IAEA-TECDOC-1084

Review of selected cost drivers for decisions on continued operation of older nuclear reactors

Safety upgrades, lifetime extension, decommissioning

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

May 1999

The IAEA does not normally maintain stocks of reports in this series.
However, copies of these reports on microfiche or in electronic form can be obtained from

INIS Clearinghouse
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria
E-mail: CHOUSE@IAEA.ORG
URL: http://www.iaea.org/programmes/inis/inis.htm

Orders should be accompanied by prepayment of Austrian Schillings 100,–
in the form of a cheque or in the form of IAEA microfiche service coupons
which may be ordered separately from the INIS Clearinghouse.

The originating Section of this publication in the IAEA was:

Planning and Economic Studies Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria

The IAEA does not normally maintain stocks of reports in this series. However, copies of these reports on microfiche or in electronic form can be obtained from

INIS Clearinghouse
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria
E-mail: CHOUSE@IAEA.ORG
URL: http://www.iaea.org/programmes/inis/inis.htm

Orders should be accompanied by prepayment of Austrian Schillings 100,– in the form of a cheque or in the form of IAEA microfiche service coupons which may be ordered separately from the INIS Clearinghouse.

REVIEW OF SELECTED COST DRIVERS FOR DECISIONS ON
CONTINUED OPERATION OF OLDER NUCLEAR REACTORS
IAEA, VIENNA, 1999
IAEA-TECDOC-1084
ISSN 1011–4289

Printed by the IAEA in Austria
May 1999

FOREWORD

The period of the 1970s and 1980s was one of rapid growth of nuclear power worldwide. A large part of the existing nuclear power plants (NPPs) started operation at that time. As the typical design life of a nuclear unit is 30–40 years, many nuclear reactors will reach the end of their planned operating period in the coming decade.

Lately, the approach to the operation of relatively old NPPs has become an important issue for the nuclear industry for several reasons. First, as noted, a large part of operating NPPs will reach the planned end of their lives relatively soon. Replacing these capacities can involve significant investment for the concerned countries and utilities. Second, many operating NPPs, while about 30 years old, are still in very good condition. Their continued safe operation appears possible and may bring about essential economic gains. At the same time, the need for operating such NPPs is often questioned at present, and in a number of cases decisions on premature shutdown were taken. Finally, with the costs of new NPPs being relatively high at present, continued operation of existing nuclear units and, eventually, their lifetime extension are viable options for supporting the nuclear input to power generation. This input is becoming especially important in view of the growing attention to the issue of global warming and the role that nuclear energy could play in greenhouse gas mitigation.

Thus, determining the attitude to the operation of older NPPs is on the agenda of nuclear operators. However, this is a complex problem involving many issues. One of these issues is economics: the question as to whether or not continued operation (or lifetime extension) of a given nuclear unit is economically justified does not have a simple and universal answer. A number of economic factors should be carefully studied in the framework of cost–benefit analysis in order to find an answer.

This report represents a review of published information related to three cost categories that are part of such cost–benefit analysis: costs of safety upgrades necessary for continued operation of a nuclear unit, costs of lifetime extension measures, and costs of decommissioning. While each of these categories is subject to detailed specialised cost studies, the report views the costs globally, mainly as input for subsequent overall economic analysis. Consistently with this approach, the report also discusses the applicability of the collected costs for decision making.

A large amount of information scattered in miscellaneous documents was reviewed and analysed during the preparation of this publication. Therefore, it can serve as a useful reference source for experts and decision-makers involved in the economics of operating NPPs, in particular in view of the lifetime extension option.

This report was prepared in 1998 in the course of two IAEA consultants meetings. The IAEA wishes to express its gratitude to all the experts who participated in the drafting and review of the report. The responsible IAEA officer was S. Kononov of the Division of Nuclear Power.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

Within a few years (2000–2010), a large number of nuclear power units worldwide are to reach the end of their licensed operating periods, although not necessarily the end of their technical or economic life. With respect to such units, governments and utilities are now considering their options:

– whether to operate the ageing units until the planned end of life, i.e. until the end of the licensed operating period; or

– to close and decommission the units earlier due to economic factors (such as increased costs of continued operation) or non-economic considerations (e.g. safety concerns, political or social intention to discontinue the use of nuclear power); or

– to extend the licensed period with relevant measures to ensure safe continued operation.

Each of these options has its costs, and this factor plays an important role in the selection of the strategy to follow. Economic viability of a nuclear power plant (NPP) depends on the costs of continued operation including the costs of technical measures to make up for the ageing equipment and the costs of safety upgrades necessary in order to comply with changing regulatory requirements. The feasibility of lifetime extension depends on the technical possibility and cost of the relevant measures necessary for safe extension of the lifetime of the plants; on economic parameters of competing electricity generation technologies including new nuclear projects; on the magnitude of the expected growth in electricity demand; on the development of environmental factors and requirements, etc. The decision to withdraw NPPs from operation earlier than in accordance with the planned schedule involves the replacement costs of power supply occurring earlier and, depending on the situation, the cost of unserved energy. Early nuclear phase-out brings forward the time of decommissioning, while the full provision for the costs of decommissioning may have not been generated yet by electricity sales.

Theoretically, the most comprehensive approach to assessing the economic viability of lifetime options would be to analyse the mentioned three options on the basis of a power system model, so that long term consequences and power system costs of this or that decision concerning the closure of an ageing nuclear unit could be determined and the trade-off of the costs of continued NPP operation versus the replacement costs directly simulated. However, such analysis requires certain cost data that are not easily available.

In view of this difficulty, the objective of this report is to make a review of the following costs that, formally, are input data for a power system analysis of the options of earlier/later retirement:

– costs of safety upgrades that are necessary for an NPP unit to be licensed for continued operation;

– costs of the upgrades aimed at extending the lifetime of the unit beyond the planned end-of-life;

– costs of unit decommissioning.

This definition excludes the "usual" operation and maintenance costs as well as the fuel costs because, first, they are generally better known and, besides, they are traditionally handled within other IAEA activities, while the listed costs are known with less certainty and their assessments tend to change from year to year. At the same time, it is the considered costs that have a significant effect on the decision to either close or not close the unit as well as determine, to some extent, the outcomes of a power system analysis with the use of corresponding models.

In order to correctly understand the presented information, it is important to note the following specific features of the approach implemented in this report:

- The review is prepared on the basis of already existing and published materials. Although the published information was in some cases complemented by expert assessments obtained in direct contacts with relevant experts, there was no attempt to conduct special studies in order to obtain new cost data of the type considered.

- The term "older reactors" widely used in this report is meant to include the reactors that already have the age of 30–40 years or will reach such age in the coming decade. Problems of safety upgrading and lifetime extension have some common features for the reactor group thus defined. However, one should also understand that within the group there are large differences both from the technical and regulatory viewpoints. For example, some reactors have a licensed operating lifetime of 30 years, others — 40 years, while in certain countries (e.g. Germany, Belgium, Spain) the operating licenses are open and continued operation is granted provided that the results of periodic safety reviews are satisfactory for the regulator. Also from the technical side, the situation may be quite different depending on the design of the plant, the extent of the current programmes of safety upgrades and their advancement status.

- Difference in the use of the terms "continued operation" and "lifetime extension" should be noted. "Continued operation" is applied when operation within the initially planned plant lifetime is meant (as opposed to premature shutdown), while "lifetime extension" relates to the possibility of plant operation beyond that period.

- As the costs are viewed in this report primarily as input data potentially applicable for subsequent economic analysis, it is not attempted here to make a detailed analysis of the cost structure and of separate cost components. Those interested in such analysis are encouraged to consult specialised publications used for the preparation of this report and referenced at the end of the document. In some cases, important background assumptions are noted in the form of footnotes to cost tables. These notes should be carefully read in order to correctly understand the meaning of the costs.

- Costs of the upgrades that are not directly related to safety such as capacity increase, improvements in instrumentation and computer networks, etc. are not considered in this report, except in cases where these costs are presented together with the costs of safety upgrades and, due to limited information, cannot be separated from the latter. Such cases are explicitly noted in the text.

- In view of lower general availability of published cost information for the so-called "Soviet-designed" reactor models (WWER-440, WWER-1000, LWGR(RBMK)-1000, LWGR(RBMK)-1500), this report places some emphasis on data for these reactors, partially received as expert assessments without background publications; for "Western" reactor models (PWR, BWR), recently published reports are the main information source.

- The draft of the report was reviewed at two IAEA consultants meetings where both the general structure of the document and the presented cost data were discussed and verified. In addition to the inputs of consultancy participants, several other experts, both in and outside the IAEA, contributed to the report with their remarks. The full list of contributors to the preparation of the document is given at the end of the report.

The report is structured as follows:

- Section 2 covers the approach to monetary conversions used for transforming costs in various national currencies of differing years into single unit ($US) costs of a selected year;

- Section 3 presents a review of the costs of safety upgrades necessary for continued operation of reactors of older generations in order to comply with changing regulatory requirements;

- Section 4 discusses the costs that the extension of reactor lifetime would necessitate;
- Section 5 is a review of the costs of decommissioning;
- Section 6 contains some general observations and conclusions.

At the end of the report, references to the information sources used are given as well as the list of abbreviations and the list of experts who contributed to the preparation of the document.

Four annexes provide complementary useful information. Annexes I and II present additional data useful for the understanding of the used monetary conversions and their uncertainty. Annexes III and IV are based mostly on the presentations made by the participants of the two IAEA consultants meetings in the framework of this project. Annex III contains additional information related to the costs of safety upgrades and Annex IV — to the costs of decommissioning.

2. METHODOLOGY OF COST CONVERSIONS

For international reviews containing cost data in different national currencies, conversion of all costs into one selected monetary unit is usually made, as well as the conversion of different year costs into costs at a selected date. In general, the following methodology is applied for such conversions:

- First, the costs expressed in a national currency for a given year and date (e.g. January 1, 1990) are recalculated to a selected common date, e.g. January 1, 1997. This procedure is applied for all costs and currencies under consideration.
- Second, the costs in different currencies for the selected base date are converted into one monetary unit, e.g. $US of the same date. As the result, one obtains cost estimations for different countries in the same unit and for the same date; in this sense, the results become comparable.

This straightforward procedure has, however, certain difficulties in application that result from the need to determine conversion factors for both conversions. Ideally, the preferable factors for year-to-year conversions would be the national price index for the group of commodities under consideration. As we are to consider costs of safety upgrades and decommissioning, Producer Price Indices (PPI) for typical equipment categories should be used as conversion factors, in combination with labour cost indices. However, such information is available only for some countries and usually in a highly aggregated form that does not allow to be sure that the indices cover exactly the categories needed.

Another difficulty lies in the conversion from national currencies to a single reference currency. Theoretically, one should use for such conversions the relative purchasing parities of the corresponding products. Again, such information is rarely available; in case there are data on purchasing parities, it is difficult to assure that they correspond exactly to the products under consideration. In view of this difficulty, most often the market exchange rates are used on the basis of relevant macro-economic studies such as [1–3]. However, it makes the results sensitive to exchange rate fluctuations which may result in unreasonably sharp changes of the resulting assessments from year to year.

All these difficulties make the results of such comparisons, as noted in many publications (e.g. in [4–6]), somewhat limited in the meaning. Nevertheless, as the comparisons are still useful and as there is no other equally practicable approach, this procedure will be applied in this report also in the following form:

- The selected base date for cost comparisons is January 1, 1997; the selected reference currency is the US dollar ($US) of January 1, 1997.

- For the conversion of national cost data to a selected base date, national Gross Domestic Product (GDP) deflators are used. This is a less accurate approach than using PPIs and labour cost indices, but it makes the task realisable in view of data availability for all countries under consideration. One should also note that all prices indices and national deflators contain their own uncertainty that results from the existence of different methodologies for their calculation. For example, even for GDP deflators the difference in the methodology may result in significant variations of the numbers. This could be seen when comparing, e.g. GDP deflators for OECD countries in different publications [1–3] (see an example in Annex I). Therefore, it is hardly possible to achieve impeccable results in such conversions, regardless of what is used: GDP deflators, producer prices indices or Consumer Price Indices (CPIs). In any case, the underlying uncertainty in their methodology makes consistency and transparency of all the conversions more important than theoretical advantages of this or that index. In this sense, the use of GDP deflators corresponds best to the task of this report.

- For the conversion of national costs of January 1, 1997 into US dollars of January 1, 1997 the average 1996 exchange rate is used. The use of the annual average is intended to minimise the possible effect of short term currency fluctuations.

Formally, the described technique of monetary conversions can be presented as follows. If $C_j(N)$ is the cost in a given national currency for year j, $esc(j)$ is the national GDP deflator for year j, and $EX(1996)$ is the average exchange rate of the national currency in 1996 to the $US, the cost converted from $C_i(N)$ to $US of January 1, 1997 (denominated as $C_{97}(\$US)$) is determined in accordance with the equation below:

$$C_{97}(\$US) = C_j(N) \times (1+esc(j)) \times (1+esc(j+1)) \times \ldots \times (1+esc(1996))/EX(1996)$$

The cost conversion factors determined in accordance with these assumptions are given in Table I.

Data in Table I relate to the group of "developed countries". Developing countries and countries that are currently in the period of economic transition sometimes represent a special case, because their national currencies may undergo relatively large changes and statistical data on GDP deflators are not always available or reliable. For these countries, a slightly different procedure is applied:

- The original estimate in the national currency of a given date is converted into $US of the same date using either the market exchange rate or other, more accurate conversion factors if possible (rather often, national assessments for countries in transition are already made in $US using this or that conversion method).

- Then, the obtained dollar value is converted to $US of January 1, 1997 using the US GDP deflator for the relevant years.

Although this procedure may be argued from the theoretical viewpoint because of the implicit use of a foreign escalation factor for national costs, it was considered more reliable than the use of fluctuating national exchange rates. One can note that the used currency conversion factors sometimes differ from those given in other publications. The effect of such differences can be checked with the additional tables presented in Annex II.

