in design (simplification and constructibility)
Reactor liner	92	Pre-fabrication of liner.
Primary containment wall	22	Improve access and crane usage.
Primary and secondary shield walls	46	Prefabrication/modularization.
Reactor building Crane erection	57	Use of factory test and prefabrication.
Commissioning	16	Integration.
Total (overall project)	**12.5**	

Note: Several tasks scheduled in parallel hence overall saving does not equate to sum.

Comparison of construction schedule for reactor types

The following table compares the construction schedules for a variety of reactor types. Comments are made regarding schedule optimisation.

Reactor type	**Original schedule (months)**	**Revised schedule (months)**	**Comments**
PWR 1 200 MWe	63	55	Modularization. Improve access logistics. Design process improvements.
CANDU 700 MWe	61	55	Staged implementation. Potential for 52 month schedule.
VVER-320 1 000 MWe	51	49	–
BWR 90 1 500 MWe	60	48	

Source: Information provided by the Expert group members in response to the NEA questionnaire.

Realised savings vary widely from 4% to 20% of the overall construction schedule. Time-scale savings require correlation and optimisation with project costs. Minimisation of time may in many cases not result in cost savings. Limited data is available and a comparison of optimisation methodologics is beyond the scope of this report.

Design improvement

The design engineering cost of a nuclear power plant accounts for about 10% of the total plant capital costs. Deficiencies in design would have significant consequences, in the construction and subsequent operation of the plant. Systematic studies of past design and construction experience have progressed in some countries, leading to improvements in design that have facilitated construction.

The benefits from improvements in design on technology rely on the consolidation of knowledge, including the proposed construction methods and process integration, within the construction schedule. New technologies have been introduced to standardise and simplify equipment. In addition, methods of manufacturing, installation and inspections have been improved.

Designers involved with the specification of new plant aim to achieve less complex systems without compromising operational efficiency and nuclear safety, thus improving constructibility. Advances in computer technology and electronics have contributed to lowering costs. These processes have led to consistent documentation and a shorter construction schedule by eliminating rework due to document deficiencies, and more accurate material lists. In many countries regulatory position has shifted and stringent criteria enforced. These factors have influenced the design processes and the systems utilised. Improvement of construction through design can be achieved in a number of areas:

Plant arrangements

Plant layout requires adequate planning. Considerations should include all aspects of activities during the whole life cycle of the plant, such as safety, reliability, and economics. Plans have commonly accounted for construction, commissioning, operation, maintenance and decommissioning. Good practices in plant layout include the following:

- Simplification of the plant configuration.
- Planned on-site roads, including paving temporary roads and construction of permanent roads as early as possible.
- Close proximity of temporary facilities, such as fabrication shops etc.
- Elimination of differential settlements, for example, using common base mats and unifying floor elevations in and between buildings.
- Temporary concrete supports designed as facilities so as to avoid their costly removal.
- Standardisation of embedments.

Accessibility

Construction has been improved without any major changes of the original design by improving access for personnel, material and equipment. Design considerations include the following:

- Ensuring areas on site and in buildings are accessible for materials, equipment, tools and personnel.

- Placing supporting or temporary facilities, such as scaffolding at locations so that accessibility is not hindered.
- Installation of permanent elevators with capacity for freight movement.

Simplification of design

Design improvements implemented over the last decade include:

- Multifunctional supports.
- Heating, ventilation and air conditioning design.
- Control process information display.
- Computer control.
- Rationalised civil works.
- Reduction in the number of components.
- Compact layout, including reducing the building volume while ensuring sufficient accessibility.
- Decontamination systems and radiation control.

Many companies have recognised that the only way to maintain quality while minimising costs is to make their products simpler to manufacture. Simplification of the plant design has resulted in reducing materials, efforts, costs and duration for manufacture and/or construction. Examples include:

- Streamlining plant configuration to reduce the number and volume of buildings by having large structures and arranging common items rationally.
- Simplifying drawings and technical specifications of components, systems and structures.
- Reducing the quantity and complexity of rebar, piping and cable construction by using new technologies.
- Rationalising quality assurance requirements for preparation, performance assessment and documentation of activities.

Application of computer technology and modelling

Over the last decade designers and constructors have effectively used computer and plastic modelling tools. Modelling approaches facilitate a logic and systematic approach in managing and verifying design and construction activities.

Computer Aided Design (CAD) and Computer Aided Engineering (CAE) have been used extensively for establishing plant and building layouts, identifying structures and system interfaces. Contractors can visualise and animate various construction scenarios, and evaluate conflicts, risks and critical path activities. This is invaluable in developing the optimum construction management and schedule. Use of these techniques improves material delivery and ensures the most efficient use of manpower and resources.

Other design issues

A variety of other design issues influence the construction of nuclear power plants. Factors include:

- Rationalisation of design tolerances.
- Reduction of field welds.
- Integration of inspection criteria into design.

Next generation reactors

As well as improvements in existing reactor designs, there is a great deal of current activity by plant designers to design new plants that are less complex and rely more on passively safe systems. Since the beginning of the eighties, a significant effort has been devoted to the development of next generation reactors by the nuclear industry throughout the world.

Depending on the nuclear programmes in all countries developing such efforts, the pace at which the objectives was pursued differed significantly and timing for construction of these new plants, or completion of the regulatory assessment process, varied greatly.

Building upon the feedback of accumulated operating experience, utilities have developed their requirement and vendors have either improved their designs or developed new concepts. For example, the European utilities developed the European Utility Requirements (EUR), while the American utilities developed the EPRI Utility Requirement Document. At the same time, the vendors separately re-analysed their former designs before deciding upon modifications ranging from change in component technology, to complete reengineering of systems.

As the basis for these new designs were operating plants, they have been identified as "evolutionary" plants. A further distinction is being made between "active" and "passive" designs, depending on the type of energy used for the operation of engineered safety systems, i.e. generated energy for the former or stored energy for the latter.

Examples of evolutionary plants in operation are N4, KONVOI and Sizewell-B.

Advanced reactors in operation, being licensed, or in the pre-design phase include ABWR, System 80+, AP 600, ESBWR, BWR 90+, EPR, KNGR and advanced CANDU.

The primary objective of the next generation reactors is to provide at the beginning of the next century a significant cost advantages over the most competitive fossil plants. The generation cost target laid down in the European Utility Requirements (EUR) is a kWh cost 15% lower than the kWh delivered by current plants for base load operation. This objective will be achieved by controlling the investment cost, by reducing the operating cost and the fuel cycle cost, taking advantage of a higher availability target.

Reliance upon natural phenomena such as natural re-circulation of cooling water, radiant heat rejection, and negative temperature coefficients of reactor reactivity is allowing for simpler designs that require less mechanical and electrical hardware. Enhanced computer aided design and engineering also contribute to the lowering of costs.

For example, the AP 600 that received final design approval from the United States NRC will contain approximately 50% fewer valves, 80% less piping, 70% less control cable, and 35% fewer pumps than the conventional LWRs.

Brief technical descriptions and their corresponding capital costs of the next generation reactors are shown in Annex 2 of this report.

New small reactor design concepts

The reduced size usually means that passive safety features such as natural convection core cooling can be introduced. In order for these small reactors to be competitive with existing reactor types (in view of the inherently increased capital costs per unit of electricity produced resulting from the reverse effects of size), any new small reactor design must:

- Decrease the amount of complexity compared to current designs (such as passive safety systems, or more integrated component construction).
- Employ conventional technology as far as possible (to reduce development costs).
- Take maximum advantage of the gains from multiple units on one site.
- Use prefabrication as far as possible to reduce construction costs.
- Operate with high availability, for example by the introduction of redundancy.
- Operate with a high thermal efficiency, which in practice means operating at higher temperatures.

So far no small reactor plant has been built that demonstrates the economic advantages of the new concepts, and all costs are based on paper studies which are likely to overstate the actual advantages achievable in practice. The paper studies, nevertheless, show where new concepts could potentially be beneficial.

Three concepts are briefly considered here, as examples of possible developments: SIR, a small integral PWR designed by a US/UK consortium, KALIMER, a small sodium cooled fast reactor being developed in the Republic of Korea, and the pebble bed modular reactor (PBMR), a high temperature gas cooled reactor under development in South Africa. Some basic parameters of these reactors are given in Table 11.

The SIR reactor offsets the increasing specific costs of a smaller turbine and electrical plant by keeping the reactor plant specific costs similar to a larger PWR. This is achieved by creating an integral design of the reactor, stream generators and pressuriser within one large pressure vessel. Other equipment costs are reduced because of the inherent safety features of the passive design. For example, concrete volume is reduced by 35%, safety related pipework by a factor of ten, and total cable lengths are reduced by a factor of two. In addition, reduced construction costs arise from a greater amount of prefabrication and a short construction period of 30 months from first concrete to commercial operation.

KALIMER again can take advantage of its passive safety to reduce costs and in addition is able to use the increased operating temperatures to improve efficiency. The PBMR takes this concept to an extreme level of aiming at very high temperature operation and further increases in efficiency. In fact, if all three reactor types were compared on capital cost per unit of heat generation they would be very similar: it is the increasing efficiency that accounts for the reduced electricity unit costs.

Table 11. **Basic details of new reactor design concepts**

Reactor	**SIR**[1)]	**KALIMER**[2)]	**PBMR**[3)]
Type	Integral PWR	Liquid metal pool	High temperature gas cooled
Design power output MWe	320	333	100
Planned maximum normal coolant temperature °C	318	530 (454 steam)	900
Planned efficiency	32%	40%	48%
Target specific capital cost[4)] compared to current 1 300 MWe PWR	100%	85%	65%

1) Information from Nuclear Energy 1991, 30 (2) 85-93 and SIR publicity data.
2) Information based on KAERI/CRIEPI Tech Mtg. on LMR, Nov. 1996.
3) Information based on ESKOM presentation to IAEA 1997 and PBMR publicity data.
4) Excludes first-of-a-kind costs and based on multiple units at site.

Improved procurement, organisation and contractual aspects

In most countries the electricity markets are being deregulated. This has prompted the utilities to introduce more competition in the procurement of goods and related work and services.

The competition is developing at various levels, between generating stations, i.e., between nuclear, gas-fired and coal fired units; between procurement methods; and between the suppliers of equipment, work and services.

Regarding the competition between nuclear, gas and coal-fired power stations, the improvements in procurement, organisation and contractual aspects are beneficial to all three types of generating plants. However, the impact on the cost of the kWh will be the greatest for the nuclear plant since its capital costs account for 60% of the kWh cost, compared to only 20% for the gas-fired plant. Furthermore, until now the market for nuclear equipment and services has generally been a much more closed one than the market for the conventional power stations, chiefly on account of the regulatory and safety aspects. It follows that the opening up of markets will be more significant in the nuclear than in the conventional sector.

Alternative procurement methods

Concerning the competition between procurement methods, project management for power station construction is based on a dedicated project team headed by a project manager. The team has full responsibility for implementing the project to schedule, quality and budget. Also, the team interfaces with licensing and other regulatory bodies.

A key element in project management is the contracting strategy applied in the procurement of the plant that depends on the owner's skills and experiences. At one end of the strategy spectrum is the Turnkey Approach. The owner purchases his facility under a Turnkey Contract with a single vendor who will supply all the equipment and co-ordinate the overall construction work. In this option the bulk of the cost and programme risk is placed with the single contractor or consortium, and interfaces between owner and responsible suppliers are minimised. To cover the cost and programme risk, the contractor or consortium may ask for a higher price for the facility under a turnkey contract, depending on the competitive environment at the time of the bidding process.

At the other end are the Multiple Package Contracts (Component Approach). The owner conducts a comprehensive multiple-contract procedure for the supply and installation on site of several hundred items of equipment. In this option, the owner will have to spend more on technical co-ordination and interface control; he will have to set up a structure for multiple supplies and supervise operations at the site. However, this will enable him to perform a less costly design, to do a direct cost control and to minimise paying contingency margins to the main contractor.

Between these two extremes are intermediate solutions which we could call the Split Package Contract (Island Approach) in which the number of packages may vary between a handful and several dozens, aimed at reducing certain interfaces without increasing too much the contractors' cost premium. Utilities' engineering resources is an important factor to separate the packages in this option.

It is impossible to assert that one particular solution is always preferable to the other and will in all cases result in lower costs compared to other options. There will always be interfaces between equipment, systems and structures that will need to be managed (be it at location that depends on the adopted procurement strategy). The optimal balance has to be found and may differ depending on the countries (authorities, engineering resources, etc.). What can be said is that by the very fact of there being several solutions, these can compete with each other and in this way lead to capital cost reduction according to how many plants will be built (series of equipment, etc.).

With respect to the suppliers of goods, work and services, the following improvements can lead to cost reduction.

The QA/QC programmes represent a significant cost for a new power plant. Often they result in extremely costly nuclear-specific components that in reality are practically identical to similar components used in a non-nuclear environment. The QA/QC programmes were fully justified in the seventies at a time when the common industrial standards included less QA/QC, and the nuclear industry faced the need for higher quality products. Thanks to modern QA/QC requirements being applied to common industrial products this difference in quality has narrowed to a point where, today, in many cases, a quality has been reached that could be demonstrated to be as good as a nuclear grade. An extensive use of non-nuclear components, even in safety systems, would lead to a significant reduction in cost without adverse influence on overall safety.

Bid invitation procedures can be optimised regardless of where the various contracts are awarded (general contractor, main contractors, owner) by:

- Arranging a break-up into items that makes it possible for the manufacturers to offer their standard products.
- Preparing calls-for-tender and specifications that are simplified and are more focused on the essentials, so that bidders may include minimal margins for contingencies and risk.

- Broadening the list of bidders so as to avoid there being maintained or created some monopolistic niches.
- Increasing the robustness of the contractual arrangements (firm and all-inclusive prices, adequate performance guarantees and liquidated damages, strict design-change processes).