TABLE I. ASSUMED COST CONVERSION FACTORS [1]

COUNTRY	GDP deflators, change from previous period,%													Exchange rates,
	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	national currency units per $US of 1996
BELGIUM	5.2	6.1	3.6	2.2	2.1	4.6	3.1	3.2	3.6	4.2	2.3	1.7	1.6	31 (Franc)
CANADA	3.1	2.6	2.4	4.7	4.6	4.8	3.1	2.9	1.2	1	0.7	1.5	1.3	1.36 (Dollar)
FINLAND	8.8	5.4	4.5	4.7	7	6.1	5.9	2.5	0.7	2.4	1.3	2.4	1.2	4.6 (Markka)
FRANCE	7.5	5.8	5.2	3	2.8	3	3.1	3.3	2.1	2.5	1.5	1.6	1.2	5.12 (Franc)
ITALY	11.6	9	7.8	6.1	6.8	6.3	7.6	7.7	4.7	4.4	3.5	5	5.1	1543 (Lira)
JAPAN	2.6	2.1	1.8	0.1	0.7	2	2.3	2.7	1.7	0.6	0.2	-0.6	0	108.8 (Yen)
GERMANY	2.1	2.1	3.2	1.9	1.5	2.4	3.2	3.9	5.6	4	2.4	2.1	1	1.5 (Deutsche Mark)
KOREA, Rep. of	5.5	4.6	4.6	5.0	6.7	5.3	9.9	10.1	6.1	5.1	5.5	5.6	3.4	804.4 (Won)
NETHERLANDS	1.4	1.8	0.1	–0.7	1.2	1.2	2.3	2.7	2.3	1.9	2.3	1.6	1.3	1.686 (Guilder)
SPAIN	11.6	7.7	11.1	5.9	5.6	7.1	7.3	7.1	6.9	4.3	4	4.8	3.1	126.7 (Peseta)
SWEDEN	7.6	6.6	6.9	4.8	6.5	8	8.9	7.6	1.1	2.6	2.4	3.7	1	6.71 (Krona)
UNITED KINGDOM	4.6	5.7	3.3	5	6	7.1	6.4	6.5	4.6	3.2	1.6	2.4	3	0.641 (Pound)
USA	3.8	3.4	2.6	3.1	3.7	4.2	4.3	4	2.8	2.6	2.4	2.5	2.3	1 (dollar)

3. COSTS OF SAFETY UPGRADES

3.1. ISSUE OF SAFETY UPGRADES

The issue of safety upgrades, i.e. the need to invest in design/operational changes of the already operating plant is a typical problem for reactors of older generations. Usually, in each country there is a permanent process of increasing safety requirements for nuclear power plants. While being quite normal, this process results also in the need to reassess, with new safety regulations coming in force, the compliance of the already operating plants that were licensed for operation under earlier, less stringent regulations with new safety requirements. Sometimes this process of following changing regulatory requirements is quasi-permanent like in the United States of America and Germany; in some countries, as in Belgium, France and the Netherlands, the compliance with safety regulations is checked periodically at relatively long intervals (up to 10 years).

Usually, it is possible for the operator of an older plant to implement some additional safety measures thus bringing the old plant in compliance with the new regulatory environment. However, the older the plant, the more probable is that safety upgrading would require considerable investments. At some point, it may become non-economic to continue operation and the operator may be forced to consider earlier retirement for economic reasons.

One example of safety upgrades at existing plants are numerous modifications implemented world-wide after the Three-Mile Island accident in the USA. Another, maybe even more representative example is the still continuing "wave" of safety upgrades at NPPs of the so-called "Soviet design" after the Chernobyl accident and social changes in the operating countries that allowed for much more intensive sharing of experience in nuclear engineering between the "East" and the "West" than before. However, one should note that even in the absence of new large nuclear accidents the progress of regulatory requirements continues and, thus, the problem of safety upgrades of older reactors remains on the operators' agenda both in the "East" and the "West".

When discussing the costs of safety upgrades in this report, an attempt is made to consider only the costs of safety measures necessary to keep the plant in compliance with the current regulatory requirements. However, this attempt has been only partially successful. As it will be shown below, rather often the available data do not allow to separate the costs of strictly safety-related upgrades from the costs of operational modifications meant to improve plant performance, or, in some cases, from the cost of routine equipment replacements. In such cases, special notes are made in the text.

It should be noted that the costs covered in this section are costs necessary for continued operation of nuclear units, i.e. for operation within the initially planned plant lifetime. Costs related to the option of lifetime extension are considered in Section 4.

3.2. REACTOR MODELS AND COUNTRIES COVERED

In order to present the scope of this review, Table II lists the countries and reactor models for which information on the costs of safety upgrades was found and, after a preliminary analysis, included. As to the costs themselves and their characteristic breakdowns, they are presented in Sections 3.3 and 3.4.

One can note that not all countries with developed nuclear programmes are presented in Table II. The major reason is the lack of published information on the costs of safety upgrades that are rarely published separately from regular O&M costs (and even O&M costs are not always readily available because of certain commercial sensibility of such data).

TABLE II. COUNTRIES AND REACTOR MODELS IN THE REVIEW OF SAFETY UPGRADE COSTS

Country	Reactor model	Reference and year of assessment
Armenia	WWER-440/270[a)]	[7] (1993) [8] (1996)
Bulgaria	WWER-440/230 WWER-1000	[7] (1993) [9] (1997)
Germany	PWR and BWR (various designs, on average and for one selected PWR plant)	[10] (1995) [11] (1995) [12] (1998)
Korea, Republic of	PWR-600 PWR-950 HWR-700	[13] (1998)
Lithuania	LWGR (RBMK)-1500[b)]	[7] (1993) [14] (1996) [15] (1998)
Netherlands	PWR-450	[16] (1997)
Russian Federation	LWGR (RBMK)-1000 WWER-440/230 WWER-440/213 WWER-1000/320	[7] (1993) [17,18] (1995)
Slovakia	WWER-440/230 WWER-40/213	[7] (1993)
Ukraine	WWER-440/213 WWER-1000/320	[7] (1993) [19] (1994)
USA	PWR (various designs) BWR (various designs)	[20] (1995)

a) The WWER-440/270 model is close in design to WWER-440/230, with major differences related to improved seismic resistance of WWER-440/270. Due to this similarity, the Armenian NPP is considered below together with the countries operating WWER-440/230s.

b) The original design capacity of the Lithuanian RBMKs is 1500 MW(e). However, some years after the start of operation the available power level was decreased to 1300 MW(e) mainly due to safety reasons. Therefore, everywhere in this report 1300 MW(e) is used as the gross capacity for these units, while the reactor model is traditionally labelled RBMK-1500.

3.3. REVIEW OF THE COSTS

3.3.1. WWER-440/230 reactors

WWER-440/230 is one of the "Soviet-designed" models that also include WWER-440/213, WWER-1000, RBMK-1000 (or LWGR-1000) and RBMK-1500 (or LWGR-1500). Of all WWERs, it is the oldest model and it is WWER-440/230 that has been criticised most for certain safety deficiencies, related, in particular, to the integrity of the reactor pressure vessel (RPV), the ability of the confinement to withstand high pressures and a limited scope of design accidents.

In order to enhance WWER-440/230 safety, safety upgrade programmes have been in progress for several years in all countries operating these reactors. International co-operation with active participation of the IAEA (see, e.g. [21]) plays an important role in this process. In the course of these programmes, numerous safety enhancements have been introduced at plants with WWER-440/230, e.g.:

- protection of the integrity of the RPV including annealing of the RPV, inspections of the RPV metal from inside, installation of dummy fuel assemblies and some other measures;
- technical and organisational measures for the implementation of the "leak before break" concept[1];
- improvements in the leak-tightness of plant sealed rooms;
- expansion of the accident analysis including application of PSA methods;
- measures to reduce the probability of common cause failures;
- measures to improve fire protection; and many others.

A detailed description of the design concept of WWER-440/230 and of relevant safety enhancements can be found, e.g. in [22, 23, 24].

Information on the costs of safety upgrades necessary for improving WWER-440/230 safety is presented in Table III. In order to allow for historical comparisons, two alternative cost estimations are presented for almost every reactor: one made relatively early and the other one most recent defined as the "reference assessment". The information on these two cost estimates in Table III is organised as follows:

- Column 1: case number (altogether, five WWER-440 cases, i.e. five NPPs with WWER-440/230 power units are covered by this review).
- Column 2: country and NPP where the WWER-440 unit is operating (4 countries are included: Armenia, Bulgaria, the Russian Federation and Slovakia).
- Columns 3–4: net and gross capacity of the unit (taken from [25]).
- Columns 5–6: the first, relatively early assessment of the total costs of safety upgrades; both the original cost estimate as published and the cost converted in the common currency unit as described in Section 2 are presented.
- Columns 7–11: the second, reference cost estimation, for which more information is given than for the first estimation. Namely, the specific costs are calculated and presented as well as the breakdown of the investments into the part already made by the end of 1997 and the part to be done yet (i.e. the implementation degree is shown if available).

---

[1] According to [76, 77], the basis of the leak before break concept is a demonstration that the primary circuit would leak significantly before a double ended guillotine break occurs. It must be demonstrated by deterministic fracture mechanisms that a crack would grow through the wall, resulting in a leak, and that this postulated small "through wall' flaw in plant specific piping would be detected by the plant's leakage monitoring systems long before the flaw could grow to an unstable size. Leakage exceeding the limit specified requires operator action or plant shutdown. The implementation of the concept is achieved by quantifying and evaluating the process of loss of integrity and accompanying leaks and prescribing safe plant shutdown on the basis of the monitored leak rate.

TABLE III. COSTS OF SAFETY UPGRADES FOR WWER-440/230 REACTORS

					Assessment 1		Assessment 2 (reference assessment)				
	1	2	3	4	5	6	7	8	9	10	11
No.	N	Country/NPP	Net Capacity, MW(e)	Gross Capacity, MW(e)	Total upgrade cost in original estimation, M$US	Total upgrade cost converted to M$US of 1/1/1997	Total upgrade cost in original estimation, M$US	Total upgrade cost converted to M$US of 1/1/1997	Specific upgrade cost, $US-1997/kW(e) (gross)	Investments already made by 1/1/1998, M$US of 1/1/1997	Investments to be made starting 1998, M$US of 1/1/1997
	1	ARMENIA Medzamor NPP, Unit 2	376	408	221 [a)] ($US-1993 [7])	**244**	63 ($US-1995 [8])	**66**	162	2	64
	2	BULGARIA Kozloduy NPP, Units 1, 2	408	440	122-129 ($US-1993 [7])	**134–142**	40 ($US-1996 [9])	**41**	93	13	29
	3	BULGARIA Kozloduy, Units 3, 4	408	440	122–129 ($US-1993 [7])	**134–142**	50 ($US-1996 [9])	**51**	116	20	31
	4	RUSSIAN FEDERATION Kola, Units 1, 2; Novovoronezh, Units 3, 4	411	440	82 [b)] ($US-1993 [7])	**90**	29–39 ($US-1994 [17])	**31–42**	70–95	no data	no data
	5	SLOVAKIA Bohunice NPP, Units 1, 2	408	430	66 [c)] ($US-1993 [7])	**73**	no data	**no data**	no data	no data	no data

[a)] This estimate includes, in addition to the cost of short- and long term upgrades, also the cost of unit re-commissioning.

[b)] This assessment is for short term upgrades only.

[c)] This assessment is for short term upgrades only.

When viewing the cost numbers, one should have in mind the following general features of the presented estimations:

- The costs are presented by reactor units, i.e. recalculations were made in cases where the original estimation was presented as a total for a multi-unit plant. Where the available information allows, separate assessments for the 1st and subsequent units are provided.

- The total costs in Assessment 1 and Assessment 2 are not necessarily comparable, because the assessments were done at different times and in each case represent the total amount of investments considered necessary at the time of assessment. If certain investments were already made during the time between the two investments, the latest cost assessment must be lower.

- As a rule, the safety upgrades assumed in the presented estimations represent a set of upgrades necessary for ensuring operation of the power units until the designed end of life. In other words, these are not only short term[2] upgrades meant to allow the plants operated for a limited period of time before premature closure, but long term upgrades (more complete descriptions of short- and long term measures can be found in the referenced information sources). For the long term upgrades, only most plausible modifications are meant. Radical but extremely difficult options such as the construction of a US-style containment for existing WWER-440/230 or, in another section, for LWGR (RBMK) units that was considered in [17] are not included in Table III. On the other hand, no lifetime extension beyond the initially designed lifetime (30 years for WWER-440s) is assumed in the given cost assessments (see Section 4 for notes on the costs of lifetime extension).

- Concerning the sets of the upgrades, one must be aware that there is no complete correspondence between the assumed sets of the upgrades for the different countries operating WWER-440/230s. Although the principles of safety improvements are the same (see, e.g. [22]), the implementation of these principles is within national responsibilities. Therefore, there exist differences among the countries in the number and extent of the assumed upgrades, the more so that the designs are not quite identical (each WWER-440/230 has its minor specific design features that depend on the year of construction, site characteristics, etc.). This remark is also true in general for the other reactor models consider in the sections below, both for "Soviet-designed" and "Western" reactors.

Notwithstanding these reasons that make generalisation difficult, some observations can still be made on the costs shown in Table III:

(1) First, one should note a rather high correlation of the assessments for the countries considered. If one excludes the untypical Armenian case (costs of unit re-commissioning are included for one assessment), both the early assessment 1 and the more recent assessment 2 are reasonably close: between 70–140 M$US/unit for the former and 30–65 M$US/unit for the latter. Taking into account the fact that the underlying sets of technical measures are likely to differ due to the different implementation level of the upgrades, one should consider this a rather good correlation.

(2) Further, the difference between the two estimates for all the countries should be noted. All later assessments are much lower than the earlier ones. One of the probable reasons, apart from possible differences in the number/nature of the upgrades assumed and in macro-economic

[2] The difference between short term and long term upgrades appeared historically. At the end of 1980s and beginning of 1990s, the question of premature closure of "Soviet-designed" reactors was under discussion at the international level (see, e.g. [7]). At that time, certain emphasis was given to measures that would allow for safe short term operation of the reactors under consideration until the coming moment of early closure. Later on, when the option of premature closure was declined by most plant operators, more extended sets of safety upgrades (so-called long term upgrades) were taken into consideration, defined as measures that would allow for safe operation until the planned end of life.

assumptions, is that a large number of safety measures have been implemented during the several years that separate the two assessments presented.

(3) The higher cost for the Armenian NPP may have for reason the lower level of implementation of the measures as compared with the other countries due to the recent restart of the unit and the lack of financial resources in the country.

(4) For Slovakia, the early assessment gave a noticeably lower number than for other countries, apparently due to a number of safety measures implemented prior to the cost assessment of [7]. Unfortunately, there is no update of these costs, so it is difficult to confirm this hypothesis.

(5) Finally, one can note a rather low assessment for the Russian Federation: 30–40 M$US/unit as compared with similar data for other countries. In addition to the possible effect of the implementation level in the Russian Federation, this may have for reason the rather rough methodology for obtaining the dollar value for investments in the Russian Federation that was applied in [17]. This methodology assumed, e.g. the factor of 0.10 for the difference between the labour cost in the Russian Federation and in the USA This assumption may have led to underestimation of the actual expenses needed. Unfortunately, more recent assessments for the Russian Federation are not available, so the validity of this explanation is unclear.

In general, one can conclude that although significant expenses for safety upgrades at WWER-440/230s have already been made, substantial expenditures for this purpose are still planned in all countries considered.

3.3.2. WWER-440/213 reactors

The presentation of the costs for plants with WWER-440/213 reactors is the same as for WWER-440/230, see Table IV. This reactor model is more recent than WWER-440/230 and contains essential safety enhancements, notably the improved capability of the confinement, extended scope of design accidents including a break of the main cooling pipe in the first circuit, better equipment redundancy in safety systems and some others.

Nevertheless, there is also an area for safety improvements at WWER-440/213s which includes, among others, the following measures:

- protection of the integrity of the RPV (measures similar to WWER-440/230 although the problem is considered less serious than for that model);
- modifications in I&C systems;
- measures aimed at the prevention of large primary-to-secondary leaks in the steam generators;
- technical and organisational measures for the implementation of the "leak before break" concept;
- prevention of hydrogen accumulation during accidents;
- expansion of the accident analysis including application of PSA methods;
- measures to reduce the probability of common cause failures;
- measures to improve fire protection.

These and other measures are subject of the programmes of safety upgrades that are under implementation in the countries operating these reactors. (A detailed description of design features of the WWER-440/213 model and of relevant safety enhancements can be found in, e.g. [26, 27, 28]).

TABLE IV. COSTS OF SAFETY UPGRADES FOR WWER-440/213 REACTORS

				Assessment 1		Assessment 2 (reference assessment)				
1	2	3	4	5	6	7	8	9	10	11
No.	Country/NPP	Net Capacity, MW(e)	Gross Capacity, MW(e)	Total upgrade cost in original estimation, M$US	Total upgrade cost converted to M$US of 1/1/1997	Total upgrade cost in original estimation, M$US	Total upgrade cost converted to M$US of 1/1/1997	Specific upgrade cost, $US-1997/kW(e) (gross)	Investments already made by 1/1/1998, M$US of 1/1/1997	Investments to be made starting 1998, M$US of 1/1/1997
1	RUSSIAN FEDERATION, Kola NPP, units 3, 4	411	440	211 ($US-1993 [7])	**233**	11–14 ($US-1994 [17])	**12–15**	27–34	no data	no data
2	SLOVAKIA Bohunice NPP, units 3, 4	408	430	154 ($US-1993 [7])	**170**	no data	**no data**	no data	no data	no data
3	UKRAINE, Rovno NPP, units 1, 2 [a)]	363 (377 *)	402 (416*)	183 ($US-1993 [7])	**202**	no data	**no data**	no data	no data	no data

[a)] Capacities for unit 2 are shown in parentheses (they slightly differ from those of unit 1).

Three countries operating WWER-440/213s are covered by this cost review: the Russian Federation, Slovakia and Ukraine. The following general observations can be made on the costs of safety upgrades shown in Table IV:

(1) The initial cost estimates for WWER-440/213 (assessment 1) correlate rather well: 170–230 M$US/unit, with the differences coming, most likely, from minor differences in the design and varying implementation level by the time of cost assessment.

(2) One can note that these first assessments for WWER-440/213s are of the same order or even higher than for WWER-440/230s (Column 6 in Table III). This is somewhat unusual, because, generally, the level of safety at WWER-440/213s is considered to be higher. A probable explanation is that the initial assessments for WWER-440/230s do not include all long term measures, while for WWER-440/213s the possibility of operation until the end of planned lifetime was assumed almost unanimously.

(3) However, for the most recent estimation the relation between the cost of the upgrades for WWER-440/213s and WWER-440/230s seems to be logical: for the Russian Federation, the costs of safety upgrades for WWER-440/213s are 2–3 times lower than for WWER-440/230s (the lack of data for Slovakia and Ukraine does not allow to verify whether the ratio is the same for their reactors as well).

It is difficult to make more conclusions on the cost data for WWER-440/213s due to the fact that relatively recent assessments are available only for one country.

3.3.3. WWER-1000 reactors

The costs of safety upgrades for plants with WWER-1000 reactors are given in Table V. Concerning the extent of the upgrades, one can note that all WWER-1000 plants are equipped with the containment, so the problem of the integrity of the first circuit is much less topical than for WWER-440 reactors. However, certain enhancements are still needed such as:

- improvement of core behaviour (prevention of the deformation of fuel assemblies during operation with the change in the water gap between the assemblies);
- additional analysis of design and beyond-design accidents including application of PSA methods;
- measures aimed at the protection of the integrity of the steam generator and its function in accident conditions; and some others, see, e.g. [29] for more technical details.

Three countries are covered by the review: the Russian Federation, Slovakia and Ukraine. The following general observations can be made on the costs of safety upgrades shown in Table V:

(1) According to both older (assessment 1) and newer (assessment 2) assessments, safety upgrades of WWER-1000s require substantial investments that are larger, even on a per kW(e) basis, than those for WWER-440s. One of the possible reasons is the fact that a large number of safety enhancements (considered as urgent) were implemented relatively early at WWER-440s, while the modification of WWER-1000s has been considered with lower priority due to the acknowledged higher safety level of these reactors.

(2) The order of total investments required is 200–300 million US dollars per unit, of which a substantial amount has to be invested yet.

TABLE V. COSTS OF SAFETY UPGRADES FOR WWER-1000 REACTORS

				Assessment 1		Assessment 2 (reference assessment)				
1	2	3	4	5	6	7	8	9	10	11
No.	Country/NPP	Net Capacity, MW(e)	Gross Capacity, MW(e)	Total upgrade cost in original estimation, M$US	Total upgrade cost converted to M$US of 1/1/1997	Total upgrade cost in original estimation, M$US	Total upgrade cost converted to M$US of 1/1/1997	Specific upgrade cost, $US-1997/kW(e) (gross)	Investments already made by 1/1/1998, M$US of 1/1/1997	Investments to be made starting 1998, M$US of 1/1/1997
1	BULGARIA, Kozloduy NPP, units 5, 6	953	1000	209 ($US-1993 [7])	**230**	234 ($US-1996 [9])	**239**	239	30	191
2	RUSSIAN FEDERATION, Balakovo NPP, units 1–4	950	1000	147 ($US-1993 [7])	**199**	16–29 ($US-1994 [17])	**17–31**	17–31	no data	no data
3	UKRAINE, WWER-1000 units	950	1000	168 ($US-1993 [7])	**227**	187–258 ($US-1994 [19])	**201–277**	201–277	no data	no data

(3) There is an important exception in the cost assessments — the amount of required investments for the Russian Federation is much lower (17–30 M$US per unit) than in the other countries. The difference is so noticeable that some explanation is needed. As with WWER-440/230s, one of the most probable explanations is the low labour rate used in [17] for the cost conversion to the Russian conditions. For example, if the same set of safety upgrades were implemented in the US conditions, the corresponding costs of safety upgrades would be of the order of 60–100 M$US [17]. The reason for the rest of the difference is unclear.

3.3.4. PWR and BWR reactors

Data for 4 countries operating PWRs and BWRs were found for this review: for Germany, the Republic of Korea, the Netherlands and the USA. For the USA, the series of analytical reviews of O&M costs for US NPPs published by the US Energy Information Administration since 1988 (the third, latest of these reports [20] published in 1995) is used here as the data source. For Germany, several publications prepared by or in co-operation with operating utilities are used [10, 11, 12]. For the Netherlands, a recent article summarising the experience with the upgrade of the Borssele PWR-480 unit is the source of information [16]. Data for NPPs operating in the Republic of Korea were presented at an IAEA consultants meeting in October 1998 [13].

3.3.4.1. US experience

The analysis conducted in [20] covers practically all large US commercial NPPs that were in operation by the end of 1993. More exactly, all NPPs with unit capacity larger than 400 MW(e) are included. This represents, in terms of installed capacity, more than 95% of the total nuclear capacity of the USA.

The cost representation in [20] is somewhat different from the pattern used above for WWERs, because the analysis was based on the use of the US standard accounting system used for reporting by NPPs. First, the data are given in $US/kW(e)/year rather than per each unit. Second, there is a distinction between O&M costs (roughly, the cost of the labour to run the plant plus the cost of consumable materials) and capital additions (roughly, the cost of the equipment replaced for which the cost is capitalised). The difference between the two categories lies in the fact that O&M costs, according to the US accounting rules, are recovered as they are spent (i.e. in the same year), while capital additions are considered to be changes in the capital that are recorded as part of the plant book value and recovered over a number of years.

Consequently, it is capital additions that are most close to the term "costs of safety upgrades" as used for WWERs above. However, one should note that, on one hand, the capital additions in [20] contain more than just safety related upgrades: according to [20, page 3], approximately 50% of capital additions are safety upgrades, i.e. actions induced by the US National Regulatory Commission (NRC). The other half is the cost of routine equipment replacements. On the other hand, some part of the O&M costs also depends on changes in NRC requirements; in this sense, the use of capital additions actually may underestimate the total cost effect of the need to upgrade plant safety. However, as for Soviet-designed models no analysis of changes in the O&M costs is available, this last factor seems to be irrelevant for the purpose of this review. (There are also other special, but less important definition features for O&M costs and capital additions, see Section 2 in [20]).

The last important point is the historical behaviour of capital additions. As emphasised in [20], the O&M costs in the USA underwent sharp escalation in the period from 1974 through 1990s: the real (with the inflation accounted for) O&M costs roughly tripled during this period. During the same period, capital additions also escalated: from about 10 $US-93 in 1974 up to about 60 $US-93 at the maximum in 1984. However, since the beginning of the 90s, the O&M costs seem to have stabilised, and capital additions generally decreased down to 20–35 $US-93 observed in 1989–1993. It is the average value for capital additions in 1990–1993 that is used in the tables below.

The capital additions for US reactors are given in the two tables below: Table VI gives the numbers for PWR reactors and Table VII — for BWR reactors. The costs are given, in accordance with [20], in $US/kW(e)/year. To make comparison with the data for WWERs and other reactors possible (where usually the costs are given per unit with some disbursement by years), a column is added showing the total cost of safety upgrades during a five-year period for a typical 1000 MW(e) unit. Unfortunately, detailed technical information concerning the technical measures that are covered by the described capital additions is out of the scope of consideration in [20]. Therefore, one can make only general remarks on the costs shown in Tables VI–VII.

TABLE VI. COSTS OF SAFETY UPGRADES FOR US PWR REACTORS [20]

Plant age category	Original cost estimate in $US per unit of plant capacity and per year, $US of 1993	Cost converted with GDP Deflators, $US of 1997	Example cumulative cost for a 1000 MW(e) reactor during a 5-year period, M$US of 1997
0–3 years	25.17	28	**140**
3–6 years	33.95	37	**185**
6–8 years	12.31	14	**70**
8–9 years	6.88	8	**40**
10–12 years	19.88	22	**110**
12–14 years	25.69	28	**140**
14–17 years	23.69	26	**130**
17–20 years	33.04	36	**180**
20–23 years	33.02	36	**180**
>23 years	25.63	28	**140**
all PWR plants considered	24.3	27	**135**

(1) The first observation is that the costs do not depend much on the type of the reactor. Although the average number for BWRs is somewhat higher than for PWRs (32 against 27 $US/kW(e)), this difference does not appear meaningful in view of the much higher differences within each reactor type.

(2) There is some common trend in the costs depending on the age of the unit, see Fig. 1 for illustration. At first, the expenditures are relatively high, apparently due to the effect of the beginning of the learning period and the need to bring the new unit in compliance with the latest regulations. Then, there is a period of relatively low expenditures. This period is

followed, however, by the period of increasing expenditures, when the factor of ageing and difficulties in following enhanced safety requirements seem to outweigh the effect of learning. As noted in [20], at some point increases in the costs can be offset by the industry allowing the unit condition to deteriorate instead of introducing upgrades.

(3) It is interesting to compare the investments for safety upgrades at US NPPs with those for WWER reactors described in Sections 3.3.1–3.3.3. While an accurate estimate can be hardly made due to insufficient level of detail in the data available, it is possible to make a rough estimation. One can assume that the most part of safety upgrades at the US NPP was implemented in the period of 1975–1984. For this period, the average costs of safety upgrades at US NPPs were, in accordance with [20] (see also Annex III), about 814 $US-93/kW(e) or roughly 900 $US-97/kW(e). If we assume that half of this amount were safety-related upgrades, we arrive at 450 $US-97/kW(e) as a rough estimation of the costs of safety upgrades at reactors started operation in the 1970s. This order of the costs correlates, especially if we take into account the higher level of prices in the US as compared with countries of Eastern and Central Europe), with the data for WWERs shown in previous chapters. Actually, expenses for safety in the US seem to be higher in view of the fact that certain safety upgrades were also implemented after 1985. This confirms that the need to upgrade older reactors and the relevant cost implications represent a general problem for the nuclear power sector of the present.