Optimised procurement strategy in the United Kingdom

A main line procurement strategy is proposed for the new PWR projects, which is based on reducing the number of major contract packages from 111 to six major packages comprising:

- Traditional buildings: site services, sewage, water, etc.
- Seashore package: cooling water inlet/outlet, radwaste, etc.
- Mechanical and electrical: pipework, valves, switch-gear, cabling C&I, etc.
- NSSS: primary circuit, inspection, etc.
- Main civil works: main building, storage tanks, etc.
- Turbine island: turbine generators, feedwater pumps, transformers, etc.

In consideration of all alternatives strategies this is perceived as being a less risky option both in terms of cost and potential programme duration. In addition a flexible approach will be adapted for individual packages of work with contractors. This will avoid unnecessary and inflationary commercial practices, taking advantage of discounts available. Schemes may include advance payments in line with international practices, restructuring of payment terms and incentive arrangements.

The main benefits of the revised procurement strategy include:

- Enhanced competition.
- Increased productivity.
- Risk reduction.
- Interface reduction.
- Decreased number of management layers.

The table below quantifies savings that may be realised by utilising an optimised procurement strategy for a new PWR project in the United Kingdom.

Table 12. **Percentage saving in comparison to original strategy**

Area of savings	% Saving in comparison to original strategy
Traditional buildings	13.0
Seashore package	11.5
Mechanical and electrical	16.0
NSSS	4.5
Main civil	8.6
Turbines	15.4
Total project	**10.6**

The French experience

EdF carries out a multiple-package contract for the supply of equipment items and their erection on the work site that enable the utility:

- To perform a less costly design because it will always select the economic optimum (in compliance with the requests of the nuclear safety authorities).
- To have full control over the dialogue with various Administrative Authorities and therefore over the cost of the requirements laid down by them.
- To bring the various sub-contractors of the main suppliers into competition and therefore obtain the best prices in its favour.
- To avoid paying contingency margins to the main suppliers for sub-contracts.
- To be able to follow up construction on site and commissioning tests to an improved extent.
- To control more easily the cost of modifications during the operation of the units.

EdF has evaluated these savings within a range of 10 to 15% of the investment cost (excluding interest during construction), that can be broken down as follows:

- Between 8 and 12% for the investment.
- Between 2 and 3% for operation savings.

Standardisation and construction in series

The benefits that derive from standardisation relate mainly to the consolidation of plant safety and the avoidance of much first-of-a-kind effort. The safety impact arises in the main from the adoption of proven approaches and the wider applicability of operational feedback. The expenditure of first-of-a-kind effort is avoided by standardising on the design, manufacturing, construction, licensing and operation approaches developed for the first project.

In repeating any complex engineering design some time after the original, a number of factors arise which affect the extent to which replication can be fully achieved. Such factors include things like the unavailability of contractors or sub-contractors, advances in applicable codes and standards, the obsolescence of parts and changes in licensing requirements. Furthermore, where replication is applied to the development of a twin unit station, the use of shared facilities between the two units will affect replication.

The main aspects of standardisation strategy ensure:

- That the global design, in terms of the major plant items and interactions, will be replicated.
- That the original design functionality and plant interactions will be maintained as far as possible.
- That replication will be provided in the embodiment of the plant, if no factors arise, which would affect or prevent this.
- That where revised codes or practices are adopted, they will be confirmed as representing equivalent requirements or ones that can be fully justified.

Modifications to the design have been limited to:

- Site specific items:
  - Ground conditions (with reference to seismic assessment).
  - Cooling water works.
  - Shared facilities.
- Amendments caused by legislation or regulatory directives.
- Equipment no longer available.

Parameterisation of the effects of standardisation and construction in series

The purpose is to propose a parameterisation of the reduction of nuclear power plant investment costs by implementing a programme of several standardised units built on one or more sites, with one or more units on the same site. The parameterisation can help the assessment of the series effect in various cases.

Effect of standardisation and construction in series

The construction of standardised units in series lowers the average investment costs:

- By the breakdown of fixed costs over all the units in the programme (programme effect).
- By productivity gains, made possible both in the shop for the fabrication of equipment and in the design office for the processing of documents specific to each site, as well as for the construction of buildings, erection and tests (productivity effect).

In addition to these two effects, there are further savings when it is possible to build several units on the same site.

The quantification of these various effects depends to a great extent on:

- The degree of standardisation of the units.
- The assessment of the fixed costs of the programme borne by the investor (first-of-a-kind extra cost).
- Expected gains from the construction of several units on the same site.
- Expected reduction of costs, due to the productivity effect, both at manufacturers’ facilities and on construction sites.

First-of-a-kind cost (FOAK)

The additional cost related to the construction of the “FOAK” unit corresponds to the fixed costs of the programme. It may be more or less substantial, according to the degree of standardisation and the procurement policy chosen.

It corresponds to the costs of the following items:

- Functional studies.
- Drawing up of technical specifications for ordering of equipment.
- Negotiation of equipment procurement contracts for several units.
- General layout of the power-block.
- Detailed design of civil engineering of standard buildings.
- Detailed design of equipment.
- Detailed design for piping and cabling.
- Drawing up of testing and commissioning procedures.
- Drawing up of operating documents.
- Safety studies.
- Qualification of equipment and facilities.

Productivity effect

The productivity effect depends on the rate of commitment of the units and on the owner's procurement policy.

The optimum commitment rate is that which provides good operational feedback from one construction project to the other, while serving to maintain the apprenticeship effect in the manufacturers' facilities and on the sites.

The most favourable procurement policy to obtain the best prices from the suppliers consists in ordering the equipment of all the units under the same contracts.

Parameterisation of the series effect

The parameterisation has been done in the case of the construction of standardised units as part of a programme of n units ordered simultaneously for phased commissioning.

It can be applied also if sites are equipped with one or more units, isolated or in pairs.

It is assumed for the parameterisation of the series effect that the units can be designed to share a number of technical services per pair of units.

It is also assumed that most of these technical services must be re-established for the construction of a second pair on the same site. However, some equipment components will remain identical regardless of the number of units built on the site (such as access roads and railways, reception, public information and safety buildings, emergency station, heliport, meteorological station, and some administrative and technical buildings).

Additional assumptions:

- Unit 1 bears all of the extra FOAK cost.
- The cost of engineering specific to each site is assumed to be identical for each site.
- The cost of facilities specific to each site is assumed to be identical for each site.
- The standard cost (excluding extra FOAK cost) of a unit includes the specific engineering and specific facilities for each unit.

Parameters selected:

- x: FOAK extra cost parameter.
- y: parameter related to the gain in building a pair of units.
- z: parameter related to the gain in building two pairs of units on the same site.
- k: industrial productivity coefficient.

The coefficients x, y and z express the “programme” effect; while the coefficient k expresses the “productivity” effect.

Formulation of the programme effect (included effect of construction of several units on the same site):

If To is the standard cost (excluding extra FOAK cost) of the sole unit on a site:

- Cost of the first unit: $\mathrm{T} = (1 + x)\mathrm{To}$
- Cost of the following units: To (if programme of 1 unit/site).
- Cost of the 2nd unit on a site with one pair: y To.
- Cost of the 3rd unit on a site with two pairs: z To.
- Cost of the 4th unit on a site with two pairs: y To (it is assumed that the cost of the 2nd unit of a pair is independent of the rank of the pair on the site).

Formulation of the productivity effect

It is considered that a productivity effect only occurs as of the 3rd unit of a series.

If n is the rank of the unit in the series, and Tn is the cost which results from taking into account the sole programme effect, it follows that:

$$\mathrm{T}'n = \mathrm{T}n / (1 + \mathrm{k})^{n-2} \text{ as of } n = 2$$

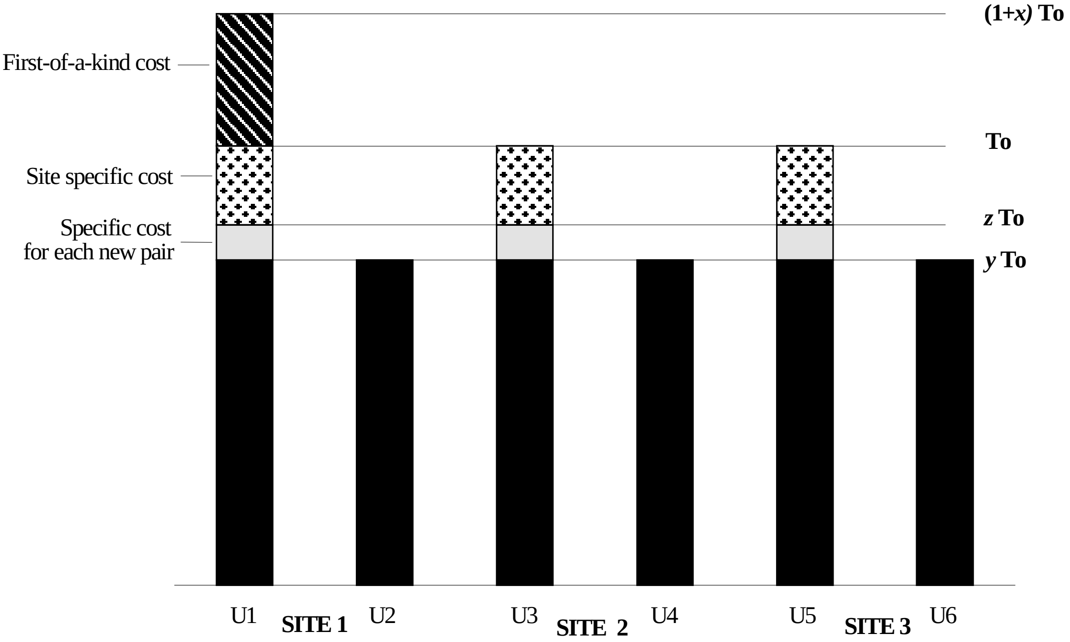
Bar graph representation

The decline of the cost of the units is shown in Figures 8 to 13.

Resulting effects of standardisation and construction in series

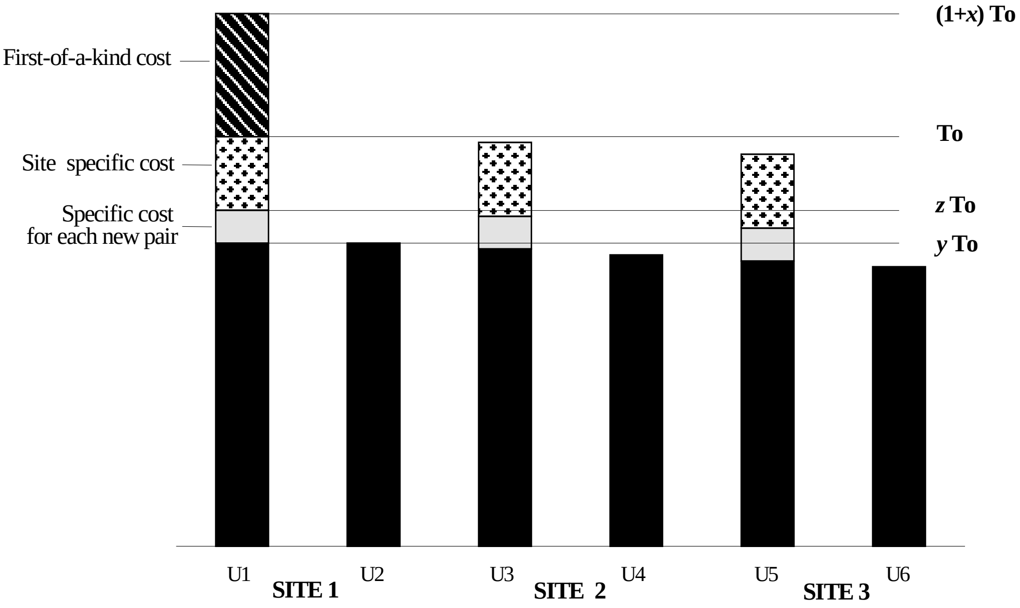
A study performed in France (EdF, Framatome) showed that the most sensitive parameter is the extra cost of the FOAK unit, x ranging from 15% to 55%, according to the nature and amount of changes in the design.

Figure 8. **Units/site with no productivity effect**



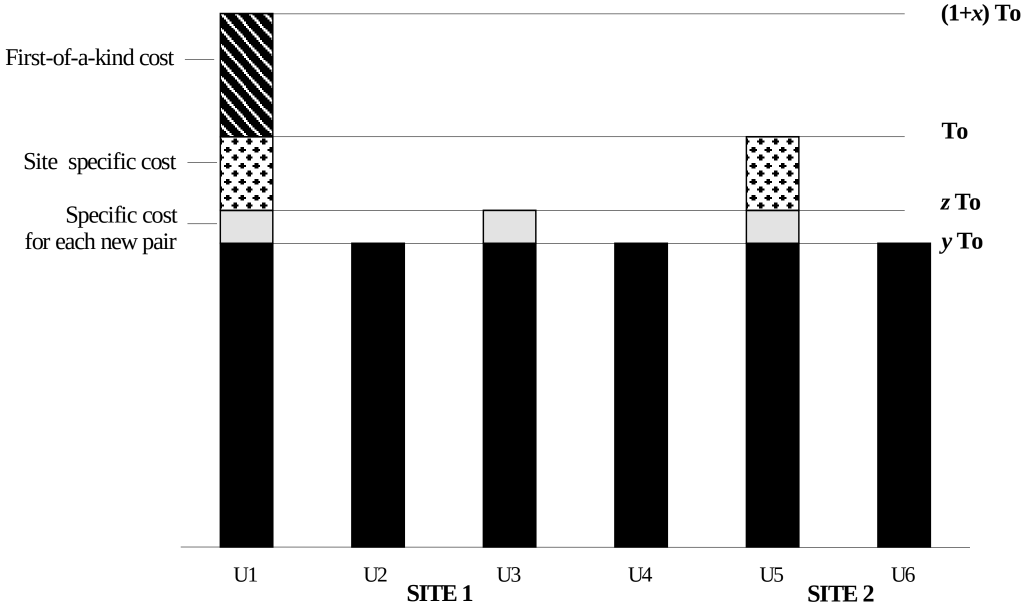
Note: Basic principle of cost reduction due to series and site effects (2 units/site; no productivity effect taken into account).

Figure 9. **Units/site with productivity effect**



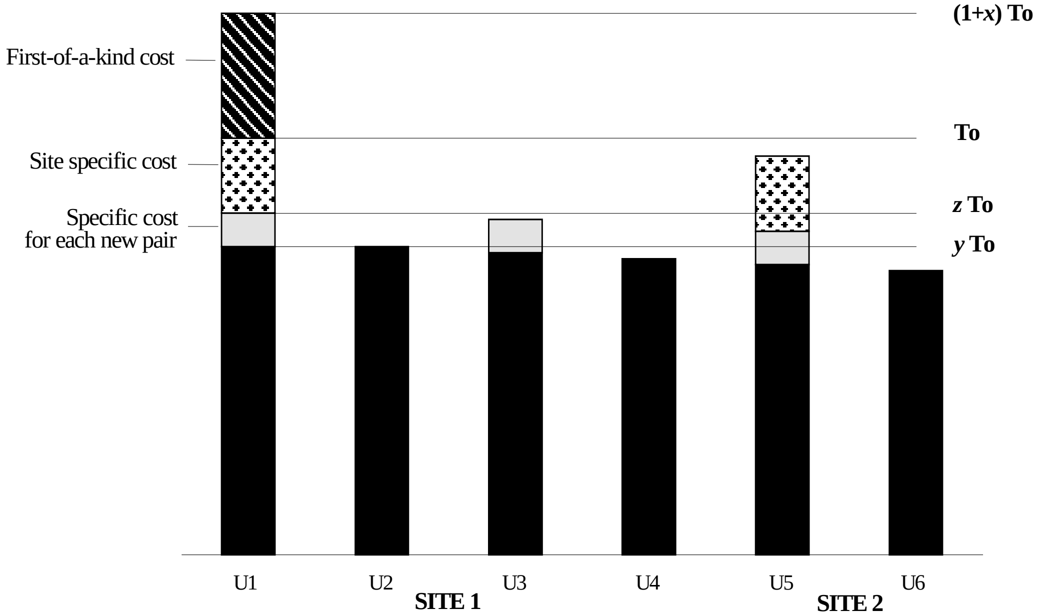
Note: Basic principle of cost reduction due to series and site effects (2 units/site; productivity effect taken into account).

Figure 10. **Units/site with no productivity effect**



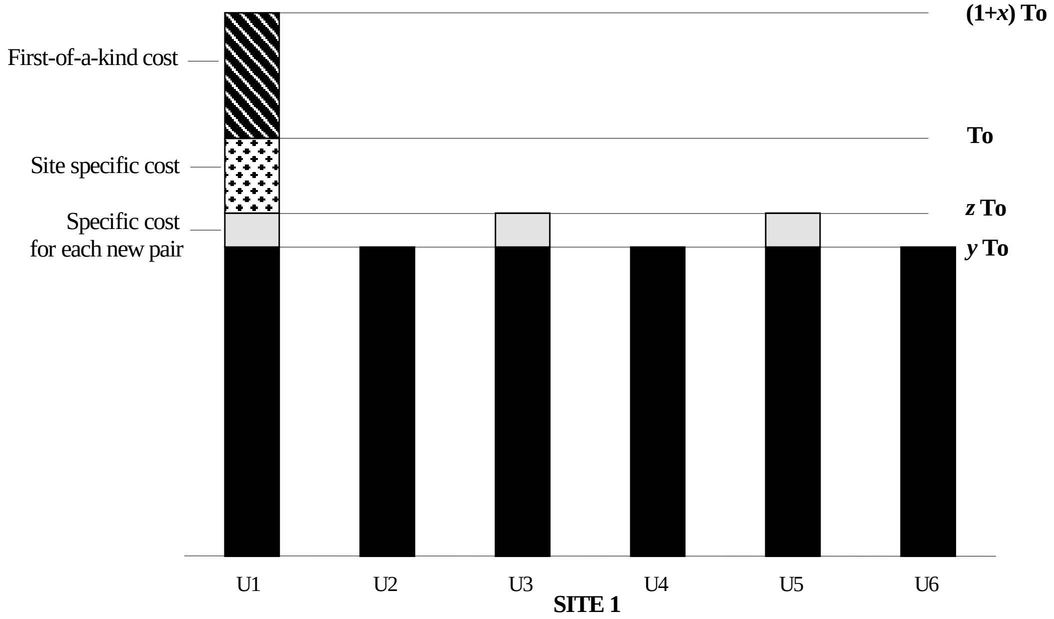
Note: Basic principle of cost reduction due to series and site effects (4 units/site; no productivity effect taken into account).

Figure 11. **Units/site with productivity effect**



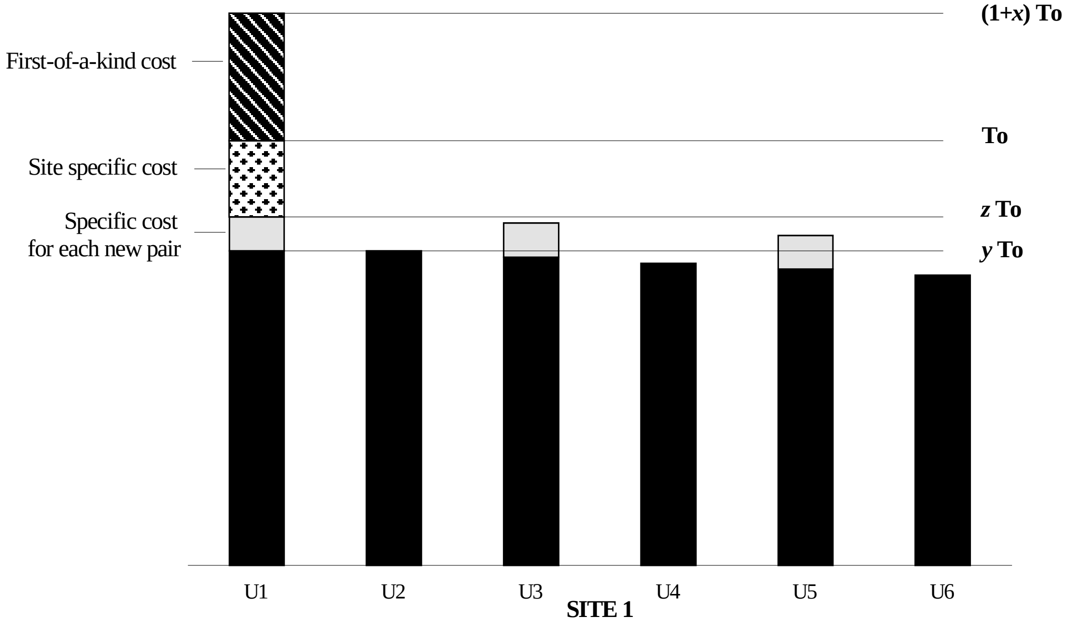
Note: Basic principle of cost reduction due to series and site effects (4 units/site; productivity effect taken into account).

Figure 12. **Units/site with no productivity effect**



Note: Basic principle of cost reduction due to series and site effects (6 units/site; no productivity effect taken into account).

Figure 13. **Units/site with productivity effect**



Note: Basic principle of cost reduction due to series and site effects (6 units/site; productivity effect taken into account).

For the effect of the construction of several units on the same site, the calculations were made for two fairly contrasted cases:

- **Case 1:** moderate decline of the cost of the units on the same site, corresponding to a low sharing of technical facilities between units.

  The corresponding parameters are $y = 85\%$ and $z = 95\%$.

- **Case 2:** higher decline of the cost of the units on the same site, corresponding to a higher sharing of the facilities between units (real case observed at EdF).

  The parameters are $y = 74\%$ and $z = 82\%$.

Each case is examined for two productivity effects:

- $k = 0$: no productivity gains.
- $k = 2\%$: the productivity gain on the 8th unit is 10% compared with the cost of this unit with no productivity gains.

The results are presented in the chart shown in Figure 14 for the case of EdF (i.e. $x = 55\%$, $y = 74\%$, $z = 82\%$, $k = 2\%$) in the three following situations:

- One unit per site.
- One pair of units per site.
- Two pairs of units per site.

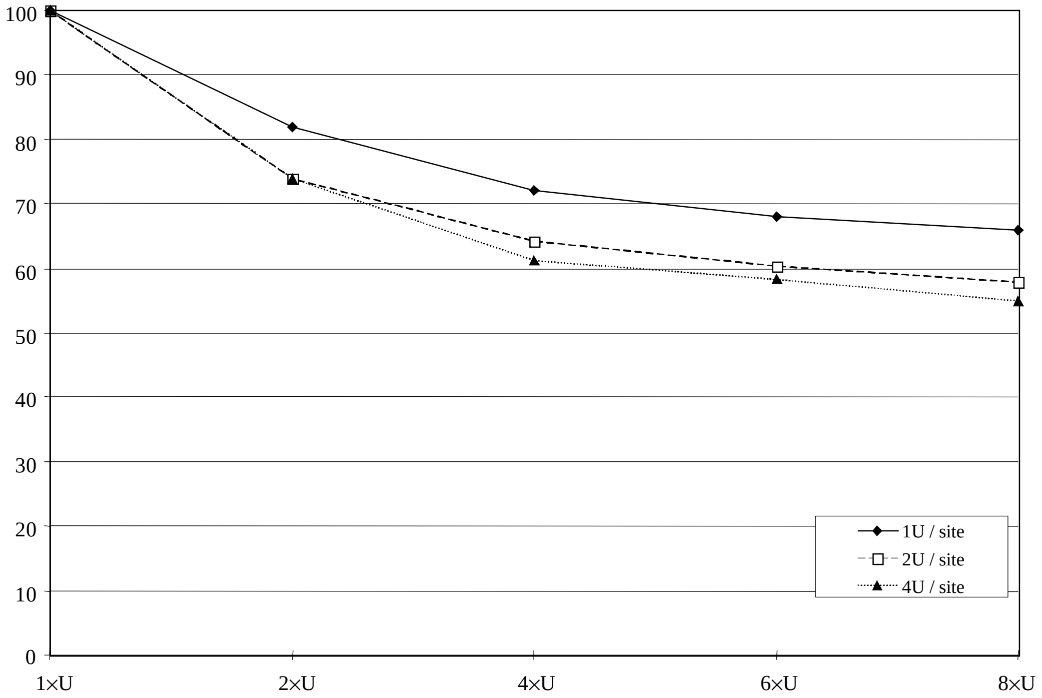
The indicated costs are the average costs of a unit in a programme of *n* units.

The Korean experience

The standardised approach to design, component and construction can substantially improve efficiencies in manufacturing, engineering, construction and schedule. Standardisation to suit a wide variety of site conditions with minimum site-specific changes provides the basis for multiple-unit replication and series manufacturing. The standardised design and construction can increase regulatory licensing stability and reduce licensing time and costs. The standardised design also offers increased assurance of public safety in the form of highly engineered system simplification and improvement. Based on repetitive fabrication, construction and operation of a series of plants, the experience gained is extensively used for the next series of plants. The construction techniques become more refined, leading to cost reduction and schedule shortening. The substantial completion of standardised designs before construction starts ensures saving from shortened construction period and much reduced costs of rework.

It was found that the construction period of 75 months which was the time taken for the first twin nuclear units could be reduced to 53 months for the second twin units with reductions in both overnight costs and in time related costs as indicated in the Table 13.

Figure 14. **Average cost of one unit in a programme of *n* units**
***x* = 55%, *y* = 74%, *z* = 82%, *k* = 2%**



The impact of standardisation on overnight costs is quite substantial, with cost savings between 15% and 20%. The impact on time related costs (interest during construction), is very important due to the substantial reduction of the construction period. The time related costs could decrease by more than 60%. When the time related cost savings are combined with those of overnight cost reductions, the total costs are decreased between 25% and 40%.

The implementation of standardisation should be co-ordinated with long-term strong commitment by the Government and utilities. A series production would add to the benefits arising from standardisation. It is reported that most of the series production benefits are achieved when more than six units are implemented.

Table 13. **Cost savings due to standardisation**

Unit: 1 000 Won/kWe

Cost components	First twin units	Second twin units
Design and managing services	169	58
Equipment and materials	608	577
Construction overheads	180	159
Owner’s costs	193	187
Total overnight costs	**1 150**	**981**

The UK experience

In the case of Sizewell-B in the United Kingdom, there were very significant costs involved in establishing PWR technology through transfer agreements with Westinghouse and Bechtel. In addition almost a complete redesign was required to meet United Kingdom standards and requirements based on the initial design and safety case for the US Standard Nuclear Unit Power Plant System. At its peak the engineering staff exceeded 1 000.

The largest single element of FOAK costs was incurred by the design team together with the sub-contracted design development work placed with consultants and design organisations. In addition, high fees were paid to civil engineering consultants.

The second largest element was the cost of the nuclear steam supply system. Significant costs resulted from the setting up of design and project teams in the United States and in the United Kingdom. Included within theses figures were detailed computer design works. The majority of this would not be incurred for a follow on station.

During the construction phase, additional FOAK costs were expended to meet design development while contracts were running. FOAK costs associated with civil contracts were relatively low, but it would be expected that in a future project the drawings and construction methods would be established well in advance of the civil works. This should result in much higher productivity, as the contractor would not be interrupted by the design revisions that inevitably take place on a FOAK construction project.

A significant amount of FOAK costs arose from the mechanical and electrical contracts. These costs generally relate to the contractors' detailed design work, manufacturing drawings, equipment qualification, establishing assurance procedures and setting up special facilities. In the case of turbine generators, which were based on established technology and production machines, FOAK costs were low.

The key extra FOAK costs related to the detailed design of Sizewell-B; the detailed development of the safety case, and contractors costs specific to the supply of plant and equipment are given below.