TABLE VII. COSTS OF SAFETY UPGRADES FOR US BWR REACTORS [20]

Plant age category	Original cost estimate in $US per unit of plant capacity and per year, $US of 1993	Cost converted with GDP Deflators, $US of 1997	Example cumulative cost for a 1000 MW(e) reactor during a 5-year period, M$US of 1997
0–3 years	not available	–	–
3–6 years	25.14	28	**140**
6–8 years	23.39	26	**130**
8–9 years	–3.42 [a)]	–4	**–20**
10–12 years	24.08	27	**135**
12–14 years	not available	–	–
14–17 years	35.48	39	**195**
17–20 years	37.22	41	**205**
20–23 years	26.46	29	**145**
>23 years	64.52	71	**355**
All BWR plants considered	29.01	32	**160**

a) The rules applied in [20] for the calculation of capital additions allow for negative values to appear in cases when the salvage value of the replaced components is high.

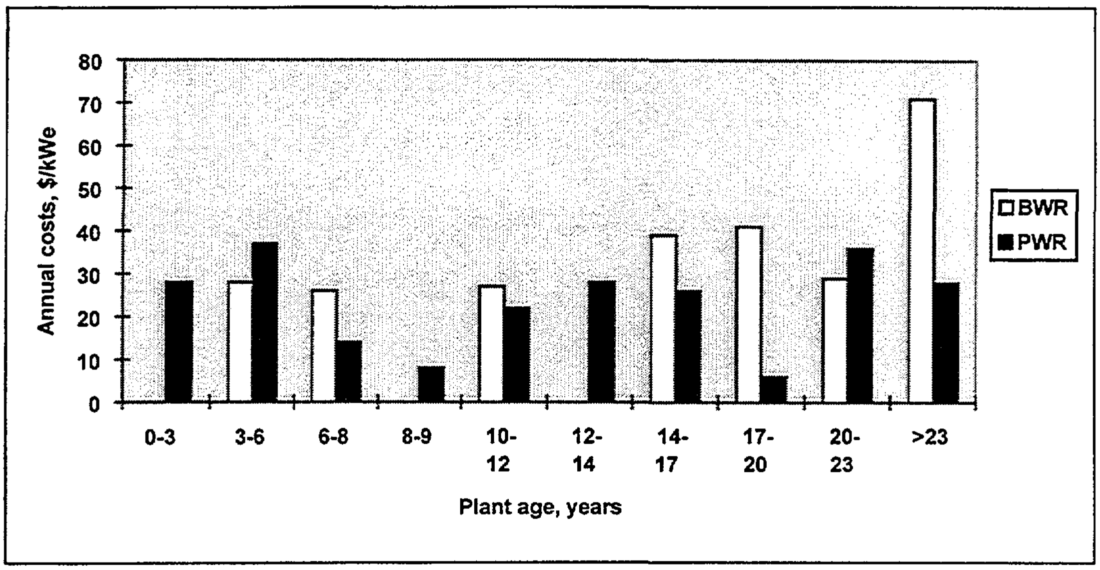

FIG. 1. Changes of capital additions at US NPPs with plant age [20].

3.3.4.2. Experience in Germany

The found information on the costs of safety upgrades in Germany is less detailed than the corresponding information on US NPPs above. According to the assessment made in [10], upgrades of an average old (i.e. built in the 1970s) operating German NPP unit cost about 50 million DM per unit annually or about 1/3 of the total annual O&M costs. This amount includes not only safety-related upgrades, but also equipment replacement and operational improvements at the plant. In this sense, the given cost category is larger than the costs for WWER reactors covered in previous sections. On the other hand, these costs are close in definition to the US costs described above. It is also important to note that the given 50 MDM/unit/year do not distinguish between PWR and BWR units: this is an average for old operating units in Germany.

The application of the technique of monetary conversion assumed in this report allows to receive the following results comparable with the other cost assessments:

- original assessment: 50 MDM of 1994[3] per year and per one PWR or BWR unit of the gross capacity of 1173 MW(e) (average unit capacity in Germany according to [25]);
- assessment in DM of 1997 in accordance with Table I: 52.3 MDM-97/unit/year;
- assessment in $US of 1997 in accordance with Table I: 34.9 M$US-97/unit/year or 29.8 $US-97/kW(e)/year.

One can note that this number corresponds surprisingly well with the corresponding data for US reactors in the beginning of the 90s (Table VI–VII above). Thus, the expenditures on operational and safety upgrades in Germany and the USA in the 90s seem to be at the same level. Unfortunately, there is no information for Germany concerning the historical behaviour of the costs, so it is impossible to judge whether the situation was the same before (e.g. whether the sharp escalation of the annual O&M costs in the USA in 70–80s was also observed in Germany).

Another important note is that the given number for Germany is the average for all plants. At each individual plant, essential differences from this number can be expected depending on the age of

---

[3] As the source publication is dated 1995, it is assumed that the costs are of 1994 (the year is not given in the text of [10]).

the plant and other factors. The magnitude of such differences can be seen by the differences in the total O&M costs at some German plants presented in [11]: the total costs vary from about 70 MDM/unit/year for the Brokdorf 1419 MW(e) PWR unit to 115 MDM/unit/year for the Unterweser 1364 MW(e) PWR unit (average 1991–1994 data). It is not clear why these costs are lower than the average of 150 MDM/unit given in [10]. Probably, the reason for the difference is the different age of the units considered: in [10], all "old" German units are meant, while only 4 selected units are considered in [11].

As a complement to the average costs presented in [10] and discussed above, one can check the specific situation of one plant on the basis of the analysis conducted in [12] for the Neckarwestheim (GKN) plant in Germany. The plant consists of two PWR units of the gross capacity of 840 and 1365 MW(e). The units have been in operation since 1976 and 1989 correspondingly. For this plant, the annual expenditures for reconstruction ("Umbau- und Reparaturmassnahmen" as defined in [12]) are assessed as 64.8 MDM, expenditures for safety upgrades being an important part of this sum. Assuming that these costs are of 1997 (the year is not given in [12]), this corresponds to 43.2 M$US-97/plant/year or 19.6 $US-97/kW(e)/year, which is in good correspondence with the average costs above taking into account the younger age of Neckarwestheim Unit 2.

It is worth mentioning that according to [12] these expenditures are expected to decline after the completion of the current programme of safety upgrades. It is also important to note that a process of power uprating is currently in progress at German NPPs. The resulting increases in unit capacity must reduce the costs of safety upgrades on a per kW(e) basis.

3.3.4.3. Experience in the Netherlands

In the Netherlands, there has been a project of safety upgrades at a nuclear power plant which one could call a representative project for such objectives [16]. An operating NPP — the 480 MW(e) Borssele PWR unit that started to operate in 1973 was thoroughly studied at the beginning of the 90s in view of latest safety regulations. As a result, the concept of safety upgrading was developed, a new design basis for the plant defined and a lump sum/turn key contract for performing all the relevant work was given to SIEMENS AG/KWU in 1992. The fulfilment of the project started in 1993 and ended in 1997, with a 5-month interruption in plant operation in 1997, immediately before the restart of the upgraded NPP. The resulting effect on safety can be seen from the change in the total core damage frequency for the plant [16]:

- for the original design, it was assessed as about 10^{-4}/year;
- in 1985, after the installation of some additional independent safety systems, the frequency changed to 5.6×10^{-5}/year;
- after the completion of the mentioned programme of safety upgrades, the core damage probability was estimated as 4.5×10^{-6}/year.

Concerning the costs, the following numbers are available for the project:

- the project budget was 467 million Fl of 1997[4]; or $US–97 250 million;
- per unit of gross capacity, this represents 501 $US-97/kW(e);
- taking into account the duration of the project of approximately 5 years, the average annual expenditures would be about 100 $US-97/kW(e)/year (this is just a example to make comparison with other data possible and does not have relevance to the actual project cash-flow which must have been quite different).

[4] The base year of the currency is not given in [16], but according to [72] the costs are of 1997.

At first look, this cost appears elevated as compared with annual expenditures for the USA and Germany that were discussed above. However, apart from possible technical differences that are not analysed here (one of them is that the initial design of Borssele plant assumed lower level of physical separation of the systems than the later nuclear projects; this drawback is relatively expensive to correct), it is possible that the higher cost can be explained by the fact that safety upgrading was implemented as one-time project. Thus, higher expenses during relatively short time may result in lower expenses for safety upgrades for the rest of the plant's life. Note that the one-time implementation can be explained by the regulatory approach in the Netherlands requiring periodic in-depth safety reassessments at regular, but relatively long intervals (of the order of 10 years).

Comparison with the cost of safety upgrades at WWERs and (below) LWGRs shows that the cost for Borssele is significantly higher. This may have for reason, again apart from probable technical differences, the different economic conditions (cost of equipment, materials and labour) in the Netherlands as compared with the countries of Central and Eastern Europe that operate Soviet-designed reactors. As the assessments made in [17] show, the difference in economic conditions may well cause cost differences of the order of 1–2 in magnitude.

3.3.4.4. Experience in the Republic of Korea

As of December 31, 1997, 12 nuclear units were operating in the Republic of Korea [25]. They include 10 PWR units with the capacity in the range of 590–950 and 2 HWR units (680 and 700 MW(e)). At present, the issue of safety upgrading is most topical for the units that started operation in late 70s and in the 80s, i.e. for 4 PWR units of the Kori plant, 2 PWRs of the Yonggwang NPP and the 680 MW(e) HWR unit of Wolsong. The total costs of safety upgrades implemented at these units in the period from 1979 through 1998 are given below in Table VIII. A more detailed presentation of the costs can be found in Annex III, where annual costs for the period 1979–1998 are presented for each of these units.

One should note that the presented costs for Korean units are costs of safety related improvements only, i.e. during data preparation care was taken to separate safety related upgrades from those of operational character. In particular, costs for such measures as steam generator replacement, turbine rotor replacement, re-racking of the spent fuel pool, etc. are not included in Table VIII. In this sense, the Korean data are very well suited for the purpose of this report, the more so that data are available for units of different age.

TABLE VIII. COSTS OF SAFETY UPGRADES IN 1979-1998 FOR KOREAN REACTORS [13]

No.	Unit Name and Type	Gross capacity, MW(e)	Start of Commercial Operating, year	Total Costs of the Upgrades, million Korean Won of 1997	Total Costs of the Upgrades, M$US of 1997	Specific Costs of the Upgrades, $US-97 per kW(e)
1	Kori 1, PWR	587	1978	49346.6	51.9	**88**
2	Kori 2, PWR	650	1983	22448.5	24.0	**37**
3	Kori 3, PWR	950	1985	20873.7	22.0	**23**
4	Kori 4, PWR	950	1986	20841.5	21.9	**23**
5	Yonggwang 1, PWR	950	1986	18496.9	19.4	**20**
6	Yonggwang 2, PWR	950	1987	18496.9	19.4	**20**
7	Wolsong 1, HWR (CANDU)	679	1983	45126.8	47.5	**70**

By comparison with the data above for other countries operating PWRs, the following observations can be made:

(1) The costs for Korean PWRs are significantly lower than for PWRs in the USA, Germany or the Netherlands. For example, the total costs of safety upgrades for a US NPP built in the 70s was assessed above as about 450 $US-97/kW(e), while the corresponding number for the Kori-1 unit is only 88 $US-97/kW(e). One of the most probable reasons is the use of local labour and materials in Korea that have lower costs than in the USA Two other reasons of importance are: 1) Difference in accounting system of the utility, i.e. no utility's internal manpower cost for management, operation, start-up, engineering, quality assurance, and, etc. spent for the implementation of safety upgrades is included in the cost; and 2) equipment replacement cost for steam generator replacement, turbine rotor replacement, condenser replacement and re-racking of the spent fuel pool are excluded from the safety upgrades cost, which is not the case with other PWRs. With these costs in consideration, the upgrades costs would be 4–5 times higher. Other reasons may include differences in the regulatory environment, specific technical features of the design and the advancement status of the upgrades (e.g. some upgrades already implemented in the USA may not have been implemented yet in Korea).

(2) Costs of safety upgrades at Korean NPPs are also lower than the corresponding costs for WWERs. The difference is especially visible for the units of large capacity: upgrades for the Yonggwang 950 units cost about 20 $US-97/kW(e) while the corresponding costs for WWER-1000s are assessed to be of the order of 200–300 $US-97/kW(e) (except for the assessment for Russian WWER-1000s in [17] which is of the same order as the Korean data: 20–30 $US-97/kW(e)).

(3) Some correlation with unit age is noticeable in Table VIII: the younger the unit, the lower the cost. This is especially visible when comparing the 20-year old Kori-1 unit (88 $US-97/kW(e)) with the 10-year old Yonggwang units (20 $US-97/kW(e)). However, it is not clear what part of the difference should be explained by the difference in the reactor age and what part is due to a different, more advanced design of Yonggwang's PWRs. To understand this factor, projections of the costs of safety upgrades for the future would be needed for each Korean unit. Such projections would also allow to better establish the reasons for differences with the costs for PWRs and WWERs. However, this information is currently not available.

It is interesting to note that the cost for the HWR reactor of Wolsong-1 (CANDU-679) is noticeably higher than for Korean PWRs of the same age. Unfortunately, no information for the costs of safety upgrades at CANDU reactors was found for this cost review, so there is no basis for the analysis of this point. (Due to the absence of information, there is no section on upgrades at HWRs in this report and the data for the Korean HWR are presented only here.)

3.3.5. LWGR (RBMK) reactors

LWGR (or, in the Russian spelling, RBMK) reactors belong to another category of "Soviet-designed" reactors. They are water cooled, graphite-moderated channel-type reactors of a one-circuit design, i.e. with the steam from the reactor going to the turbines. Often these reactors are called "Chernobyl-type" because of the well-known nuclear accident with one of the RBMKs at the Chernobyl NPP in 1986. Following the Chernobyl accident, numerous analyses of RBMK safety were conducted that allowed to identify areas where safety enhancements were needed, such as, e.g.

- reduction of the positive steam reactivity coefficient;
- improvement of the efficiency of the reactor scram system (improvement of the existing scram system, introduction of a second independent scram system, the prevention of the input of positive reactivity with control rods);

- emergency protection at reduced operation reactivity margins;
- improvement of testing/control of primary circuit components;
- modification of the emergency core cooling system; and others, see, e.g. [30, 31] for the description of RBMK design features and relevant safety enhancements.