Cost area	Extra FOAK costs (% of total costs)
NSSS	27
Civil	6
Other electrical	35
Other mechanical	28
Software	42
Turbines	1.5
Total project	**26**

The NII is the Nuclear Installations Inspectorate through which the Nuclear Safety Division of the Health and Safety Executive administers the Nuclear Installations Act 1965.

Based upon licensing experience gained from Sizewell-B it is anticipated that satisfactory resolution of the NII items regarding a twin station can be achieved without disruption to the project programme. Hence the licensing of Sizewell-C should not pose a significant constraint.

The NII have estimated that some 350 man-years of effort were expended on the safety assessment of Sizewell-B. For Sizewell-C, which would closely replicate Sizewell-B, the NII have estimated that the effort would be in the order of only 35-70 man-years. This substantial reduction in effort demonstrates the considerable advantages of replication.

In the assessment of the nuclear utility design, savings in the order of 90% would be realised. However, it has been noted by the NII that, even with the transfer of experience gained from Sizewell-B, the cost for the inspection of construction, testing and commissioning would remain at a similar level to Sizewell-B. Limited information is available regarding the costs of NII site works.

Multiple unit construction

Construction of several units on the same site provide opportunities for capital cost reduction, e.g. in:

- Siting.
- Licensing costs.
- Site labour.
- Common facilities.

In addition to the obvious sharing of the site acquisition and land costs, site-licensing costs are shared among multiple units. During the construction phase, considerable efficiencies and associated savings can be gained from phased construction and rolling the various craft teams from one unit to the next. In addition, by construction repetition, there is the craft labour learning effect that reduces the time to perform a given task and correspondingly reduces both labour cost and schedule.

Finally, multiple-unit plants can obtain significant cost reduction by using common facilities such as:

- Access roads and railways.
- Temporary work site buildings.
- Administration and maintenance buildings.
- Some technical buildings according to the design adopted, e.g. production of de-mineralised water, auxiliary steam, compressed air, emergency power supply, gas storage, oil storage, etc.
- Warehouses, workshops, laboratories.
- Reception and public information buildings and guardhouse.

It also makes it possible to reduce the average cost per unit of some services or items of equipment:

- Environmental impact and hazard studies.
- Administrative procedures.
- General platform earthworks.

- Water intakes and outfalls.
- Roads and utility networks.
- On-site fire protection.
- Surveillance facilities.

The multiple-unit construction experiences at the same site in a number of countries can be summarised as follows:

Canada

Multiple unit construction at the same location will lead to considerable savings. For example, the specific cost of building a 4 × 670 MWe plant in Ontario is about 14% less than that for a 2 × 670 MWe plant on the same site. The estimated saving is more pronounced for the larger 900 MWe class reactors.

Estimated costs of CANDU plants to be constructed in Canada shows the benefit of unit size and multiple unit construction (see Table 14). The following specific costs were used by Ontario Hydro in 1992 as the basis on which the future power system expansion programmes in Ontario were evaluated and formulated. As Ontario Hydro is moving towards the privatisation path, no publicly available cost data has been released from Ontario Hydro since 1992. It is estimated that these cost values have been increased by about 12% in the period 1991 to 1997.

Table 14. **Specific overnight costs of CANDU plants in Canada**

Number of units	Unit size (MWe)	Specific capital costs* (1991 C$/kWe)
1	670	3 140
2	670	2 600
4	670	2 240
2	881	2 750
4	881	1 980

* Costs include initial fuel and heavy water inventory but no interests during construction.

Mexico

The Laguna Verde Units 1 and 2, both being BWR 654 MWe, were built at the same site with the time span of 48 months. The Laguna Verde Unit 2 performance was higher as it could be verified using installation performance indices for all disciplines such as civil, mechanical, etc. The improvement was estimated at 20%. The construction time for the last 50% of Unit 1 was 6 years, whereas it was 4.5 years for Unit 2. The start-up took about 17 months for Unit 1, whereas it took 7 months for Unit 2.

Czech Republic

The Temelin and Dukovany NPPs sites were originally prepared for the construction of four units. Such preparation saved a significant amount of money on common temporary facilities, infrastructure, engineering etc. However, after the political decision to reduce the number of units at the Temelin site, invested capital in the site and project development was locked in. Such experience leads to the observation that the expenditures on common temporary facilities and engineering can be split 60:40 between the first and the next unit.

France

The impact of building twin units on the same site is assessed on the cost of the serial unit. In other words, the assessment excludes the extra costs of building the first of the kind of the series, which is carried out only once for the entire series (including all of the generic studies, equipment qualifications, etc). The extra cost is evaluated at 30% of the cost of the first pair of units.

All construction of nuclear units in France has been carried out for at least two twinned units. Except for equipment specific to the units, this type of construction includes facilities common to both units: site accesses, administrative buildings, shops, stores, auxiliary services (de-mineralised water, fire protection, compressed air, auxiliary steam, various roads and utility networks, etc.). The cost of building a single unit on a site, compared with the average cost of a power plant with a pair of units, was estimated by applying ratios varying from 0.5 to 1.0 to the costs of the main items of equipment and structures.

In general, it is assessed that the construction cost of a single unit is about 15% higher than the average cost of a unit for a site with two units.

In the same way, the construction of several pairs on the same site provides savings in:

- Single construction of certain facilities: site access, site buildings, etc.
- More economical construction cost of paired structures: earthwork, development, water intake and discharge structure, etc.

An analysis of the cost of EdF’s projects with several pairs shows a reduction in the construction cost for a second pair of about 10%.

EdF has no representative operational feedback for the construction of more than two pairs on the same site. It is estimated that there is no significant gain as of the second pair and that the subsequent pairs (apart from the series effect) are built at the same cost as the second pair.

Sweden

Replication effect could make the construction costs of second, third and fourth project to be 15-20% cheaper than the first project.

United States

Analyses of realised nuclear power plant construction costs suggest that there are economies from building more than one unit on the same site. That is, these analyses found that the overnight cost of a single unit or the first unit at a multiple-unit site was about 25 to 35% greater than the second or third unit at the multiple-unit site. Such economies result from the fact that fixed common costs such as site preparation and security can be spread over all the units at a site. It must be noted that some of the cost savings found in these studies were due to the US regulatory accounting practice of allocating a disproportionate fraction of the common costs to the first unit of a multiple-unit site.

United Kingdom

British Energy has limited quantitative information regarding the construction of multiple nuclear power units. The figures presented below are based upon a comparison between Sizewell-B – a single unit PWR station and the proposed Sizewell-C – a twin unit PWR station.

The savings resulting from building twin units come from three major areas:

- Reductions in contract prices due to the economies of scale.
- Shared facilities.
- Reduction in management costs.

Contract prices

The ability of the contractor to manage his manufacturing and erection activities over a twin-unit station coupled with a discount which could be expected from purchasing two sets of equipment rather than one would reduce the price of the contracts. Cost savings are realised from improved:

- Productivity.
- Quantity discount.
- Site management.
- Continuity of work.

Shared facilities

The sharing of facilities can result in a significant saving in capital cost. The main shared elements on the proposed twin station are:

- A single cooling water pump-house would serve both units.
- Reduction in the number of diesel generators required for back-up electrical supplies.
- Rationalisation of the auxiliary cooling water system.
- Single radwaste building.
- Common services (Towns water reservoirs, nitrogen storage, etc.).
- Common administrative building, gatehouse, fire station and other support buildings.

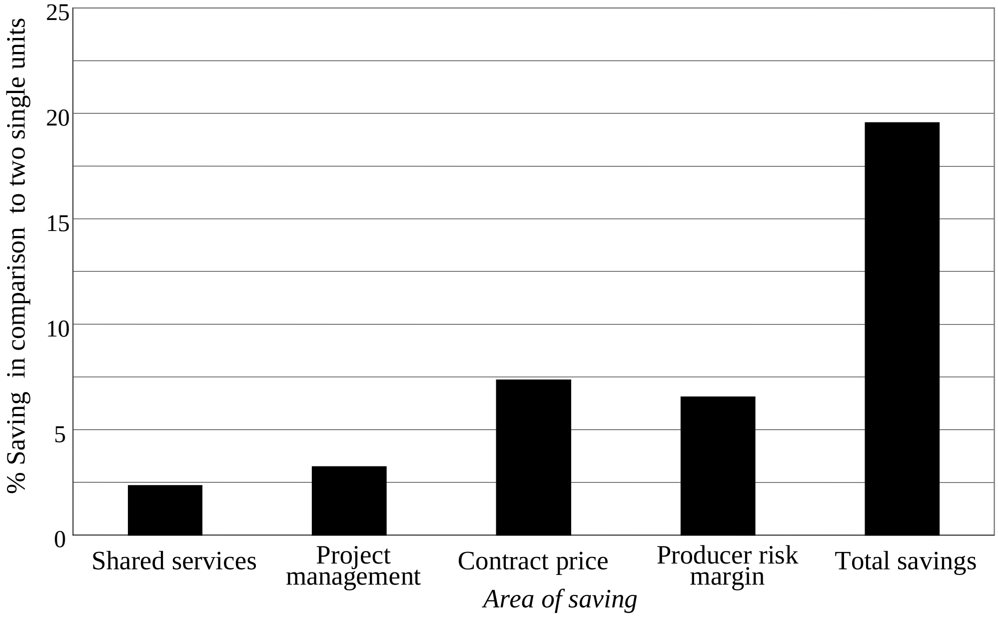
Reduction in management/licensing costs

There will be significant savings in the area of owner/architect engineering, project management and site supervision required for a twin unit station.

Capital cost estimate for Sizewell-C with replication of Sizewell-B

The graph below quantifies the savings from building a twin station in comparison to the cost of two separate units of a similar design.

Figure 15. **Cost saving in comparison to total capital cost of two single units**



Figures shown are based on units similar to Sizewell-B with adjustments for first-of-a-kind (FOAK) costs and design changes. Pre-generation costs are excluded.

Including pre-generation costs, savings in the order of 11% could be realised by building a twin station in comparison to two single units.

Cost savings of constructing a twin station in comparison to the total capital cost of two single units are given below in percent.

NSSS : 6.1%
Civil : 6.6%
Other mechanical : 8.1%
C&I : 11.3%
Electrical : 8.5%
Construction and commissioning : 10.2%
Software : 33.8%

Costs factors for utility type

A preliminary study has been conducted in the United Kingdom comparing the twin-factor cost (the cost of a twin unit in comparison to a single) for a variety of reactor types.

The estimated figures for specific reactor types are given below. Data is based upon a basic turnkey contract including risk margin and United Kingdom weighting for Primary Circuit Plant, Inspection and Validation.

Reactor type	**N4**	**KONVOI**	**ABB-CE**	**MHI/W**	**MHI 4 Loop**
Factor	1.69	1.76	1.71	1.76	1.73

Regulations and policy measures

Regulatory requirements can have significant impacts on the design itself and on the duration of the design and construction period. By having a firm design and licence acceptability in advance of construction, the financial risk in a project is reduced. After the establishment of a nuclear programme, stabilisation of the licensing process will have the next greatest impact on capital cost reduction, by avoiding last minute changes, delays and back-fitting. The American experience described below illustrates these points.

Past experience

Past experience in the United States provides a useful illustration of the influence that plant design and associated licensing activities can have on power plant costs. In the late 1960s and early 1970s, over 50 US utilities began separate and independent nuclear plant procurement programmes. In response, at least six nuclear vendors, 20 architects/engineers, and 26 construction contractors entered the market to supply the needed equipment, materials and services. The end result is 54 utilities managing 110 plants, most having unique design and operating characteristics.

Each of these plants has been required to meet a growing number of regulatory requirements, particularly after the Three Mile Island accident. Over the entire decade of the 1970s, there were numerous NRC-related design changes affecting both existing nuclear power plants as well as those under construction. These changes produced increased capital modification costs for operating plants. Statistical analysis suggests that about 60% of the capital modification costs have resulted from regulation and other factors associated with calendar time.

During the last 8 to 10 years, the US nuclear industry has undergone major managerial and operational process transformations. These include various regulatory aspects that have experienced serious transformations for the benefit of nuclear technology competitiveness in the arena of current privatisation and market deregulation that is paving the road to a more competitive energy industry structure.

Some of the benefits are related to the reduction of generating and capital costs of currently operating plants, others to reduction of generating and capital costs of future nuclear power plants.

The nuclear energy industry and the NRC have complementary responsibilities. The utilities are responsible for seeing that their nuclear plants are operated correctly to insure that public health and safety are protected. The NRC is responsible for oversight – for seeing that the utilities follow through on their responsibilities, and has the authority and responsibility to order immediate shutdown of a plant or revoke a licence, if necessary.

The nuclear plants regulating process is in need of reform; “The regulations are so complex that immense efforts are required by the utility, by its suppliers, and by the nuclear regulatory body, to assure that regulations are complied with … This Commission believes that it is an absorbing concern with safety that will bring about safety – not just the meeting of narrowly prescribed and complex regulations”.

The above, were the words written 20 years ago by the Kerneny Commission, responsible for reviewing the accident at the Three Mile Island nuclear power plant.

The nuclear energy industry is mature with over 2000 reactor-years of safe operating experience behind it. New analytical tools provide tremendous insight into the relative safety significance of various plant equipment and systems.

The US industry has identified four major areas for improvement in the process of regulating nuclear power plants:

- Prescriptive: the process is overly prescriptive, a legacy from the 1950s and 1960s when knowledge of nuclear safety was limited.
- Shifting regulatory interpretations: striving for perfection, the NRC shifts its interpretation of requirements even though the rules themselves may remain unchanged.
- Use of generic communications: the regulatory party often uses generic communications to attempt to impose new requirements because this approach is faster and lacks the rigor of the rule-making process required.
- Reluctance to use risk insights*:* many aspects of the regulatory process could be made more efficient and safety-focused through the use of risk insights.

There is a broad support within the industry and the NRC to move toward a risk-informed, performance-based regulatory process, made possible by the development of a new analytical tool called “Probabilistic Safety Assessment” (PSA), also known as “Probabilistic Risk Assessment” (PRA).

In a risk-informed, performance-based approach, the regulator would establish basic requirements and set overall performance goals. Plant management would then decide how best to meet the stated goals. It is more sharply focused on safety than the current approach, because resources are applied to plant equipment and systems in a way that corresponds to its safety relevancy. This approach makes operating experience and engineering judgement concur with information on the relative safety significance of systems and equipment. Performance-based regulation focuses on results as the primary means of regulatory oversight, using measurable parameters for monitoring the performance of plant systems, equipment and management.

Jointly with the regulator, plant management establishes objective criteria for assessing performance based on risk insights, engineering analysis and performance history. The plant management has the flexibility to determine how to meet the established criteria and the procedures for monitoring and maintaining them. If management itself is not satisfied with performance or fails to meet the operating criteria, they can fine-tune the program as needed to get the desired results without having to go through a lengthy regulatory process for approval. The regulator is only concerned whether the established criterion is met or not.

The NRC and the industry are conducting a pilot project in Risk-Informed, Performance-Based Regulation, started in August 1997. During the project, volunteer plants will look for mismatches between safety importance and the level of resources to meet current requirements. Information gained through this project will contribute to identify potential improvements to the regulatory framework. For example, revisions needed in rules or guidance to achieve a proper balance between resources and safety.

Most "performance based regulations" for current plants have potential to reduce costs, like the "fitness for duty policy" change (10CFR26) which reduced drug testing population sample from 100% equivalent station population to a 50% sample in routine sample types. A second example could be the changes to 10CFR50 Appendix J – In Service Inspection and Testing. That resulted in significant savings for existing operating plants. There is also the introduction to the Maintenance Rule – To conduct maintenance that precludes critical failures, which still remains to prove its cost effectiveness; it will probably be an advantage in the long-term.

Nuclear power plant licensing

Today's nuclear power plants were licensed under a system that dates back to the 1950s when commercial nuclear energy was in its infancy. The 1950s vintage licensing process had two major steps: (1) the construction permit, and (2) the operating license. Both steps required formal adjudicative hearings with opportunities for participation by members of the public and others who had questions or concerns about the plant.

The licensing process for future nuclear power plants ensures that all major issues – design, safety, siting and public concerns – will be settled before a company starts building a nuclear power plant.

Under the process, the Nuclear Regulatory Commission approves reactor designs in advance and addresses site suitability – including emergency planning – before construction begins. Opportunities for public participation are provided at each stage. If all applicable regulations are met, a combined construction permit/operating license can be issued.

This process (provided for in the Energy Policy Act of 1992) will be used to license the nuclear power plants of the future. Plants operating today were licensed under a two-step system that was appropriate for plants built in the 1970s and 1980s. Utilities received construction permits based on preliminary, conceptual designs; design details were not known at that point. So potential safety issues could not be fully resolved until the plant was built. Future nuclear power plants will be almost fully designed before construction begins. As a result, design and safety issues as well as emergency planning and other regulatory issues can be resolved before construction begins.

The Energy Policy Act of 1992 included provisions on nuclear plant licensing reform that have been codified by the Nuclear Regulatory Commission in its rules and regulations.

Nuclear licensing reform ensures that all major design, safety, siting, emergency planning and other regulatory issues are resolved as early as possible before construction begins and billions of dollars are spent. This is possible because future nuclear power plants will be almost fully designed when they are ordered. US electric utilities will not have to seek permission to build a nuclear plant that is only partly designed. Utilities will not find it necessary to perform extensive design and engineering work during construction.

This process improves the former licensing process in two significant ways.

First, it requires the availability of all necessary information to allow public input on design, siting and construction issues early in the process, when such input is most meaningful.

Second, it provides a more stable regulatory environment that is required before utilities or other organisations undertake the large financial investment involved in building a nuclear power plant.

Impact on nuclear power plant costs

While the 62 American nuclear power plants built before 1979 took an average of only five years to build and license, the most recent nuclear plants took an average of almost 12 years to build and license – twice as long as nuclear plants in France, Japan, Sweden and some other countries. Longer construction times meant higher costs. This was one reason why the cost of nuclear power plants in the United States rose from US$300-500 million in the 1970s to an average of about US$3 billion in the 1980s. In a few cases, interest expenses represented half the total cost of these plants.

In many cases, longer construction times were caused by changing regulatory requirements in such areas as fire protection and seismic criteria, and as a result of lessons learned from the 1979 accident at Three Mile Island Unit 2. Because of regulatory changes, plants under construction in the 1980s had to make extensive and costly design and equipment changes during construction.

The reforms in nuclear plant licensing will reduce the likelihood of that situation being repeated in the future by creating a stable, predictable process that ensures meaningful public participation at every step. With new standardised plants and a reformed process for licensing them, the public will be able to satisfy itself that nuclear plants are safe and safely built. Utilities will have all regulatory issues settled before construction begins and can count on a stable, predictable process; and utility customers will have a cost-effective source of electricity. The reformed licensing process turns a no-win situation into a win-win situation.

The ALWR utility requirements document (URD)

The Utility Requirements Document (URD) provides the first level of standardisation of future families of ALWRs and specifies the technical and economic requirements for both a simplified evolutionary plant and a midsize plant that incorporates passive safety features. The URD contains more than 20 000 detailed requirements for ALWR designs.

The ALWR Program was managed for the US electric utility industry by the Electric Power Research Institute (EPRI) and includes participation and sponsorship of several international utility companies and close co-operation with the US Department of Energy (DOE). The cornerstone of the ALWR Program is a set of utility design requirements that are contained in the ALWR requirements document.

Purpose of the requirements document

The purpose of the requirements document is to present a clear, complete statement of utility desires for their next generation of nuclear plants. The requirements document consists of a comprehensive set of design requirements for future LWRS, grounded in proven technology of 30 years of commercial US and international LWR experience. Furthermore, the design requirements build on this LWR experience base, correcting problems that existed in operating plants and incorporating features that assure a simple, robust, more forgiving design.

ALWR simplification policy

Since unnecessary complexity is considered to be the root cause of a wide range of problems in existing plants, ALWR designs will pursue simplification opportunities with very high priority. Therefore, simplicity is incorporated in the ALWR design in many ways, particularly from the point of view of plant operations. ALWR simplification requirements include:

- Use a minimum number of systems, valves, pumps, instruments, and other mechanical and electrical equipment, consistent with essential functional requirements.
- Provide a man-machine interface that will simplify plant operation and reflect operator needs and capabilities.
- Provide system and component designs that assure that plant evolution minimises demands on the operator during normal operation as well as transient and emergency conditions (e.g. minimising system realignments to accomplish safety functions, segregation of safety and non-safety functions unless otherwise justified).
- Design equipment and arrangements that simplify and facilitate maintenance.
- Provide protective logic and actuation systems that are simplified compared to those in existing plants.
- Use standardised components to facilitate operations and maintenance.
- Design for ease and simplification of construction.

Scope of the requirements document

The requirements document covers the entire plant up to the grid interface. It is therefore the basis for an integrated plant design, i.e. nuclear steam supply system and balance of plant, and it emphasises those areas that are most important to the objective of achieving an ALWR that is excellent with respect to safety, performance, constructibility, and economics. The document applies to both Pressurised Water Reactors (PWRs) and Boiling Water Reactors (BWRs).

The requirements document is organised in three volumes. Volume I summarises ALWR Programme policy statements and top tier requirements.

Volumes II and III present the complete set of top-tier and detailed requirements for specific ALWR design concepts. Volume II covers Evolutionary ALWRS. These are simpler, much improved versions of existing LWRS, up to 1 350 MWe, employing conventional but significantly improved active safety systems. Volume III covers Passive ALWRS, greatly simplified, smaller (i.e. reference size 600 MWe) plants which employ primarily passive means (i.e. natural circulation, gravity drain, stored energy) for essential safety functions.

ALWR policies

The ALWR Program has formulated policies in a number of key areas in order to provide guidance for overall Requirements Document development, and to provide guidance to the Plant Designer in applying the requirements. While not design requirements themselves, the policies cover fundamental ALWR principles that have a broad influence on the design requirements. A summary of key policy statements is as follows:

Simplification

Simplification is fundamental to ALWR success. Simplification opportunities are to be pursued with very high priority and assigned greater importance in design decisions than has been done in recent operating plants; simplification is to be assessed primarily from the standpoint of the plant operator.

Design margin

Like simplicity, design margin is considered to be of fundamental importance and is to be pursued with very high priority. It will be assigned greater importance in design decisions than has been done in recent operating plants. Design margins that go beyond regulatory requirements are not to be traded off or eroded for regulatory purposes.

Human factors

Human factor considerations will be incorporated into every step of the ALWR design process. Significant improvements will be made in the main control room design.

Safety

The ALWR design will achieve excellence in safety for protection of the public, on-site personnel safety, and investment protection. It places primary emphasis on accident prevention as well as significant additional emphasis on mitigation. Containment performance during severe accidents will be evaluated to assure that adequate containment margins exist.

Design basis versus safety margin

The ALWR design will include both safety design and safety margin requirements. Safety design requirements, referred to as the Licensing Design Basis (LDB), are necessary to meet the NRC’s regulations with conservative, licensing-based methods. Safety margin requirements, referred to as the Safety Margin Basis (SMB), are Plant Owner-initiated features that address investment protection and severe accident prevention and mitigation on a best estimate basis.

Regulatory stabilisation

ALWR licensability is to be assured by resolving open licensing issues, appropriately updating regulatory requirements, establishing acceptable severe accident provisions, and achieving a design consistent with regulatory requirements.

Standardisation

The ALWR requirements will form the technical foundation that leads the way to standardise certified ALWR plant designs.

Proven technology

Proven technology will be employed throughout the ALWR design in order to minimise investment risk to the plant owner, control costs, take advantage of existing LWR operating experience, and assure that a plant prototype is not required. Proven technology is that which has been successfully and clearly demonstrated in LWRs or other applicable industries such as fossil power and process industries.

Maintainability

The ALWR will be designed for ease of maintenance to reduce operations and maintenance costs, reduce occupational exposure, and to facilitate repair and replacement of equipment.

Constructibility

The ALWR construction schedule will be substantially improved over existing plants and must provide a basis for investor confidence through use of a design-for-construction approach, and completed engineering prior to initiation of construction.

Quality assurance

The responsibility for high quality design and construction work rests with the line management and personnel of the Plant Designer and Plant Constructor organisations.

Economics

The ALWR plant will be designed to have projected bus-bar costs that provide a sufficient cost advantage over the competing base-load electricity generation technologies to offset higher capital investment risk associated with nuclear plant utilisation.

Sabotage protection

The design will provide inherent resistance to sabotage and additional sabotage protection through plant security and through integration of plant arrangements and system configuration with plant security design.

Good neighbour

The ALWR plant will be designed to be a good neighbour to its surrounding environment and population by minimising radioactive and chemical releases.

The European utility requirements (EUR)

In late 1991, electricity producers from five European countries entered an agreement to produce a joint utility requirement document aimed at the LWR nuclear power plants to be built in Europe beyond the turn of the next century. The first issue of the EUR document (Revision A) was released in March 1994. Since December 1995, an updated and augmented Revision B is available. The first version dedicated to the power generation plant was released in December 1996. Nine countries participate in the EUR as of today: Belgium, Finland, France, Germany, Italy, Netherlands, Spain, Sweden, and United Kingdom.

Objectives of the EUR document

The EUR document develops requirements addressed to the LWR plant designers and vendors. It is basically a tool for promoting the harmonisation of the most important plant features that are today often country specific. The main policies being considered for this convergence process are:

- Safety approaches, targets, criteria and assessment methods.
- Standardised environmental design conditions and design methods.
- Design features of the main systems and equipment.
- At a lower level, equipment specifications and standards.

Benefits are expected essentially in two fields:

- Strengthening of nuclear energy competitiveness.
- Improvement in public and authorities acceptance, thus paving the way to an easier licensability of a design developed under EUR in all European countries.

The competitiveness of nuclear power is enhanced by the EUR in:

- Giving the utilities means for controlling construction costs through standardisation, simplification, series ordering and optimisation of maintenance at the design stage.
- Establishing an area large enough in Europe to allow the vendors to develop standard designs that can be built everywhere without changing any fundamental feature in question.
- Establishing stable market conditions for a broader competition between suppliers.

- Making sure that acceptable operation and fuel cycle costs can be achieved – flexible and efficient design features that allow an easy adaptation to future evolution are required.
- Prescribing ambitious but yet achievable availability and lifetime targets.

The EUR document sets out to provide a specification that will result in a number of standard designs which could be built in any of the participating European countries with minimum adaptations to the basic design, and acceptable economic objectives.

Structure of the document

The EUR document is structured into four volumes. Each volume is divided into chapters that deal with a specific topic:

- *Volume 1. Main policies and top tier requirements*: this volume defines the major design objectives, presents the main policies that are implemented in the EUR document.
- *Volume 2. Generic nuclear island requirements*: this volume contains all the generic requirements and preferences of the EUR utilities for the nuclear island.
- *Volume 3. Specific nuclear island requirements*: this volume is divided into a number of subsets. Each subset is dedicated to a specific design that is of interest to the participating utilities.
  It contains the design dependent requirements and preferences of the EUR utilities related to the given design. It also includes a description of the plant and an analysis of compliance with the generic requirements set out in Volume 2.
- *Volume 4. Power generation plant requirements*: this volume contains the generic requirements related to the power generation plant.

Main policies related to capital costs

The EUR aim at the next generation of nuclear power plants. The requirements are generic and they cover both PWR and BWR plants with either passive or active safety features.

Plant size

The plant size must be within the medium-large and large size range, from 600 MWe up to 1 500 MWe nominal electric power.

Level of standardisation

For each vendor, standardisation of the nuclear islands must be achieved and extended as a minimum to the basic design and layout, the safety case, the functional requirements and specifications for systems and equipment, the interface with the remaining parts of the plant, and the set of codes and standards.