Currently, three countries operate RBMK reactors: Lithuania, the Russian Federation and Ukraine. These countries have already implemented many of the required upgrades, but the process of safety upgrading still continues. Cost assessments of RBMK safety upgrades were available for Lithuania and the Russian Federation. These assessments are presented in Table IX.

In addition to the costs of safety upgrades, one can note that for LWGRs the replacement of fuel channels is required as part of operating procedures. This replacement is required after 15–20 years of service. The cost of the operation is, according to the assessment for the Ignalina plant, 70–100 M$US of 1997 per unit, or 54–65 $US-97/kW(e) [15].

The following observations can be made for the costs in Table IX:

(1) Safety upgrades at RBMK reactors require investments of the same order of magnitude that other reactors: 40–160 M$US/unit depending mainly on the implementation level reached.

(2) A large part of these investments has been already made. However, more financing is needed. For example, in Lithuania almost 1/3 of the total investments required has been made.

(3) As for the other "Soviet-designed" models, the assessments for the Russian Federation made in [17] give a lower number than the other assessments. It seems to be desirable to verify both the absolute number and the implementation level for the Russian RBMKs.

3.4. ADDITIONAL INFORMATION AND NOTES ON COUNTRY-SPECIFIC FEATURES

In addition to the standardised cost presentation in Section 3.3, some more information concerning the costs of safety upgrades was found for certain countries, in particular in the course of an IAEA consultants meeting of October 27–28, 1998. While being valuable, this information varies from country to country and can be hardly standardised similar to the tables for Section 3.3. Therefore, this complementary diverse information structured by country is presented in Annex III. Annex III covers the following countries:

- Armenia: Section III.1;
- Bulgaria: Section III.2;
- Republic of Korea: Section III.3;
- Lithuania: Section III.4;
- USA: Section III.5.

TABLE IX. COSTS OF SAFETY UPGRADES FOR LWGR (RBMK) REACTORS

				Assessment 1		Assessment 2 (reference assessment)				
1	2	3	4	5	6	7	8	9	10	11
No.	Country/NPP	Net Capacity, MW(e)	Gross Capacity, MW(e)	Total upgrade cost in original estimation, M$US	Total upgrade cost converted to M$US of 1/1/1997	Total upgrade cost in original estimation, M$US	Total upgrade cost converted to M$US of 1/1/1997	Specific upgrade cost, $US-1997/kW(e) (gross)	Investments already made by 1/1/1998, M$US of 1/1/1997	Investments to be made starting 1998, M$US of 1/1/1997
1	LITHUANIA, Ignalina NPP, Units 1, 2	1185	1300	92 ($US-1993 [7])	**102**	93–151 [a] ($US-1994 [14])	**99–162**	76–125	60	39–101
2	RUSSIAN FEDERATION, All NPPs with RBMKs	925	1000	43 [b] ($US-1993 [7])	**47**	35–90 [c] ($US-1994 [17])	**38–97**	38–97	no data	no data

[a] The range has the following meaning: the minimum is for urgent and short term upgrades only assuming early closure of the unit while the maximum assumes unit operation until at least the time of fuel channel replacement (15–20 years).

[b] This number is for short term upgrades only.

[c] The range shows possible variations among the existing 11 RBMK units in the Russian Federation that depend on the implementation level at each site in the year of cost assessment, i.e. in 1994.

4. COSTS OF LIFETIME EXTENSION

4.1. GENERAL: ON THE OPTION OF LIFETIME EXTENSION

At present, the majority of operating reactors are between 10 and 25 years old as illustrated in Fig. 2; dozens of reactors have the age above 25 years. As the typical licensed operation time is 30–40 years, the situation shown in Fig. 2 means that very soon a process of large-scale nuclear shutdowns may commence. This will necessitate significant investments for the construction of replacement capacities. In some countries, such as Bulgaria, the Russian Federation, the USA, "old" reactors provide a notable part of electricity generation and their coming shutdown represents a certain problem for the national power systems.

However, often "old" reactors have a good operating record. Moreover, during their operating period the processes of ageing have been studied and it can be reasonably expected that they can operate longer than initially planned.

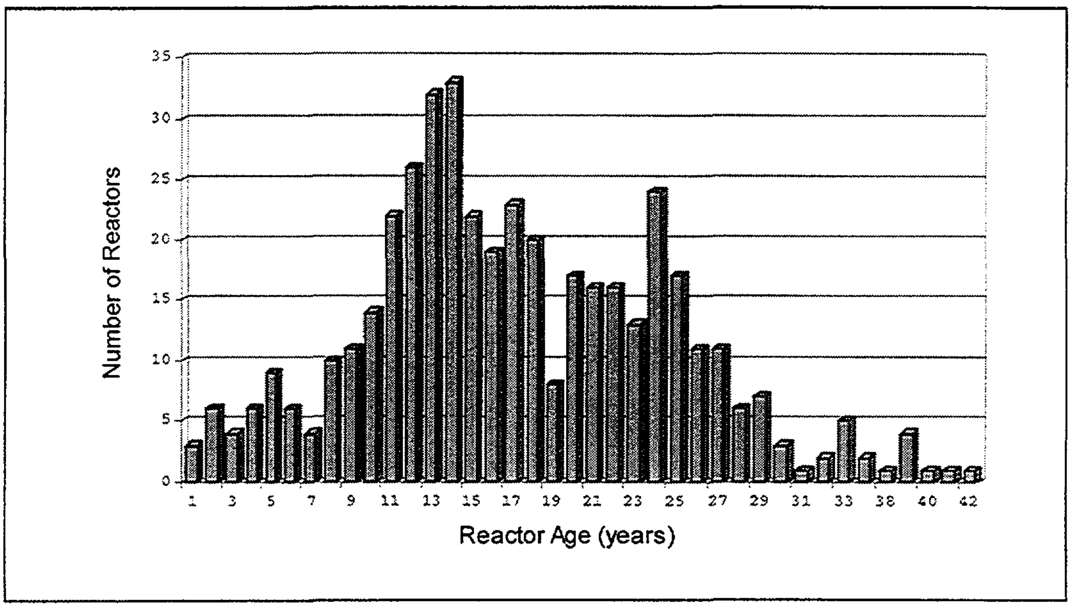

FIG. 2. Distribution of operating reactors by age as of December 1997 [25].

For example, US reactors are normally licensed for 40 years of operation, but an extension for 10 more years for some of them is considered as a possible option [32]. Specifically, two US utilities have already applied for a 20-year lifetime extension for their operating units: Baltimore Gas & Electric for the Calvert Cliffs NPP and Duke Power Co. for its Oconee NPP [33]. In the Russian Federation, there is a discussion of the possibility to extend the planned 30 year operating period by 5–10 years depending on the reactor model [34]. Lifetime extension is under consideration in Japan, Canada and some European countries with developed nuclear programmes; in the United Kingdom, the lifetime of old MAGNOX reactors has already been extended from the original 30 to 50 years [35].

In general, the principal incentive for lifetime extension is clear: if the plant simply continues to operate longer than planned and it operates as well as before, it is certainly cheaper to implement lifetime extension than to construct a new plant, especially taking into account the fact that all depreciation charges have already been paid for by that time. In addition, lifetime extension can delay decommissioning activities thus reducing the net present value of decommissioning costs. However, the situation is usually complicated and certain problems need to be faced before lifetime extension could be implemented.

4.2. CONSIDERATIONS FOR LIFETIME EXTENSION OPTIONS

The problems to be addressed for the implementation of NPP lifetime extension can be structured into the following categories:

- technical possibility of lifetime extension;
- plant safety in the period of lifetime extension;
- regulatory framework for extended operation;
- social acceptability of nuclear power;
- economic considerations, i.e. economic substantiation of lifetime extension.

First, it should be proved that the plant can operate longer from the technical viewpoint. During the period of planned operation all equipment items experience processes of ageing that naturally reduce design margins foreseen in order to ensure reliable operation. For some minor elements such as sensors, valves, smaller pumps, etc., this may not be relevant, because such elements can be routinely replaced and may have already been replaced during regular operation. However, for larger equipment items such as the reactor pressure vessel (RPV), steam generators (SGs), pressurizers, containment structures the possibility of extended operation is not guaranteed. This possibility must be proved by relevant studies which is not a simple task. Normally, such studies should prove that [36] 1) the processes of ageing are well understood for all design elements of relevance; 2) there is monitoring of ageing elements that allows to detect component degradation before it fails; 3) procedures for the mitigation of the ageing and its effects are established.

On one hand, these tasks are not new and, normally, they are taken care of during normal operation in order to manage the ageing of plant components during the planned lifetime period of the plant. However, they become more difficult to solve when applied for the substantiation of a long term lifetime extension, because the ageing is supposed to be at the maximum by the end of the designed lifetime of the unit, with a number of key components reaching their operating limit.

The difficulties become even more serious due to the need to ensure the same safety level as during normal plant operation. It is not only required that the plant should be able to operate; it is obligatory that the plant operate as safely as before while being older. Among the components subject to the effects of ageing there are elements critically important for plant safety. A short list of top-priority systems that should be thoroughly reviewed in order to allow for safe extended operation illustrates the seriousness of the task [37]: RPV, containment's basements, reactor coolant piping and safe-ends, steam generators, reactor coolant pump body, pressurizers, control rod drive mechanisms, cables and connectors, emergency diesel generators, RPV internals, RPV supports and the biological shield.

All these systems (and many other less important ones) should be properly examined. Moreover, their fitness for extended operation should be duly and timely confirmed by the competent regulatory body.

The regulatory factor is important, because in order to issue a license for continued operation, the regulator must have in place established procedures for this task and have applied these procedures for the applicant, i.e. the utility applied for lifetime extension. While the establishment of such procedures does not represent a difficulty in principle, it may take time. Therefore, the readiness of the national regulator to handling the problem of lifetime extension is one of the important factors for the realisation of this option.

Another issue of importance is the social acceptability of nuclear power. It may happen that the social attitude to nuclear power has changed while the plant was in operation. For example, while at the beginning nuclear power was seen acceptable and desirable, it may be not so anymore at the time when the plant reaches its planned end of life. Such situation is typical for many countries of Western Europe at present. Therefore, even if it is technically possible to safely extend the plant lifetime, this option may not be accepted socially.

These problems are serious but, at the same time, they do not seem insurmountable either. However, when solving these problems one can find that although the solution can be reached, it is too expensive. Therefore, economic analysis is part of the pre-requisites for the implementation of lifetime extension.

4.3. FACTORS FOR COST ESTIMATION

In general, estimation of the costs of lifetime extension for a NPP is similar to the usual cost assessment procedures that are applied for plant upgrades, design changes, plant decommissioning, new construction, etc. However, there are certain specific features that make this cost estimation, on one hand, more difficult than usual and, on the other hand, highly dependent on the specific conditions at each site. These features are the following.

Diversity of designs

Potential candidates for lifetime extension are NPPs that are relatively old, i.e. NPPs that started operation some 20–30 years ago. At that time, nuclear technology was at a relatively early phase of development that was characterised, among other features, by diversity of designs. Thus, plants to be considered can have much larger differences in both basic design and unit capacity than reactors of recent generations with more or less standard design features within a limited capacity range. Therefore, cost estimations for lifetime extension are likely to be highly dependent on the design/vintage of the plant.

Technical uncertainty for a given design

However, even for a given reactor type it is reasonable to expect differing situations. As both the technical possibility of lifetime extension and its costs depend on the technical condition of the unit at the end of the planned lifetime period, each unit with its unique operating history would have its specific parameters. For example, one unit may have experienced problems with a steam generator that resulted in its replacement by a new one. This can make later lifetime extension for this unit easier and less expensive than for a unit that does not plan to replace the SG until the planned end of life. Another example is the irradiation history for the RPV: as the operational ability of the RPV depends on the integrated neutron flux on the RPV internal surface, the final condition of the RPV depends on the whole operating history of the unit (the power levels at which the plant operated, existence/parameters of the shield to protect the RPV from neutron exposure, implementation/possibility of annealing, etc.)

Therefore, plant operating history with its effect on the condition of plant components has to be considered among key factors for lifetime extension. Consequently, for each unit a special study would be needed in order to verify the condition of all critical components and determine what measures should be implemented in order to permit for lifetime extension.

Correlation between operational upgrades and lifetime extension measures

Another difficulty for the estimation of the cost of lifetime extension lies in the fact that rather often one cannot draw a definite line between operational upgrades that are intended to improve plant's characteristics and withstand the processes of ageing, and the measures aimed specifically at lifetime extension. In some cases, for example in Germany where operating licenses do not have a formal time limit, the upgrades that allow for lifetime extension simply cannot be formally distinguished from "normal" plant upgrades. The mentioned problem of SG replacement is an example: the plant management decides to replace the SG in order to ensure reliable operation, maybe without consideration of the possibility of lifetime extension. However, the fact that the SG was replaced during normal operation time becomes a favourable factor for lifetime extension. Similarly, extensive safety upgrading during the normal operating period increases the chances for the plant to be licensed for extended operation.

Thus, higher expenses for plant upgrades during the normal operating period may noticeably decrease the expenses necessary for lifetime extension — and visa versa.

Country-specific conditions

In most cases, a new license would need to be obtained for NPP operation beyond the planned lifetime. This involves certain additional costs that are necessary in order to perform all the work that the regulator would require the operator to do before issuing this new license. These costs would depend not only on the design features and the operational history, but also on the regulatory environment in each country. As regulatory environments differ, the costs would also differ from country to country.

Commercial sensitivity of the issue

Apart from the above-mentioned difficulties, one should also note the commercial sensitivity of cost data on lifetime extension. Utilities naturally consider the issue of lifetime extension to be within their own responsibility and they are reluctant to publish/release relevant cost data. This reluctance tend to grow as electricity market becomes more and more deregulated and the importance of competitive prices grows.