Standard site design conditions

A list of the environmental design conditions that envelop the majority of potential European sites is given. The standard design should be capable of adapting to a range of more extreme site conditions without prejudicing the basic design and safety case.

Plant lifetime

The design life of the main pieces of equipment shall be 40 years without the need for major refurbishment. For the components and structures that are not replaceable, the design life shall be 60 years. All other structures and equipment shall be replaceable.

Availability targets

The overall availability of the plant shall be greater than 87%. The average refuelling and maintenance outage shall be shorter than 25 days per year, and refuelling only outage shorter than 17 days.

Construction time

For the *n*th plant of a kind, the vendor shall demonstrate that the construction time can be between 48 months and 60 months, from first permanent concrete to commercial operation. For the first-of-a-kind plant, the construction time must not be more than 12 months longer than the reference objective for *n*th-of-a-kind plant.

Economic targets

The EUR document sets out to avoid over-elaboration of the design by seeking simplicity, and encourages reasonably extensive construction programmes over a shorter period of time so as to minimise interest during construction. Supplemental benefit can be obtained through series ordering and manufacture of plant and equipment.

CONCLUSIONS

Since the mid-1980s, the declining real prices of fossil fuels and the significant improvements in thermal efficiencies of combined cycle power plants have eroded the economic competitiveness of nuclear power plants in most OECD countries. In order for nuclear power to remain a viable option for the next millennium, the cost of electricity from nuclear power plant must be greatly reduced to be competitive with alternative sources. Of the three major components of nuclear generation cost – capital, O&M and fuel – the capital cost component makes up approximately 60% of the total.

Therefore, identification of the means to reduce the capital costs of nuclear power plants is a high priority activity toward keeping nuclear power competitive. This report represents a synthesis of experience and current views of selected experts from the NEA Member countries.

Among a number of capital cost reduction measures, the principal ones were agreed by the Expert group as follows:

- Increased plant size.
- Improved construction methods.
- Reduced construction schedule.
- Design improvement.
- Improved procurement, organisation and contractual aspects.
- Standardisation and construction in series.
- Multiple unit construction.
- Regulatory and policy reform.

Whenever the power system characteristics can accommodate it, building nuclear power plants with larger unit sizes and building several replicate units on the same site will result in the most reduction in specific capital costs (US$/kWe). In Canada, the specific cost of building a single 881 MWe plant instead of a 670 MWe plant (a 31% increase in unit size) will result in a 12% saving in specific capital cost (US$/kWe). This is consistent with analysis in France, showing that the specific cost of building a single 1 350 MWe plant instead of a 1 000 MWe plant (a 35% increase in unit size) will result in a 13% saving in specific capital costs. Results from the United States are similar. However, “increased plant size” measure may not necessarily be the same when considered from more encompassing total capital cost considerations.

Effects of standardisation and construction in series may be the greatest potential for capital cost reduction in nuclear power plants. The benefits that derive from standardisation relate mainly to the consolidation of plant safety and the avoidance of first-of-a-kind costs. A study performed by EdF and Framatome shows that the average cost of one unit in a programme of *n* units decreases by 20-40% compared to the cost of single unit, which depends on the pairs of units per site. According to the Korean experience, the effects of standardisation on overnight costs resulted in cost savings between 15% and 20%. In Sweden, replication effect could make the construction costs of second, third and fourth project to be 15-20% cheaper than the first project. Similar effects by replication and series construction are reported from Canada and the United States.

In addition to building larger unit size and standardised design in series, further savings can be realised when more than one unit is built on the same site. In France, the specific capital cost of building two plants on the same site will lead to a 15% saving in specific capital cost, as compared with building only one unit. Such level of savings is also consistent with reported data from Canada.

Other significant cost reductions are achieved by improving construction methods such as: Open top access, modularization, slip-forming, parallel construction, improved cabling. Potential cost savings resulting from improved construction methods are reported from a small amount to about 5% of total construction cost, which are much dependent on reactor type and site condition.

Shortening construction schedule will lead not only to decrease of interest during construction, but also to earlier profits from the start of commercial operation. Benefits of shorter construction will also include reducing administrative costs and get ride of a variety of risks such as: escalation in equipment, material and labour costs, changing of licensing requirement, public opposition, and political risks, etc.

A key element in project management is the contracting strategy applied in procurement of the equipment and materials. The optimal balance for the cost reduction and project management in procurement and contractual aspects has to be found according to the country's nuclear infrastructure and engineering resources of owners, and the number of plants that will be built in series.

As one aim of next generation reactors is to increase competitiveness of nuclear power plants, a number of significant cost reductions in the design area are expected in the next generation reactors through design simplification and new technology, e.g. passive safety systems.

The Expert group recognised that there was a limitation to quantify the effects of different cost reduction measures and that some specific conditions of the power plants were not fully taken into consideration in analysing the effects. However, it is clear that nuclear power can be much more competitive if countries engaging in nuclear programmes utilise and combine the advantages of above mentioned means to reduce capital costs.

Several necessary steps to further reduce the capital costs of nuclear power plants, such as commitment to a well-defined nuclear construction programme, optimisation of the generation mix to meet power demand, financing, economics and siting issues are country and site specific, and have not been addressed in this study.

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Annex 1

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Annex 2

CAPITAL COSTS OF NEXT GENERATION REACTORS

The European pressurised water reactor (EPR)

The main objectives of the EPR are:

- Improvement of the safety level compared with existing plants, in terms of both deterministic and probabilistic considerations.
- Mitigation of hypothetical severe accidents by restricting their consequences to within the plant itself.
- Power generation costs competitive with other primary energy sources.

The economic requirements have led to a large electrical output, around 1 525 MWe, which keeps the specific (per kW) capital cost competitive. To further reduce the per kW investment cost and taking into account the large design margins which are inherent in the large EPR core, a power increase will be studied in the next engineering phase. The final value was expected to be validated at the end of 1998.

Fuel cycle costs will be improved by achieving a high average fuel burn-up (up to 60 GWd/t). Furthermore, the core design will provide savings in terms of uranium enrichment efforts. Looking to potential requirements of the 21st century, the design also gives consideration to plutonium recycling (up to 50% of the core).

The design allows for cycle lengths of between 12 and 24 months, while 18 months is assumed as the basic option.

An average availability target for the design has been set at 87% over the entire 60-year lifetime of the plants. Therefore, preventive maintenance features are incorporated in the design from the outset to minimise the duration of outages. Refuelling outages of 17 days are envisaged, and the feasibility of this target is being demonstrated.

Description of the technical features

An evolutionary approach has been taken to develop the EPR, which is based on the experience gained in the construction and operation of the existing plants in France and Germany.

The primary system design, loop configuration and the design of the main components is very close to that of the existing designs and can therefore be considered as well proven.

Important safety systems and their support functions (safety injection, emergency feed-water, component cooling, and emergency electric power) are arranged in a four-train configuration, with clear separation of systems and a straightforward operating mode. Combination of several safety functions in a complex system is avoided. Thus operators and maintenance staff get a clearer understanding of the plant status in all conditions.

Different redundant trains of all safety systems are installed in four separate layout divisions for which a strict separation is ensured so that common mode failure, for example due to internal hazards, can be ruled out.

A further reduction in common mode failure potential is obtained by ensuring systematic functional diversity. The complete loss of all redundant trains of a safety system is postulated. It is ensured by design that other functionally diverse systems can maintain the plant in a safe state (e.g. in the event of complete loss of the RHR system, or complete loss of all SG feed, or complete loss of all medium-head safety injection).

The system organisation fulfils the principle of simplification as well as the principle of diversification, since any safety-grade system function can be backed-up by another system (or a group of systems).

The I&C systems used for automatic actuation and control of safety functions are organised into four separated divisions, as are the electrical and fluid safety systems, thus providing a high level of redundancy and ensuring high signal reliability.

Preference is given to equipment relying on digital technology, with the use of “off the shelf” components where possible.

The human factor is fully considered at the design stage of the EPR, taking into account operational situations as well as testing and maintenance. The man-machine interface concept respects the properties and abilities of the operators and uses the capabilities of the I&C systems for operational and safety tasks in an optimum way, without overloading the operator.

Sufficient and appropriate information is available to the operators for clear understanding of plant status, including under severe accident conditions, and render a clear assessment of the effects of their actions. Emphasis is placed on using computerised techniques for reliable diagnostics to provide operator assistance.

Computerised displays providing condensed information and operator controls with touch-sensitive displays are widely used.

All post-accident actions are expected to be performed automatically within the first 30 minutes, with the requirement that the operator be kept in the loop and able to override the automatic process under certain conditions.

The EPR design incorporates the following features for core melt mitigation and the prevention of large releases:

- Prevention of high pressure core melt by having highly reliable decay heat removal systems, complemented by means for depressurisation. A dedicated line will be installed on the pressuriser to handle events that could result in core damages.

- Hydrogen combustion causing high loads is prevented by reducing hydrogen concentration in the containment at an early stage by means of catalytic H_2-recombiners and, if necessary, by selectively arranged igniters.
- Prevention of molten core-concrete interaction by spreading the corium in a dedicated spreading compartment equipped with a protective layer and a system for cooling the structural concrete to ensure its integrity.
- Limitation of containment pressure increase by means of a dedicated containment heat removal system with the possibility, over a few days, of decreasing the containment pressure down to atmospheric pressure.
- A double wall containment ensures all leaks are contained and collected and prevents bypass of the confinement.

Through these measures, the external source terms are limited such that the need for stringent emergency countermeasures (e.g. relocation or evacuation of the population) is restricted to the immediate vicinity of the plant and restrictions on the use of foodstuffs are limited to the first year's harvest.

The reactor building, the fuel building and the four safeguard buildings are protected against external hazards, such as earthquake and explosion pressure wave. All these buildings are situated on a common raft.

Protection against aircraft crash is achieved by bunkerisation of safeguard buildings 2 and 3, the reactor building and the fuel building. The main control room and the remote shutdown station are also located in these bunkered safeguard buildings.

Main technical data of the EPR

Rated thermal power (NSSS)	4272 MWe
Related electrical power (gross)	approx. 1 525 MWe
Efficiency	36%
Reactor coolant system	
Number of loops	4
Operating pressure	155
RPV inlet/outlet temperature	291.3/326.3 °C
Total flow rate	21050 kg/s
Main steam pressure at full load	72.5 bar_{abs}
Main steam pressure at hot standby	84 bar_{abs}
Core	
Number of fuel assemblies	241
Number of rod control cluster assemblies	89
Fuel assembly array	17×17–25
Active height	420 cm
Average linear heat rate	155 W/cm
Maximum enrichment	5%
Total inventory of fuel	approx. 141 t
Batch discharge burn up	max. 60 MWd/kg

Capital cost of the EPR

The following table compares the first-of-a-kind EPR costs with those of the last Konvoi plant that was to be constructed in the 1990s as a series of plants. With the anticipation that the EPR can be built in multiples of twin units, the prices would develop according to the following principle. The ordering of two units at the same time and with a construction interval of at least twelve months will result in a benefit of approximately 15% for the second unit. If the second unit is part of a twin unit the benefit for the second unit is approximately 20%. The ordering of additional units in the same series will not lead to significantly more cost savings. The standardisation effect for more than two units of identical design is expected to be negligibly low.

Capital costs of turnkey nuclear power in Germany

DEM

		KONVOI (Greifswald) 1 380 MWe		**EPR 1 528 MWe (FOAK value)**	
		Historical value 01/1990	**Historical value 01/1990 %**	**Constant value 01/1997**	**Constant value 01/1997 %**
1.	Direct costs				
1.1	Land and civil rights	80 000 000	1.9	80 000 000	1.8
1.2	Reactor plant equipment	1 360 000 000	32.0	1 500 000 000	32.9
1.3	Turbine plant equipment	970 000 000	22.8	800 000 000	17.5
1.4	Electrical plant equipment	250 000 000	5.9	200 000 000	4.4
1.5	Heat rejection equipment	130 000 000	3.1	30 000 000	0.7
1.6	Miscellaneous equipment			90 000 000	2.0
1.7	Construction	760 000 000	17.9	900 000 000	19.7
	Direct costs total	**3 550 000 000**	**83.4**	**3 600 000 000**	**78.9**
2.	Indirect costs				
2.1	Design and engineering	550 000 000	12.9	690 000 000	15.1
2.2	Project management	40 000 000	0.9	90 000 000	2.0
2.3	Commissioning				
	Indirect costs total	**590 000 000**	**13.9**	**780 000 000**	**17.1**
3.	Other costs				
3.1	Training	15 000 000	0.4		
3.2	Taxes and insurance				
3.3	Transportation	25 000 000	0.6		
3.4	Owner's cost	75 000 000	1.8	180 000 000	3.9
3.5	Spare parts				
3.6	Contingencies				
	Other costs total	**115 000 000**	**2.7**	**180 000 000**	**3.9**
TOTAL CAPITAL COSTS		**4 255 000 000**	**100**	**4 560 000 000**	**100**

Safe integral reactor (SIR)

Design intent

The Safe Integral Reactor (SIR) was designed to achieve:

- Small unit size.
- Passive safety features.
- Novel design layout to reduce the unit cost and overcome scale factor effects.

The reactor has a design power output of 320 MWe and a design lifetime of 60 years. The main change in design from a conventional pressurised water reactor is to contain all the major primary components within a single pressure vessel.

In terms of safety, the primary circuit flow is entirely contained in the pressure vessel, thus avoiding large bore pipe failure leading to loss of coolant accidents. In addition, the system provides primary circuit natural circulation decay heat removal and a large contained heat sink in the reactor vessel.

The reactor core has a low power density of 55 kW/litre and has been designed to operate without soluble boron reactivity control. A long refuel cycle of 24 months is achieved through the low power density and burnable poison reactivity control, improving availability.