4.4. AVAILABLE GENERIC COST ESTIMATIONS

The described factors make the task of obtaining/comparing information on the costs of lifetime extension measures rather difficult. The estimates available are rare and even the available data seem to have little general applicability because of the noted importance of reactor and site specific features.

In order to illustrate the magnitude of possible cost parameters and the underlying difficulties for their use, two cost estimations are considered in this report: 1) generic cost estimates for US PWRs and BWRs (this section and Section 4.5) and 2) cost results of a lifetime extension study for a Korean nuclear unit (Section 4.6).

The first estimation [38] is based on two utility studies for BWR and PWR reactors in the USA (BWR-525 Monticello plant and PWR-775 Surry 1 plant). As average cost numbers applicable for a generic analysis, [38] suggested the costs shown in Table X.

As one can see in Table X, the order of the costs is much lower than most current cost estimates for new nuclear power plants (about 2000 $US/kW(e)), so in this sense lifetime extension appears attractive. However, for a utility to decide on lifetime extension, these costs should be compared not with new NPPs, but with the best competitor. In this respect, one can note that the pessimistic assessment is of the same order of magnitude that the typical overnight construction cost for new combined-cycle units (700–900 $US/kW(e)). Thus, in the pessimistic case NPP lifetime extension may turn out non-competitive (of course, for a meaningful comparison between NPP lifetime extension and new gas-fired plants, not only the capital costs should be considered but also the other cost components, the fuel costs in particular).

TABLE X. GENERIC COST ESTIMATES FOR LIFETIME EXTENSION FOR US NPPS [38]

Case	Original cost estimate (net overnight cost) in $US of 1986 per kW(e)	Estimate in $US of January 1, 1997 per kW(e) [a)]
Optimistic	150	210
Baseline	300	420
Pessimistic	600	840

[a)] In accordance with Table I, the cost conversion factor from 1/1/86 to 1/1/97 is 1.404.

4.5. COST DRIVERS FOR LIFETIME EXTENSION COSTS

With the shown wide range of the cost assessments (210–840 $US/kW(e)) it is clear that one can hardly make general conclusions. Instead, one should analyse every case specifically. In [38], an attempt was made to identify site/plant specific factors that can influence the costs and force the numbers go either closer to the low optimistic estimate or up to the high pessimistic value. Among these factors, the following ones appear most important:

- plant design;
- plant age and vintage;
- plant condition (especially the need to replace SGs);
- implementation schedule for lifetime extension measures;
- costs of replacement power;
- cost of the licensing procedure and public opposition.

Plant design

The need to take into account plant design is obvious. The set of technical measures to allow for lifetime extension is somewhat different for PWRs than for BWRs. For PWRs, SG replacement and RPV annealing can be most important cost categories, while for BWRs the replacement of pipes and RPV internals can be the driving costs.

Plant age and vintage

The factor of age or, in another interpretation, of the plant vintage is also important. Due to permanent development of construction and operating practices as well as the development of regulatory requirements, newer plants are likely to have lower costs of lifetime extension (per kW(e)) than plants of older generations. Ultimately, for new nuclear projects lifetime extension tends to become a part of the standard design life, i.e. new nuclear reactors can have the design lifetime of 50–60 years instead of the current 30–40 years.

Plant condition

Its impact can be seen from the two estimates provided in [38] in addition to the given three generic cases:

- For PWRs, lifetime extension costs can range from 100 $US-86/kW(e) (or 140 $US-97/kW(e)) for a simple case when only maintenance activities are needed to as high as 700–800 $US-86/kW(e) (1000–1100 $US-97/kW(e)) for the case when replacement of major components is needed as well as RPV annealing.

- For BWRs, the range of probable costs is 80–250 $US-86/kW(e) (or 110–350 $US-97/kW(e)) depending on the amount of piping to be replaced and the need to replace RPV internals.

One can note specifically the impact of steam generator replacement on the costs of lifetime extension for PWRs, see Table XI.

TABLE XI. IMPACT OF SG REPLACEMENT ON LIFETIME EXTENSION COSTS [38]

Cost Item	Original cost estimate (net overnight cost) in $US of 1986 per kW(e)	Estimate in $US of January 1, 1997 per kW(e)
SG Purchase	30–40	40–55
SG Installation	30–40	40–55
Total for SG replacement	60–80	80–110

Implementation schedule for lifetime extension measures

Another issue of importance is the schedule of lifetime extension measures. To be able to start the period of extended operation immediately or almost immediately after the end of planned lifetime, the operator must start the preparation for lifetime extension well in advance. In financial terms it means that the cash-flow of the investments must be considered using a discount rate for different time expenditures. It is reasonable to assume that a large amount of lifetime extension measures could be implemented during scheduled outages. The corresponding effect of the capital cost is shown in Table XII (calculated with a 5% discount rate).

Although the relative range of the numbers is the same as for the overnight costs, the increased absolute value can deteriorate the attractiveness of the option for the operator, especially if higher discount rates are applied.

Costs of replacement power

If a special outage is needed for the plant before starting the period of extended operation, one should add one more component to the costs of lifetime extension the cost of replacement power necessary to serve the demand when the considered NPP unit is unavailable. This cost is highly specific, i.e. it depends very much on the situation in the power system that would produce the replacement power. For a system with a large reserve capacity the replacement cost may be relatively low, while for a system with a limited margin the replacement costs may become essential.

TABLE XII. IMPACT OF THE IMPLEMENTATION SCHEDULE ON LIFETIME EXTENSION COSTS [38]

Cost Item	Original cost estimate in $US of 1986 per kW(e)	Estimate in $US of January 1, 1997 per kW(e)
Lifetime extension overnight costs	150–600	210–840
Lifetime extension costs with interest accumulated during the implementation time	250–1000	350–1400

Cost of public opposition

Normally, a new license is required for a plant to extend operation beyond the designed lifetime. To obtain the license, the operator may be required to demonstrate to the regulator that the plant will operate safely. This demonstration depends on the formulation of regulatory requirements for lifetime extension and it may be rather costly. In addition, as noted in [38], overcoming local opposition to nuclear power may add its noticeable share to the costs of licensing. This additional cost is assessed in [38] as 10–30 million $US of 1986 (15–40 million $US of 1997).

4.6. SPECIFIC LIFETIME EXTENSION STUDY FOR A KOREAN NPP

This cost estimation is much more recent than the one given above for two US NPPs. It is based on the results of the first phase of the "Nuclear Power Plant Lifetime Management Study (I)" [13, 39, 40], which was conducted for unit 1 of the Kori NPP, a 587-MW(e) PWR unit that started operation in 1978. Normally, the operating license for the unit should expire in 2008, i.e. after 30 years of operation. The mentioned study was a feasibility study for unit lifetime extension and was aimed, as one of the main objectives, at the identification of the components critical from the viewpoint of the possibility of continued operation.

In the course of the study, 13 critical components were identified (the list does not include the steam generators because they were replaced in 1998):

- reactor pressure vessel;
- reactor vessel internals;
- control rod drive mechanisms;
- pressurizer;
- reactor coolant system piping;
- reactor coolant pump;
- reactor pressure vessel supports;
- pressurizer nozzles;
- turbine;
- cables;

- containment building;
- generator.

For the identified critical components as well as for other relevant equipment items, a cost estimation procedure was applied in order to assess the amount of investment that the lifetime extension of the Kori-1 unit would necessitate. This procedure included the assessment of the replacement probability for each component of relevance depending on the duration of extended operation. Three duration options were considered: 10, 20 and 30 years. For each of these options, the mathematical expectation of the lifetime extension cost (the sum of products of the replacement cost and the replacement probability for every considered component) was determined in the study. The methodology of cost estimation is illustrated in Table XIII.

The results of this cost estimation are given in Table XIV for the three PLEX duration options considered (10, 20 and 30 years) and for two implementation options. Option 1 assumes that only refurbishment and component replacement would be needed, while Option 2 includes, in addition to these, also the estimated costs of safety backfitting (in the area of fire protection, equipment qualification and withstanding the station black-out) and the costs of licensing.

As Table XIV shows, the costs of lifetime extension are assessed to be in the range of 230–770 $US-97/kW(e) depending on the duration of lifetime extension and the implementation option, i.e. the extent of required backfitting. These numbers correspond very well with the results of the two US generic cost studies given above. Thus, the same observation that at lower cost lifetime extension is likely to be competitive while at high costs the PLEX option would have to compete with new gas-fired units seems to be valid in this case also. At the same time, one should note that according to the Korean estimates, the benefit/cost ratio in all cases is higher than 1, i.e. lifetime extension is assessed to be still a viable option even at the highest cost found, although the absolute value of the ratio decreases from about 3.8 for a 10-year extension with option 1 down to about 1.9 for a 30-year extension with option 2. (Details of the calculation of the ratio are not available in [13], so it is difficult to discuss the exact meaning of this parameter.)

4.7. CONCLUSION ON ECONOMIC VIABILITY OF LIFETIME EXTENSION

As shown above, a number of factors can affect the cost of lifetime extension for a given plant. Therefore, a plant specific analysis is needed in order to obtain a reliable cost estimation. However, in order to determine whether for this or that plant lifetime extension is competitive, the found cost of lifetime extension should be compared with the cost of alternative power sources, such as new construction, refurbishment of conventional plants, power purchases from independent power producers or other utilities. This makes the task close to the usual power system analysis when the most economic alternative of power generation is sought — with all known advantages and disadvantages of such sophisticated analyses.

Thus, one can conclude that the assessment of economic viability of lifetime extension is a rather complex task, first of all due to the technical complexity of the issue (technical diversity of possible situations, strong effect of reactor and site specific features), but also due to the need to compare the lifetime extension option with other alternatives. If such cost assessments are done without a direct contact with the operator of the concerned plant, the commercially sensitive character of the relevant costs becomes an additional practical difficulty for a more or less valuable cost analysis. Therefore, it appears difficult, if not impossible, to give generic conclusions on the economic viability of lifetime extension. Instead, country and site specific analyses, preferably by or in close co-operation with the concerned utility, should be the proper means to approach the problem.

TABLE XIII. EXAMPLE COST ESTIMATION TABLE FROM THE KOREAN STUDY FOR KORI-1 [13]

Component	Replacement cost (A)	PLEX10 years		30 years PLEX	
		Replacement probability %(B)	Expected Cost (=A×B)	Replacement probability %(B)	Expected Cost (=A×B)
...	...	...	...	...	...
Containment basement liner	...	...	...	...	...
Steam generator	...	...	...	...	...
...	...	...	...	...	...
I&C equipment items	...	...	...	...	...
Building refurbishment	...	...	...	...	...
...	...	...	...	...	...
LP turbine rotors	...	...	...	...	...
HP turbine	...	...	...	...	...
...	...	...	...	...	...
TOTAL for PLEX					

TABLE XIV. COSTS OF LIFETIME EXTENSION FOR THE 587-MW(E) PWR KORI-1 UNIT IN KOREA [13]

Extension period, years	Extension option	Total overnight costs in million won of 1996	Total overnight costs in M$US of 1997	Specific overnight cost, $US-97 per kW(e)	Benefit/cost ratio [a)]
10	1	103 900	134	228	3.84
	2	164 800	212	361	2.42
20	1	197 900	254	433	2.92
	2	258 800	333	567	2.23
30	1	291 800	375	639	2.24
	2	352 700	453	772	1.86

[a)] The benefit/cost ratio was calculated on the basis of the net present values of the costs and benefits.

5. COSTS OF DECOMMISSIONING

5.1. REACTOR MODELS AND COUNTRIES COVERED

Similarly to the data on safety upgrades, Table XV presents the scope of this review, i.e. the countries and reactor models for which decommissioning costs were found. Altogether, about 50 cost estimates are included in the review covering the most widely used NPP types:

- pressurised water reactors (of the PWR and WWER type);
- boiling water reactors (BWRs);
- heavy water reactors (HWRs);
- light water cooled, graphite moderated reactors (LWGR or RBMK type);
- gas cooled reactors (GCRs and AGRs).

5.2. REVIEW OF THE COSTS

The review of total costs of decommissioning is presented similarly to the review of the costs of safety upgrades in Section 3, i.e. a number of cost estimates for a given reactor may be presented in order to make historical comparisons possible. However, only one estimate which is called the reference estimate (usually the latest one) is considered to be most reliable. For this reference estimate, more details are provided in the tables.

The cost assessments for decommissioning are structured into two main categories. The first one is for the decommissioning approach assuming prompt (often called immediate) dismantling of the plant up to the "green-field" (non-restricted use) or "gray-field" (somewhat restricted use) condition (Stage 3 decommissioning). The other one (Stage 1 and/or Stage 2 decommissioning followed eventually by Stage 3) assumes long term storage of the unit, mainly in order to allow for natural decay of radioactive substances, which makes subsequent dismantling operations substantially easier.

This structuring follows the well-established IAEA terminology on decommissioning stages [62, 63, 64] used in many international decommissioning studies, e.g. in [4, 5, 50].

As noted in Section 1, this review is primarily intended to give information on the total costs. Therefore, only general observations are made on the presented cost assessments in the subsequent sections. It is not attempted to provide a detailed analysis of the cost structure and the relative importance of various cost components. Such analyses are usually subject of special studies, see, e.g. [5, 1, 51]; details concerning the implemented approach to cost estimation can be found in the referenced information sources.

It must be noted that very often it is only in background publications that one can find sufficient information on the meaning of this or that cost component or explanations for cost differences among the countries considered. For example, the scope of decommissioning activities differs from country to country, which obviously affects the cost numbers[5]. While such information was looked for and

[5] As one of possible examples, one can mention here the different approaches to the cost of fuel unloading. In some countries (Korea, Slovakia, Bulgaria) this cost is a standard part of the decommissioning costs. In other countries, e.g. in Germany [50], it is not included in the costs of decommissioning. There are also cases when for a given country some studies include the cost of fuel unloading while the others do not. For example, the two US reference decommissioning studies [59,60] consider, according to [51], the cost of fuel unloading within the decommissioning costs. At the same time, most of utility decommissioning studies in the US (see Annex IV.5) do not include the cost of defueling [65]. A similar situation is in the Russian Federation: some analyses (e.g. [55,56]) include it while others (as in [17,57]) do not.

analysed during the preparation of this review, it was considered neither possible nor appropriate to include a detailed cost analysis in the scope of this document.

One should note also that the costs presented are total overnight costs. Although some decommissioning schedules are given in Annex IV, estimations including the procedure of discounting are considered to be out of scope for this review.

In case where the cost estimate relates to a specific reactor unit, the name of the unit is given in the cost tables below, while for generic estimates, i.e. without the exact specification of the site, names are absent.

5.2.1. Decommissioning with immediate dismantling

5.2.1.1. PWR rreactors

The review of decommissioning costs for PWR reactors is presented in Table XVI. Estimates are given for the following countries: Belgium, France, Germany, Republic of Korea, the Netherlands, Sweden, the United Kingdom, and the USA. Reactor units in the capacity range of 500–1400 MW(e) are considered. For selected decommissioning projects, some representative parameters that influence the cost of decommissioning are presented in Table XVII.

The following general observations can be made on the basis of Tables XVI–XVII:

- Decommissioning costs for the considered PWR reactors range between 150 and 700 $US/kW(e). This large range confirms the conclusion made in earlier studies (e.g. [4,5]) that wide variability is a usual feature of decommissioning costs due to the distinct importance of country, reactor and site specific factors. Table XVII that gives values of certain cost drivers allows to see large variations in the parameters that are essential for the costs of decommissioning. In particular, differences in labour requirements, in the amount of decommissioning wastes and in the duration of decommissioning activities should be noted. Some additional information illustrating the variability of decommissioning costs for US reactors can be found in Annex IV.5.

- Certain cost dependencies can be suggested, e.g. the dependence of the specific cost on unit capacity (see, e.g. the rather high value for the decommissioning of the PWR-450 in the Netherlands). However, the effect of reactor size is small as compared with large differences among countries and differences between the estimates made for the same reactor at different times.

- Of the countries considered, Finland, Sweden and the USA have, on average, lower decommissioning costs. Various reasons of this phenomena (higher labour rates in Germany, lower costs of waste management in Sweden, etc.) are analysed in [51].

- The cost of decommissioning of PWR-450 in Netherlands is noticeably higher than the other cases. Apart from the possible effect of scale, one of the reasons identified and discussed in [41] is the cost of post-shutdown operations that is not included in decommissioning costs in Germany and Belgium.

- For Germany, several cost estimates for the same reactor are available. The comparison of these assessments shows a noticeable growth in the estimated decommissioning costs. Reasons for this trend, in particular the improved knowledge of certain decommissioning activities, are reviewed in [50].

TABLE XV. COUNTRIES AND REACTOR MODELS IN THE REVIEW OF DECOMMISSIONING COSTS

Country	Reactor Model	Reference and Year of Assessment
Belgium	PWR-900	[41] (1994)
	PWR-1390	[6] (1991)
Bulgaria	WWER-440 (model 230)	[42] (1996) [43] (1996) [9] (1997) [44] (1998)
Czech Republic	WWER-440 (model 213)	[45] (1997)
Canada	HWR-542	[4] (1984)
	HWR-600	[5] (1989)
	HWR-935	[6] (1991)
	HWR-1300	[4] (1984)
Finland	WWER-440 (model 213)	[4] (1984) [5] (1989) [46] (1991) [47] (1991)
	BWR-735	[4] (1984) [5] (1990) [48] (1991)
	BWR-1000	[6] (1991)
France	PWR-1400	[6] (1991)
Germany	WWER-70	[49] (1990)
	WWER-440 (model 230)	[49] (1990)
	BWR-806	[4] (1984) [50] (1993) [41] (1994) [51] (1994)
	PWR-1200	[4] (1984) [5] (1990) [50] (1992) [41] (1994) [51] (1994)
	PWR-1300	[6] (1991)
India	HWR-194	[6] (1991)
Italy	BWR-160	[5] (1990)
Japan	BWR-1100	[5] (1984)
	PWR-1160	[5] (1984)
	BWR-1350	[6] (1991)
Republic of Korea	PWR-587 PWR-650 PWR-950 PWR-1000	[52, 53] (1995)

Country	Reactor Model	Reference and Year of Assessment
	HWR-679 HWR-700	[52, 53] (1995)
Lithuania	LWGR (RBMK)-1500	[54] (1995) [15] (1998)
Netherlands	BWR-60	[41] (1995)
	PWR-450	[41] (1995)
Russian Federation	WWER-440 (model 230)	[17, 18] (1995) [55] (1995) [56] (1998)
	LWGR (RBMK)-1000	[17,18] (1995) [55] (1995) [56] (1998) [57] (1998)
Slovakia	WWER-440 (model 230)	[58, 74, 75] (1992)
	WWER-440 (model 213)	[58, 74, 75] (1997)
Spain	GCR-500	[5] (1990)
Sweden	BWR-460	[4] (1984)
	BWR-780	[5] (1990)
	BWR-900	[4] (1984)
	BWR-1050	[4] (1984)
	BWR-1205	[41] (1994) [51] (1994)
	PWR-860	[41] (1994)
	PWR-920	[4] (1984) [5] (1990) [51] (1994)
Ukraine	LWGR (RBMK)-1000	[19] (1994)
United Kingdom	GCR-60	[5] (1989)
	GCR-219	[5] (1990)
	AGR-660	[5] (1990)
	PWR-1200	[5] (1990) [6] (1991)
USA	BWR-1129	[51] (1994) [59] (1994)
	BWR-1155	[4] (1984)
	PWR-1155	[51] (1994) [60] (1994)
	PWR-1175	[4] (1984) [5] (1986)

TABLE XVI. DECOMMISSIONING COSTS FOR PWR REACTORS (IMMEDIATE DISMANTLING)

				Assessment 1		Assessment 2		Assessment 3 (reference assessment)		
No.	Country	Reactor	Gross (or net if noted) capacity, MW(e)	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Specific Cost, $US1997/kW(e) (gross)
1	Belgium	PWR-900	900					11545 [a] (BEF-94 [41])	394	438
2		PWR-1390	1390 (net)					10066 [b) c)] (BEF-91 [6])	376	271
3	France	PWR-1400	1400 (net)					2268 FRF-91 [6]	492	351
4	Germany	PWR-1204 (Biblis-A)	1204	283 (DM-84 [4])	268	346 (DM-85 [5])	320			
5		PWR-1225 (Biblis-A)	1225	426 [d)]-435 [e)] (DM-90 [49])	353-361	473 (DM-93 [50])	346	548 (DM-94 [51])	386	315
6		PWR-1300	1300					796 [f)] (DM-91 [6])	628	483
7	Republic of Korea	PWR-587 (Kori-1)	587					188 [g)] ($US-95 [53])	197	336
8		PWR-650 (Kori-2)	650					153017 [h)] (Won-95 [53])	208	320
9		PWR-950 (Kori 3&4, Yonggwang 1&2, Ulchin 1&2)	950					165906 [h)] (Won-95 [53])	225	237
10		PWR-1000 (Yonggwang 3&4, Ulchin 3&4)	1000					168113 [h)] (Won-95 [53])	228	228

[a)] Here as well as in other tables with data from [41], the costs were converted from DM (as given in [41]) into the specific national currencies.
[b)] It is not specified whether stage 3 is implemented immediately.
[c)] Here as well as in other tables with data from [6], the base date for the original cost assessment is, in accordance with [6], July 1, 1991.
[d)] With Konrad-type containers making use of some part of the activated steel.
[e)] Without recycling of some part of activated materials.
[f)] It is not specified whether stage 3 is implemented immediately.
[g)] A 10-year period of mothballing before dismantling is assumed; includes contingency estimation at 25%.
[h)] Does not include contingency estimation.

TABLE XVI (cont.)

No.	Country	Reactor	Gross (or net if noted) capacity, MW(e)	Assessment 1: Original cost estimate, national currency unit (n.c.u.) or $US, millions	Assessment 1: Cost in M$US of 01/01/97	Assessment 2: Original cost estimate, national currency unit (n.c.u.) or $US, millions	Assessment 2: Cost in M$US of 01/01/97	Assessment 3 (reference assessment): Original cost estimate, national currency unit (n.c.u.) or $US, millions	Assessment 3 (reference assessment): Cost in M$US of 01/01/97	Assessment 3 (reference assessment): Specific Cost, $US1997/kW(e) (gross)
11	Netherlands	PWR-450 (Borssele)	481					526 (G-95 [41])	321	667
12	Sweden	PWR-917 (Ringhals-2)	917	640 (SEK-84 [4])	184	805 (SEK-90 [5])	156	902 (SEK-94 [51])	144	157
13	United Kingdom	PWR-1155 (Sizewell-B)	1155					253 (GBP-90 [5])	517	448
14		PWR-1245~1400	1245 ~1400 (net)					330 (GBP-91 [6])	634	509-453
15	USA	PWR-1155 (Trojan)	1155					172 [i] ($US-94 [51])	184	159
16		PWR-1175	1175	88 ($US-84 [4])	133	104 ($US-86 [5])	145			

[i] For this project, which is a reference PWR project in the US, publication [51] is used as the data source instead of the original US report [60]. The main reason is that the analysis of [51] made an important adjustment by adding the cost of final unit demolition, while this cost component was not considered in [60].

TABLE XVII. Potential cost drivers for PWR reactors (immediate dismantling).

		Potential cost drivers					Duration breakdown, years				
No.	Reactor type/Country/NPP Unit	Total mass to be handled, t	Mass of contam. wastes, t	Volume of contam. wastes, m3	Labour req., person-years	Labour req., person-years per MW(e)	Duration of post-shutdown activities, years	Pre-shutdown	Shutdown operations	Decontam. & dismantling	Building demolition & site restoration
1	PWR-1225 (Germany) Biblis-A	169 670	3864	4863	1740	1.42	11	1	3	6	2
2	PWR-917 (Sweden) Ringhals-2	–	5245	7497	1240	1.35	7.5	3~4	1.5	3	3
3	PWR-1155 (United Kingdom) Sizewell-B	-	12500	–	–	–	–	–	–	–	–
4	PWR-1155 (USA) Trojan	–	4805	6992	868	0.75	10.1~10.6	2	6.9	1.7	1.5~2
5	PWR-1175 (USA)	–	8500 [a]	17830	301	0.26	–	–	–	–	–

[a] Including packaging.

5.2.1.2. BWR reactors

The review of decommissioning costs for BWR reactors is presented in Table XVIII; potential cost drivers are presented in Table XIX. Estimates are given for Finland, Germany, Japan, the Netherlands, Sweden, and the USA. Reactor units in the capacity range from 60 to 1300 MW(e) are considered.

The following general observations can be made on the basis of Tables XVIII– XIX:

- Qualitatively and quantitatively, the situation with BWRs is very similar to that of PWRs discussed in the previous section. Except for the very small unit of 60 MW(e), decommissioning costs for the considered BWR reactors are in the range between 170 and 650 $US/kW(e), i.e. the same variability as for PWR reactors exists. This variability can be partially explained by the differences in the typical cost drivers shown in Table XIX.

- The effect of scale, i.e. the dependence of the specific cost on unit capacity is a little more visible for BWRs than for PWRs. Nevertheless, as with PWRs, the effect appears smaller than inter-country differences or changes of the assessments with time.

- Like PWRs (and it should be for similar reasons), BWRs in Finland, Sweden and the USA have, on average, lower decommissioning costs (see [51]).

- The effect of increasing cost estimates for the same reactor noted for German PWRs is even more distinct for German BWRs. Unfortunately, the lack of data for other countries does not allow to make judgements as to whether the process is universal or it is a special German feature.

5.2.1.3. WWER reactors

Although, theoretically, WWERs belong to the PWR category, there are certain design differences (in particular, the high share of common systems and components for twin units) that make it justified to consider decommissioning costs for WWERs separately. Due to the importance of common systems for WWER decommissioning, some of the costs for WWER in this and other sections are presented for two units, and not by one unit as for other reactors.

The review of decommissioning costs for WWER reactors is presented in Table XX; typical cost drivers are presented in Table XXI. Estimates are given for Bulgaria, Finland, Germany, the Russian Federation, and Slovakia. Reactor units are almost all of the capacity of about 440 MW(e) (WWER-440 in the 440/230 and 440/213 modifications), with the exception of a small WWER-70 reactor in Germany.

The following observations can be made on the basis of Tables XX– XXI:

- On average, assessments for WWERs are of the same order of magnitude (in $US/kW(e)) as for PWRs and BWRs. However, two important exceptions should be noted: Germany and the Russian Federation.

- Decommissioning of German WWERs is assessed to be significantly more expensive, both in absolute costs and in $US/kW(e), than in other countries. This relates not only to the very small WWER-70 of Rheinsberg, but also for WWER-440s of Greifswald. The limited information available for this cost review does not allow to understand reasons for this large difference. To some extent, the reasons should be the same as for the other reactor models as noted above (in particular, higher labour rates in Germany). It is doubtful however that they account for the total difference shown.