There are twelve identical steam generators arranged in an annular space in the pressure vessel above the core, which are of a "once-through" design directly producing superheated steam. Secondary water circulates in the tubes making the steam generator less vulnerable to corrosion damage than in conventional steam generators. A defective steam generator can be isolated and the plant can continue to operate at high power, again maintaining availability. Six circulating pumps are mounted around the upper circumference of the pressure vessel, designed without seals. An integral pressuriser is situated in the vessel closure head above the primary circuit components. Spray and surge behaviour is induced entirely by primary circuit volume changes making the operation passive.

Major site welds are not necessary, and this helps to lead to a short construction time of 30 months between first concrete to commercial operation.

Main technical data of SIR

Thermal power	1000 MW th
Electrical power	320 MWe
Efficiency	32%
Reactor coolant system	
Type	Integral
No of steam generators	12
Operating pressure	15.5 MPa
Core inlet temperature	295°C
Core outlet temperature	318°C
Flow rate	7500 kg/s
Main steam pressure	5.5 Mpa

Core	
Number of fuel assemblies	65
Number of CEAs	65
Fuel assembly array	22 × 22
Active height	347.2 cm
Average linear heat rate	91 W/cm
Maximum enrichment	4%
Total fuel inventory	52.3 t
Maximum discharge burn-up	50 GWD/t

Capital costs

Major work on the reactor concept was carried out in 1989. Based on the estimated costs generated by this programme, the overnight capital costs of a production single unit SIR reactor compared with a state of the art 1 300 MWe PWR are given in the following table.

	Fraction of SIR costs compared to PWR costs
Land rights	0.8
Reactor plant equipment	1.2
Turbine-generator plant equipment	1.6
Electrical plant equipment	1.8
Miscellaneous equipment	0.4
Construction	0.8
Total direct costs	1.2
Design and engineering services	0.4
Project management services	0.7
Total indirect costs	0.6
Contingencies	1
Total costs	**1**

As can be seen from the table, the creation of the integral design can reduce some costs per unit of output below that of a conventional PWR in spite of its being a much smaller plant. This is largely achieved by the lowered cost per kW of output resulting from the integral design of the NSSS, although the reduction is limited by the need for the more conventional costs of the turbine generator and electrical plant. Most other costs are reduced as a result of the simplicity of the design and the need for less extensive safety systems. For example, the concrete volume is reduced by 35%, safety related pipework is reduced by a factor of ten and total cable lengths reduced by a factor of two. Construction costs are reduced because much of the plant can be made off site.

The advanced CANDU 9

CANDU 9 is a stand-alone version of the successful integrated multiple-unit 900 MWe plants at Darlington and Bruce Nuclear Generating Stations in Ontario, Canada. Its design evolved in much the same way that CANDU 6 evolved from the Pickering A plants.

Added to all the proven CANDU advantages, CANDU 9 offers more output, better site utilisation, shorter construction time, improved station layout, safety enhancements, and better control panel layout.

Efficiency

Whereas light water reactors evolved from military programs, CANDU was specifically designed for electricity generation. Efficiency was a key consideration. CANDU's efficient use of neutronsis part of its design. On a once-through fuel-cycle basis, CANDU produces about 30 to 40% more electricity per ton of mined uranium than a conventional light water reactor.

Further enhancing CANDU's performance is its unique ability to refuel during full-power operation. This eliminates the need for refuelling outages, and gives utilities greater flexibility in outage planning, as well as shorter overhaul periods. When both CANDU and light water reactors (LWR) are used on a grid, CANDU's operational flexibility complements the fixed fuel cycles and bulk refuelling practice of LWR.

Fuel cycle flexibility

CANDU uses low-cost natural uranium fuel. It can also use a variety of other fuels, and countries that have both CANDU reactors and LWRs have a real advantage because of the fuel cycle synergy between the two reactor types. Potentially, twice as much energy can be extracted from spent LWR fuel recycled in a CANDU reactor than in LWRs.

Long life

A CANDU reactor has a design life of 40 years; 60 years is possible with the replacement of major components. CANDU's modular design allows components to be more easily replaced than in light water reactors. For example, it is much easier to replace the fuel channels in CANDU than the reactor vessel in a light water reactor.

Safety

Canada is a world leader in minimising risk in reactor operation through advanced computer control, superior plant design and construction, the use of the highest quality equipment, and rigorous training for operators.

Advanced CANDU 9 features

CANDU 9 emerges from the experience of 32 CANDU reactors operating or under construction worldwide. Standardisation, a key feature of CANDU, means that all-key components such as steam generators, coolant pumps and pressure tubes are proven with years of successful operation.

CANDU 9 is a single-unit design based on Canada's multiple-unit Bruce and Darlington nuclear generating stations. Combined, Darlington and Bruce offer 120 reactor-years of 900 MWe class operating experience.

This evolutionary approach to CANDU 9 follows the same highly successful experience in adapting the single unit CANDU 6 from the multiple-unit Pickering A plants.

CANDU 9 operates as a single, stand-alone unit, but the design is also suitable for multiple-unit installation at the same site. The following tabulates the key technical data for the 900 MWe class CANDU plants.

	Bruce	**Darlington**	**CANDU 9**
In-service dates	1977-1987	1990-1993	
Number of fuel channels	480	480	480
Fuel bundle	37 elements	37 elements	37 elements
Reactor coolant pressure	9.1 MPa(g)	9.9 MPa(g)	9.9 MPa(g)
Coolant outlet quality	0.7%	2.0%	2.0%
Maximum channel flow	24.0 kg/s	25.2 kg/s	25.2 kg/s
Number of coolant loops	1	2	1
Number of coolant pumps	4	4	4
Number of steam generators	8	4	4
Steam generator surface area	2 400 m^2	4 900 m^2	4 900 m^2
Containment design	multiple-unit	multiple-unit	single-unit

The overnight cost of CANDU 9

The overnight cost of the N^{th} of a kind CANDU 9 (based on the construction of two units on the same site) is estimated at C$3 420 million, in 1 January 1998 Canadian Dollars.

C$ millions

Cost components	**Two unit costs**
Buildings and structures	720
Reactor plant equipment	930
Turbine-generator plant equipment	355
Electrical and I&C plant equipment	448
Water intake and heat rejection	235
Miscellaneous plant equipment	42
Sub-total direct	**2 730**
Engineering	160
Project management	130
Commissioning	100
Sub-total indirect	**390**
Contingencies	200
Insurance and miscellaneous	100
Sub-total other	**300**
Overnight cost	**3 420**

Note: The above cost estimate excludes initial fuel and heavy water inventory, which could add about 10-12% to the overnight cost.

The CANDU 9 advantage

CANDU 9 uses proven strengths and features of CANDU. However, in its evolution from a multiple-unit station to a single-unit station, regular interaction and feedback from current owners, operators, and potential customers ensured that it better met their needs with specific design and technology improvements.

Improved station layout

After extensive review and evaluation of existing station layouts, the CANDU 9 station layout was developed, using 3D Computer Aided Design and Drafting (CADD).

The improved layout features a narrow footprint for better site utilisation. It also provides better safety separation and reduces personnel exposure to radiation. Access for maintenance and testing is improved and there is more space for removal and replacement of equipment.

Shorter construction time

Construction time costs money. CANDU 9 is designed for more efficient construction; for example, pre-fabricated assemblies and parallel construction techniques are used. Additionally, "open-top construction" allows access during construction to the entire interior of the reactor building from outside the perimeter walls, using a very heavy lift (VHL) crane.

Better site utilisation

Its low-leakage containment design ensures that CANDU 9 meets an Exclusion Area Boundary (EAB) requirement of 500 meters. Its containment design features a steel liner and improved containment isolation reliability. CANDU 9 has a narrow footprint that contributes to better site use. The building arrangement achieves minimum spacing between reactor units, while keeping the necessary access for construction and maintenance.

Safety enhancements

Safety is a guiding principle in CANDU design. CANDU 9 incorporates CANDU's proven safety features and improves reliability and performance with: a simplified emergency core cooling system; the use of less complex and more modern software engineering techniques and computer technologies; and improved heat sink capability.

Smart control panel layout

Extensive consultation and feedback from operators led to an improved CANDU 9 control room which has been thoroughly tested at AECL's offices where a mock-up of the control room exists. The operator is firmly in the management seat at the main operations consoles, able to control the full range of power operation and evaluate plant status. Extensive information access and control capability is provided right at the consoles, including plant controls and displays, improved monitoring and testing capability for safety systems and annunciation, critical safety parameters, and critical production indicators.

The CANDU future

Where does CANDU go from here? Evolutionary technologies and products will be developed to enhance proven CANDU strengths and designs. Extensive research and development will be continued to search for cost effective means to improve safety and performance, develop faster construction methods, lower operating and construction costs, and increase plant operating life.

For large utilities, or for countries with a high electrical load growth, larger CANDU reactors, based on CANDU 9 systems and layout, can be designed for outputs up to 1 300 MWe. The major system concepts and equipment, such as steam generators, reactor coolant pumps and pressure tubes, remain the same. However, the number of fuel channels, type of fuel, size of heat removal equipment and other components are easily modified to increase output.

Its ability to use various types of fuel has always been a CANDU advantage that doesn't require a large investment in new reactor design. Options under development include: slightly enriched uranium, Direct Use of spent Pressurised water reactor fuel In CANDU (DUPIC), Recovered Uranium (RU), plutonium, thorium and actinide waste.

CANDU's potential fuel cycle flexibility is particularly attractive in countries that have both CANDU reactors and PWRs. Recycling spent PWR fuel in CANDU can reduce the quantity of spent fuel and its subsequent storage. Other advantages of CANDU's ability to use a variety of nuclear fuels include increased power output, improved performance, and the potential for energy self-sufficiency.

ABWR

ABWR safety features

The ABWR incorporates improvements that reduce the chances of an accident occurring and to mitigate the consequences should one occur. Because of this, the chances are exceedingly small that any radiation will be released to the public, even if an accident worse than Three Mile Island should occur.

A measure of safety commonly used by regulatory bodies is "Core Damage Frequency" (CDF), which is the probability of an accident occurring which results in some damage to the reactor fuel or core (as occurred at Three Mile Island). The CDF of nuclear plants has declined over time as new designs were introduced. Continuing this trend, the CDF of the ABWR is 50 to 100 times better than that of any existing nuclear plant.

The reasons why an accident leading to core damages are much reduced can be explained by the following:

More margin of safety

The ABWR has more design margins, more reliable equipment, modern control and instrumentation systems using digital technologies, and are designed to be easier for humans to operate. This reduces the number of malfunctions and abnormal conditions that lead to the activation of safety systems.

The design has been simplified

The ABWR has simplifications that enhance safety in a significant way. For example, the ABWR uses a new Reactor Internal Pumps that obviates the need for major piping found in earlier BWR designs. As a result, there is no pipe break and therefore no accident in this plant that could result in a loss of water covering the reactor core, ultimately leading to core damage.

Safety systems are more redundant and diverse

Safety systems are even more redundant and diverse than before. The ABWR has three completely separate divisions of safety. Each division, in turn, has two safety systems, each of which is sufficient to keep the reactor core safe. Each division has a dedicated source of power, a dedicated source of backup power, and is physically separated from the others by fire walls and flood barriers. In the event of a fire, flood or some other accident that disables one division, the other two divisions are not affected. Each division has a heat removal system to ensure that the core remains in a safe condition after the accident has occurred and the plant has been shutdown. Finally, the ABWR has been designed to ensure that safety systems work even in the event that all off-site power to the plant has been lost.

Severe accident mitigation

The ABWR is furthermore designed to meet the US Nuclear Regulatory Commission's (USNRC) new requirements for severe accidents. This means that the ABWR has features that prevent the release of radiation even in the unlikely event that the core and plant are "severely" damaged. Furthermore, in the case of the ABWR, these features do not require operator action. Such features are referred to as "passive" safety features because they use natural forces such as gravity or convection to work. These features have been fully approved by the USNRC.

Because the ABWR has features which mitigate the consequences of a severe accident, there is virtually no chance that any radiation will be released to the public, even should an accident worse than Three Mile Island occur. This provides a high degree of assurance that the public's health and safety will never be jeopardised by the operation of the plant.

Reduced capital costs

Less equipment and quantities

Design simplification and the use on new technology has reduced the amount of equipment and construction quantities in the ABWR compared to the previous generation of BWRs. For example, the ABWR uses Reactor Internal Pumps (RIPs) mounted directly to reactor vessel to recirculate core flow. Pump speed is controlled by adjustable speed motors or drives (ASDs).

Use of RIPs and ASDs eliminates the large external recirculation loops found in previous BWRs. This has many cost benefits. The large recirculation pumps, flow control valves, jet pumps, piping and pipe supports have all been eliminated. Also, the containment and reactor building are more compact, thereby reducing the quantities of material needed to construct them. Finally, because there are now no large nozzles below the top of the core, the safety systems can keep the core covered with water having less capacity. For example, the low-pressure systems of the ABWR have a flow capability of 19 000 gallons per minute compared to 29 000 gpm for BWR/5 and BWR/6, a 35% reduction. This is an example of improving safety and reducing costs.

The design of the control rod systems has also been simplified. Fifty percent of the hydraulic control units (HCUs) in the control rod drive systems have been eliminated. Because the new Fine Motion Control Rod Drives (FMCRDs) discharge water directly into the reactor during a scram, the scram discharge volume and the accompanying piping have also been eliminated.

The use of new technology further reduces the amount of plant equipment and construction quantities. The use of fibre optic networks, which carry substantially more information instead of copper cabling, has eliminated 1.3 million feet of cabling and 135 000 cubic feet of cable trays. Use of microprocessors and solid state devices in the control networks has reduced the number of safety system cabinets in the control room from 17 to only 3.

The ABWR containment is a Reinforced Concrete Containment Vessel (RCCV). This technology was first introduced in a limited number in Mark III containment. The advantage of re-introducing this technology is that the containment can be made more compact, especially in comparison with the freestanding steel version of the Mark III design. The ABWR containment volume is over 50% less compared to that design.

Shorter, predictable construction schedule

Use of the RCCV has another important advantage – it reduces the construction schedule. Use of this containment, together with modular construction techniques reduces the overall construction schedule by an impressive seven months. In constructing steel containment, the containment vessel is completed first, then the outer biological shield is erected, and finally the reactor building is constructed. For the RCCV, however, the construction of the containment vessel can take place concurrently with the construction of the floors and walls of the reactor building so that the entire construction schedule of the whole plant can be shortened. Also, RCCVs can be built in any shape. In the case of the ABWR, this is generally a right circular cylinder, which was chosen because it is easier to construct.

The use of fibre optic cabling also reduces the construction schedule, in this case by one month, simply because there is less cable to install.

It is perhaps not generally appreciated that extensive use of large modules was used in the construction of the ABWR. The entire control room (400 tonnes), the steel lining of the containment, the reactor pedestal, the turbine generator pedestal, and the upper drywell structure with piping and valves are notable examples.

Economics of the ABWR

The design, licensing and construction of the ABWR have made the capital cost economically competitive with other power generation options.

A breakdown of the capital cost for the next pair of ABWR units is given in the table below. The table refers to a capacity of 1 400 MWe. Capital cost for output of 1 500 MWe, which can be achieved with a nominal (US$60M) changes, would be 5% less than that shown here.

The actual costs would vary from country to country since they depend upon labour rates, productivity, the amount of local content and so on.

ABWR Nuclear plant cost breakdown

10^9US$

Average capital cost of next two ABWR units if built in the United States		
EEDB accounts		
Direct costs		
21	Structures and improvements	430
22	Reactor plant	520
23	Turbine plant	230
24	Electrical plant	150
25	Miscellaneous plant	45
26	Main heat rejection system	45
Total direct costs		**1 420**
Indirect costs		
91	Construction services	250
92	Engineering home office	70
93	Field office services	190
Total indirect costs		**510**
Total overnight construction cost		**1 930**
Contingency		125
Owner's cost		200
Total capital cost		**2 255**
Total capital cost in US$/kWe		**1 611**

Summary

The design, licensing, construction and operating performance of nuclear plants is vastly different – and better – than 10 to 20 years ago. Nuclear plants in the 1990s and in the new millennium will have a higher degree of safety and the ABWR in particular will be licensed in multiple countries. The ABWR plant can be constructed in just four years for US$1 600/kWe and suppliers are willing to undertake a project on a fixed price, fixed schedule basis. As a result, the ABWR nuclear plant has proven itself in Japan and Chinese Taipei to be economically competitive with other power generation options and estimates indicate that it can be economic in other countries as well.

AP600

Key AP600 design features

The ALWR URD is based on the extensive experience of existing LWRs to minimise the risk for the plant owner, to provide confidence relative to credibility of costs and schedules, and to avoid the need for a prototype plant. This philosophy has been strictly followed from the beginning of the AP600 Program. The overall plant design follows in the decade-long tradition of Westinghouse two-loop PWRs, which have operated with average lifetime availability of 81% – significantly better than the US national average of approximately 60%. The core, primary components, instrumentation and controls, and natural, passive safety systems are all based on technology that has been proven in service or by rigorous testing.

A fundamental AP600 design principle is that ample margins be included in the design as a means of ensuring plant reliability and tolerance for off-normal conditions. These design margins contribute significantly to plant safety through the avoidance of plant changes. The low power density core of the AP600 will provide substantial margin between the fuel operating conditions and the experimentally established limits for ensuring fuel rod integrity. For example, departure from nucleate boiling and peak clad temperature margins are increased by at least 15% and more than 200^0F relative to current plants with equivalent peaking factors. Similarly, corrosion protection measures and thermal design margins for the AP600 steam generators will increase the margin for primary to secondary plant pressure boundary integrity. The AP600 Pressuriser has a 30% greater volume, which will contribute to the safety margin by providing the capacity to sustain a wide range of off-normal plant transients without approaching conditions that call for protective actions. For example, in case of a full load rejection, no pressuriser relief will be needed in order to prevent the primary system pressure from reaching the reactor trip setpoint.

Simplification

Simplification is the key technical concept that drives the safety and economics of the AP600. These passive systems depend on the reliable natural forces of gravity, natural circulation, convection, evaporation, and condensation instead of AC power supplies and motor-driven components to achieve naturally safe systems. The new approach to safety simplifies plant systems and equipment, operation, inspections, maintenance, and quality assurance requirements by greatly reducing complex components, especially those most subject to regulation. The AP600 will use 50% fewer valves, 80% less safety-grade pipe, 70% less control cable, 35% fewer pumps, and 45% less seismic building volume than other conventional reactors.

Standardisation

The First-of-a-Kind Engineering Program results in the design of a standardised AP600 Plant with reduced uncertainties and cost contingencies. Replication of construction of a standardised plant allows learning curve effects to occur and significantly reduces costs of successive plants. In the operating area the combination of standardisation and replication (particularly at the same site) reduces the number of operating personnel per reactor and lowers the operating cost significantly. In addition, outages at standardised AP600 plants will have shorter duration resulting in higher availability. Standardisation is not only being applied between plants, but also with the equipment and components within a plant to reduce the cost of engineering, procurement, training and spare parts.

Advanced construction techniques

Modularization, prefabrication, prudent consolidation of temporary construction facilities and permanent plant facilities, and commodity standardisation are techniques being used to shorten schedule time and reduce construction costs. Modular construction, in particular, is key to shorter schedules, as it creates parallel construction paths and greatly reduces overall construction time. In addition, fabrication in the controlled environment of a module facility increases productivity, produces a higher quality product compared to field construction and allows better craft training to be performed.

Cost goals

The general economic cost goal for ALWR plants is that they will have a sufficient cost advantage over competing baseload electricity generation technologies to offset the higher capital investment. Specifically, the URD establishes on a 30-year, 1994 constant dollar levelised basis for a US site, a median bus bar cost for the advanced plant that is sufficiently less than 4.3 cents/kWh to offset the higher capital investment associated with nuclear plant utilisation. In addition to median bus bar cost, the URD establishes a cost uncertainty goal, i.e. that the projected 95th percentile non-exceeding cost will be substantially less than 5.3 cents/kWh.

In the "First-of-a-Kind Engineering" (FOAKE) work on the AP600, probabilistic estimates have been made on the overnight capital cost and electricity generation cost of an *n*th-of-a-kind twin AP600 reactor. Although this work is preliminary in nature and will undergo further refinements, it represents a starting point at studying generation costs of nuclear reactors in a probabilistic manner.

The approach to the probabilistic study was to use a US utility revenue requirements model in conjunction with the @Risk statistical software package. The combined model was developed and entailed twenty input cost variables that were varied probabilistically – eleven capital cost items, five fuel cost components, O&M and decommissioning costs, capacity factor and schedule length. Financing factors and escalation were not varied statistically in the initial study.

Completed capital cost

The completed capital cost of the twin plant is shown in the following table, assuming an inflation rate of 4.1% per year and an average cost of capital of 9.2% per year. The twin plant is estimated to cost US$2 655/kWe when it is completed in the year 2004. The base construction cost with owner's cost and schedule effects equals US$1 470/kWe, before escalation and interest during construction. Escalation and interest during construction total US$1 185/kWe, or 45% of the completed cost.

Capital cost	US$/kWe
Base construction cost (no owners or schedule effects)	1 270
Base construction cost (with owners and schedule effects)	1 470
Escalation (pre-construction)	327
Escalation (during construction)	257
IDC	601
Nominal US$	2 655
Constant US$	1 699

KNGR (Korean next generation reactor)

KNGR has been developed in a way that especially emphasises safety and economic aspects, and is based on the reviews of the advantages of some foreign advanced reactors as well as the experience in domestic design, construction and operation of the operating nuclear power plants in the Republic of Korea. Both the Advanced Design Features (ADF) of some foreign advanced reactors and the Passive Design Features (PDF) are well incorporated in the KNGR to enhance safety and to mitigate the consequences of severe accidents. The important factors like safety, operability and maintainability have been sufficiently considered in the design of the systems in the KNGR adhering to simplicity, reliability and economic aspects.

Some instances of the features in the KNGR are as follows:

The operational margin is increased with the lower Reactor Coolant System (RCS) hot leg temperature of 615°F during full power operation. The design life is extended up to 60 years with the improvement of the reactor vessel material and with the interim replacements of major components like steam generators. The impacts of a transient are minimised with a larger volume of pressurizer.

In addition, there are also essential changes in the Safety Injection System (SIS), which is equipped with four trains and direct injection to the reactor vessel. The function of Low Pressure Safety Injection (LPSI) is eliminated from SIS and the design pressure is increased up to 900 psig for the enhancement of reliability. The Safety Depressurization System (SDS), which can rapidly depressurize the RCS, is adopted for the feed and bleed in the event of the loss of all feedwater and for the prevention of the High Pressure Molten Eject (HPME) in case of severe accidents. The effort to improve the operation and reliability in SIS is the introduction of the In-containment Refuelling Water Storage Tank (IRWST) inside the Reactor Building which could obviates the need to change operational modes between re-circulation and injection during the operation of SIS and/or Containment Spray System (CSS).

The passive hydrogen ignitors as well as the active hydrogen recombiners are introduced to limit the hydrogen concentration below 10% in case of severe accidents. The passive fusible metal plug is added to the reactor cavity flooding system that functions to cool the molten core for improved reliability. Spray additive function is eliminated from CSS to amplify the system configuration; in addition, CSS and Shutdown Cooling System (SCS) are modified and interconnected with each other to increase the reliability of both systems. The closed Passive Secondary Condensing System (PSCS) with an isolation condenser and a condenser tank is adopted to dissipate the sensible and decay heat generated in the core for 72 hours following reactor shutdown. The Emergency Feed Water System

(EFWS) is modified to use the two separate feedwater tanks of the safety class as a suction source instead of condensate storage tanks to improve its function.

Man-Machine Interface System (MMIS) which is composed of MMI and I&C system is designed utilising the advanced digital I&C technologies based on systematic human factors engineering. They are also designed to be a compact workstation type operator console, hence only one operator will be able to operate the plant during normal operation by virtue of the systematic plant information and operator aid displays. In the I&C system, proven digital technologies are adopted instead of the conventional analogue type predecessors and it is designed with an open architecture based on standardised system design, hardware, software, and data communication network. Besides testability and maintainability, the adoption of multiple-loop controllers for effectiveness and local signal multiplexers for reducing I&C cabling are some of the main characteristics in the I&C system.

Factors like construction convenience, optimum layout and compact building configuration are well taken into consideration in the plant structural design. Especially the double concrete containment with an improved reactor cavity is adopted to withstand any loads that are expected during Design Basis Accidents (DBA) and severe accidents and to reduce the impacts from the external hazards. The auxiliary building is designed to completely surround the containment, to combine the traditional auxiliary and fuel buildings, and to have a common mat with the containment building.

Capital cost estimate

The economic advantage of the KNGR is calculated according to the plant scale economy, design simplification and optimisation, and reduction of the construction period. The following table shows the construction costs of the KNGR.

Construction costs of KNGR*

(US$/kWe)

Items	KNGR N^{th} (1 350 MW × 2)
Direct costs	**946.8**
Equipment and materials	586.0
Labour costs	360.8
Indirect costs	**259.2**
Engineering and services	123.9
Owner's costs	68.1
Site costs	9.8
Contingency	57.4
Overnight costs	**1206.0**

*Reference date: January 1997.

Design simplification and optimisation is largely achieved through removal of unnecessary systems and components, improvement in general arrangement, and application of new technology.

For example, all digital I&C systems with extensive use of multiplexing will eliminate a large portion of cabling and associated cable trays.

In addition, in view of the capacity of the KNGR, the bulk material quantity per MWe in the KNGR is considerably reduced. This decrease in bulk material per MWe will lead to the reduction of material purchase and installation costs.

When the KNGR is standardised, the detailed design will be about sixty per cent completed, enabling more accurate cost estimation, assuring construction schedule reduction, and expediting the licensability review by the regulatory body during design development.

The standardisation also allows promotion of effective equipment supply management. Thus, it is possible to achieve a short schedule through the proper linkage between a standardised design and well planned construction sequences. After repetitive construction of the KNGR, the goal of a forty-eight month construction period should be achieved in the N^{th} plant. This schedule shortening will contribute considerably to the reduction of investment costs.

Annex 3

LIST OF ABBREVIATIONS AND GLOSSARY OF TERMS

ABWR	Advanced Boiling Water Reactor
A/E	Architect Engineer
AECL	Atomic Energy of Canada Limited
ALARA	As Low As Reasonably Achievable
ALWR	Advanced Light Water Reactor
BOP	Balance of Plant
BWR	Boiling Water Reactor
CADD	Computer Aided Design and Drafting
CANDU	Canadian Deuterium Uranium Reactor
CDF	Core Damage Frequency
CHP	Combined Heat and Power
DUPIC	Direct Use of Pressurised Water Reactor Fuel in CANDU
EC	European Commission
EdF	Électricité de France
EPR	European Pressurised Reactor
EUR	European Utility Requirements
FOAK	First-of-a-kind
GWe	Giga Watt electric (1GWe = 1 000 MWe)
HVAC	Heating, Ventilation and Air Conditioning
IAEA	International Atomic Energy Agency
I&C	Instrumentation and Control
IDC	Interests During Construction
IEA	International Energy Agency
KNGR	Korean Next Generation Reactor
LDB	Licensing Design Basis
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
OECD	Organisation for Economic Co-operation and Development
O&M	Operation and Maintenance
PBMR	Pebble Bed Modular Reactor
PHWR	Pressurised Heavy Water Reactor
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Assessment
PWR	Pressurised Water Reactor
RCCV	Reinforced Concrete Containment Vessel
RHRS	Residual Heat Removal System
SIR	Safe Integral Reactor
SMB	Safety Margin Basis
TMI	Three Mile Island
UNIPEDE	International Union of Producers and Distributors of Electrical Energy
URD	Utility Requirements Document
US mill	US$0.001

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