TABLE XVIII. DECOMMISSIONING COSTS FOR BWR REACTORS (IMMEDIATE DISMANTLING)

No.	Country	Reactor	Gross (or net if noted) capacity, MW(e)	Assessment 1: Original cost estimate, national currency unit (n.c.u.) or $US, millions	Assessment 1: Cost in M$US of 01/01/97	Assessment 2: Original cost estimate, national currency unit (n.c.u.) or $US, millions	Assessment 2: Cost in M$US of 01/01/97	Assessment 3 (reference assessment): Original cost estimate, national currency unit (n.c.u.) or $US, millions	Assessment 3 (reference assessment): Cost in M$US of 01/01/97	Assessment 3 (reference assessment): Specific Cost, $US1997/kW(e) (gross)
1	Finland	BWR-1000	1000 (net)					749 (FIM-91 [6])	178	178
2	Germany	BWR-806 (Brunsbüttel)	806	587 (DM-93 [50])	430	672 (DM-94 [51])	473	740 (DM-94 [41])	521	646
3	Germany	BWR-806 (Brunsbüttel)	806	313 (DM-84 [4])	296					
4	Japan	BWR-1350	1350					36803 (YEN-91 [6])	349	259
5	Netherlands	BWR-60	60					342 (G-95 [41])	209	3483
6	Sweden	BWR-465	465					440 (SEK-84 [4])	127	273
7	Sweden	BWR-780 (Ringhals-1)	780					940 (SEK-90 [5])	183	235
8	Sweden	BWR-900	900 (net)					840 (SEK-84 [4])	242	269
9	Sweden	BWR-1050	1050 (net)					920 (SEK-84 [4])	265	252
10	Sweden	BWR-1205 (Oskarshamn-3)	1205					1258 (SEK-94 [51])	201	167
11	USA	BWR-849 (Shoreham)	849					186 ($US-94 [42])	200	236
12	USA	BWR-1129 (WNP-2)	1129			228 ($US-94 [41])	245	212 ($US-94 [51])	228	202
13	USA	BWR-1155	1155	100 ($US-84 [4])	151					

TABLE XIX. POTENTIAL COST DRIVERS FOR BWR REACTORS (IMMEDIATE DISMANTLING)

		Potential cost drivers					Duration breakdown, years				
No.	Reactor type/Country	Total mass to be handled, t	Mass of contam. wastes, t	Volume of contam. wastes, m3	Labour req., person-years	Labour req., person-years per MW(e)	Duration of post-shutdown activities, years	Pre-shutdown	Shutdown operations	Decontam. & dismantling	Building demolition & site restoration
1	BWR-806 (Germany) Brunsbüttel	215 000	5085	6230	2059	2.55	11	1	3	6	2
2	BWR-780 (Sweden) (Ringhals-1)	-	5540	10 000	1000	1.28	–	–	–	–	–
3	BWR-1205 (Sweden) Oskarshamn-3	336 200	9660	11 944	1440	1.20	7.5	3~4	1.5	3	3
4	BWR-849 (USA) Shoreham	–	–	2246	218 [a)]	0.26	–	–	–	–	–
5	BWR-1129 (USA) WNP-2	–	12 644	14 282	894	0.79	7.8~8.3	2	4.6	1.7	1.5~2

a)

TABLE XX. DECOMMISSIONING COSTS FOR WWER REACTORS (IMMEDIATE DISMANTLING)

				Assessment 1		Assessment 2		Assessment 3 (reference assessment)		
No.	Country	Reactor	Gross (or net if noted) capacity, MW(e)	Original cost estimate, national currency unit (n.c.u.) or $US, *millions*	Cost in M$US of 01/01/97	Original cost estimate, national currency unit (n.c.u.) or $US, *millions*	Cost in M$US of 01/01/97	Original cost estimate, national currency unit (n.c.u.) or $US, *millions*	Cost in M$US of 01/01/97	Specific cost, $US1997/kW(e) (gross)
1	Bulgaria	WWER-440/230 (Kozloduy 1, 2)	2×440	8035 (BGL-93 [42])	no data [a]	229 ($US-96 [9])	234	9650 (BGL-96 [43,44])	193	220
2	Finland	WWER-440/213 (Loviisa)	465	215 (FIM-84 [4])	78	441 (FIM-89 [5])	120	468 (FIM-91 [47])	113	243
3	Germany	WWER-70 (Reinsberg)	70					410 [b]- 425 [c] (DM-90 [49])	340–352	4857–5029
4	Germany	WWER-440/230 (Greifswald)	440					640 [b]-660 [c] (DM-90 [49])	531–547	1207–1243
5	Russian Federation	WWER-440/230	440					48 [d]-64 [e] ($US-94 [17])	52–69	118–157
6	Slovakia	WWER-440/230 (Bohunice 1–2)	2×430					12284 [f] (SK-96 [58, 74, 75])	353 [g]	410
7	Slovakia	WWER-440/213 (Bohunice 3–4)	2×430					10603 (SK-96 [58, 74, 75])	305 [g]	355

[a] No value in $US due to the absence of the conversion factor for 1993 in [42].
[b] With Konrad-type container making use of some part of activated steel.
[c] Without recycling of some part of activated materials.
[d] Minimum assessment, i.e. for the 2nd and other units on site.
[e] Maximum assessment, i.e. for the 1st unit on site.
[f] The decommissioning study for units 3, 4 of Bohunice is much more recent than that on Bohunice 1, 2 completed in 1992. Therefore, data on Bohunice 1, 2 are less reliable than data on units 3, 4. Currently, there is a new decommissioning study on Bohunice 1, 2 in progress that should update earlier estimations of decommissioning costs.
[g] This assessment (and the resulting per kW(e) value) is in $US of 1998; conversion to $US of 1997 was not done.

TABLE XXI. POTENTIAL COST DRIVERS FOR WWERs (IMMEDIATE DISMANTLING)

No.	Reactor type/Country	Gross capacity, MW(e)	Total mass to be handled, t	Mass of contam. wastes, t	Volume of contam. wastes, m3	Labour req., person-years	Labour req., person-years per MW(e)
1	WWER-440/230 (Bulgaria) Kozloduy 1, 2	2×440	-	9560	4190	-	-
2	WWER-440/213 (Finland) Loviisa	440	-	3837	6200	1460	3.14
3	WWER-440/230 (Russian Federation)	440	-	-	-	1501 [a)]	3.41
4	WWER-440/230 (Slovakia) Bohunice 1, 2	2 × 430	384 000	19716	-	1337	1.55
5	WWER-440/213 (Slovakia) Bohunice 3, 4	2 × 430	834 000	20879		1153	1.34

[a)] Taken from detailed cost tables in [66].

- Cost estimates for Russian WWERs are significantly lower than for the other countries. As with safety upgrades, rather low labour rates used in [17] may be one of the principal reasons, the more so that the labour requirements for decommissioning in the Russian Federation are assessed to be higher than, e.g. in Slovakia as shown in Table XXI.
- The noticeable difference in labour requirements between, on one hand, the Russian Federation and Finland and, on the other hand, Slovakia (Table XXI) may reflect important differences in the approach to decommissioning and the assumptions used for cost estimation. Identifying reasons for such differences may reveal useful information for the concerned countries. In general, the following three areas should be reviewed when searching for the reasons: 1) difference in the decommissioning activities that are taken into account; 2) methodology of labour requirements estimation for individual decommissioning processes (activities) that is different in each country; 3) definition of the labour requirement unit (person-years) that could be different. However, with the information available, it is not possible to make definite conclusions on this point at present. The issue is known to be complicated and a special study would be needed in order to arrive at meaningful results.
- The effect of increasing cost estimates noted above for German NPPs appears now, to some extent, for Finnish WWERs.

5.2.1.4. HWR reactors

There are much fewer data for HWRs than for PWRs and BWRs, mainly because there are fewer HWRs operating. Also, very little information on most representative cost drivers was found, so the table of cost drivers for the option of immediate dismantling is not included. The available decommissioning costs for units with HWR reactors are presented in Table XXII. Estimates are given for Canada, Republic of Korea and India covering the capacity range 200–1300 MW(e). In general, decommissioning costs for HWRs are of the same order as for the other reactor models considered above. The cost variation from case to case appears smaller than for PWRs and BWRs, but the reason is probably simply the limited number of the HWRs cases considered. Nevertheless, one can note that the assessments for Korean PWRs are noticeably higher than those for both Canada and India. A probable reason is that the Canadian assessments are relatively old, and the use of monetary conversions for a relatively long period can have a noticeable effect on the resulting estimate.

5.2.1.5. LWGR (RBMK) reactors

The review of decommissioning costs for LWGR (RBMK) reactors is presented in Table XXIII; the few typical cost drivers found are presented in Table XXIV. Of the three countries that currently operate LWGRs, estimates for the option of immediate dismantling were found for Lithuania (LWGR-1500) and the Russian Federation (LWGR-1000).

TABLE XXII. DECOMMISSIONING COSTS FOR HWR REACTORS (IMMEDIATE DISMANTLING).

No.	Country	Reactor	Gross (or net if noted) capacity, MW(e)	Assessment 1 (reference assessment)		
				Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Specific Cost, $US1997/kW(e) (gross)
1	Canada	HWR-542	542	66 ($CAN-84 [4])	68	125
2	Canada	HWR-935	935	231 ($CAN-91 [6])	183	196
3	Canada	HWR-1300	1300	180 ($CAN-84 [4])	185	142
4	Republic of Korea	HWR-679 (Wolsong-1)	679	154268 [a)] (Won-95 [53])	209	308
5	Republic of Korea	HWR-700 (Wolsong 2,3,4))	700	155174 [a)] (Won-95 [53])	211	301
6	India	HWR-194 (net)	194	24 ($US-91 [6])	28	144

[a)] Does not include contingency estimation.

The following observations can be made on the basis of LWGR cost data in Tables XXIII–XXIV:

- On average, assessments for LWGRs are lower (in $US/kW(e)) than assessments for other reactor types, especially in the case of the Russian Federation. This has for reason, at least in the case of the Russian Federation, the low labour rate used in the assessments. If it is also the case with Lithuania, one can suppose that if labour rates grow in these countries due to general economic reasons, estimations for decommissioning costs would also grow, maybe substantially.
- The cost estimates for Russian LWGRs in [17] do not include the handling of irradiated graphite. The assessment for Lithuania takes this factor into account[6]. This may become another reason for the Russian costs growing higher than presented in Table XXIII.
- The available information on the typical cost drivers for LWGRs is very limited. Only the amount of manpower needed for Russian LWGRs is available from [17, 18]. This amount is considerable (compare, e.g. with PWR, BWR and WWER data presented in the sections above), so the shown low level of decommissioning costs appears again somewhat doubtful.

5.2.2. Decommissioning with long term storage

In general, the qualitative character of the cost assessments for decommissioning assuming long term storage is the same as for immediate decommissioning, i.e. the costs substantially vary from country to country and from case to case. Accordingly, observations on the costs below will concentrate mainly on cost differences between the options of immediate dismantling and long term storage.

5.2.2.1. PWR reactors

The review of decommissioning costs for PWR reactors is presented in Table XXV; typical cost drivers for selected decommissioning projects are presented in Table XXVI. Estimates are given

[6] The cost of graphite dismantling is assessed in [54] as 6000 [m^3 of graphite] × 50000 [SEK/m^3] = 300 MSEK-95 (40 M$US-97) for two RBMKs at Ignalina or about 16% of the total decommissioning costs.

for the following countries: Belgium, Germany, Japan, the Republic of Korea, the Netherlands, and the USA. Reactor units in the capacity range of 500–1300 MW(e) are considered. The following general observations can be made on the basis of Tables XXV–XXVI:

- Decommissioning costs for the considered PWR reactors range between 200 and 700 $US/kW(e). For the considered capacity range, no distinct effect of the economy of scale is visible.
- In most cases, the total overnight costs of decommissioning with long term storage are higher than the costs of immediate decommissioning. However, as it is well known [4], the situation with the net present value would be normally on the contrary, the magnitude of the difference depending on the schedule of decommissioning and the assumed value of the discount rate. The following example taken from [4] illustrates the effect that the procedure of discounting has on the comparison of decommissioning options:

Decommissioning option	Decommissioning costs in the USA, million of $US of 01/01/84			
	Overnight costs		Discounted at 5%	
	PWR	BWR	PWR	BWR
Stage 3 immediately	97	113	86	100
Stage 1/30 year storage/stage 3	121	141	41	49
Stage 2/100 year storage/stage 3	158	186	56	68

TABLE XXIII. DECOMMISSIONING COSTS FOR LWGR (RBMK) REACTORS (IMMEDIATE DISMANTLING)

No.	Country	Reactor	Gross (or net if noted) capacity, MW(e)	Assessment 1 (reference assessment)		
				Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Specific Cost, $US1997/kW(e) (gross)
1	Lithuania	LWGR-1500 (Ignalina NPP)	1300	902–1009 [a] (SEK-95 [54])	121–136	93–100
2	Russian Federation	LWGR-1000 [b]	1000	49 [c]-78 [d] ($US-94 [17])	53–84	53–84

[a] The lower assessment is for unit 2 and the higher assessment is for unit 1.
[b] This estimate was obtained, within the framework of [17], by US experts using typical US assumptions concerning the DECON option.
[c] Minimum assessment, i.e. for the 2nd and other units on site.
[d] Maximum assessment, i.e. for the 1st unit on site.

TABLE XXIV. POTENTIAL COST DRIVERS FOR LWGR REACTORS (IMMEDIATE DISMANTLING)

No.	Reactor type/Country	Total mass to be handled, t	Mass of contam. wastes, t	Volume of contam. wastes, m^3	Labour req., person-years	Labour req., person-years per MW(e)
1	LWGR-1000 (Russian Federation)	-	-	-	1 893 [a]	1.89
2	LWGR-1500 (Ignalina NPP)	-	-	-	1 800	1.38

[a] Taken from detailed cost tables in [66].

TABLE XXV. DECOMMISSIONING COSTS FOR PWR REACTORS (LONG TERM STORAGE)

				Assessment 1		Assessment 2		Assessment 3 (reference assessment)		
No.	Country	Reactor	Gross (or net if noted) capacity, MW(e)	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97.	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Specific cost, $US1997/kW(e) (gross)
1	Belgium	PWR-900	900					13607 (BEF-94 [41])	464	516
2	Germany	PWR-1204 (Biblis-A)	1204	291 [a] (DM-84 [4])	275	325 [b] (DM-85 [5])	301			
3		PWR-1225 (Biblis-A)	1225			437 [c]-445 [d] (DM-90 [49])	362–369	490 [e] (DM-93 [50])	359	293
4	Japan	PWR-1160	1160					30200 [f] (YEN-84 [5])	326	281
5	Republic of Korea	PWR-587 (Kori-1)	587					210–293 [g] ($US-95 [53])	307	375–523
6	Netherlands	PWR-450 (Borssele)	481					560 (G-95 [41])	342	711
7	USA	PWR-1175	1175			109 [h]- 143 [i] ($US-84 [4])	164–216	238 [j] ($US-93 [60,61])	262	223

[a] Assumed decommissioning schedule: stage1/30-year storage/stage3.
[b] Assumed decommissioning schedule: 30 years/stage3.
[c] With Konrad-type containers making use of some part of activated steel.
[d] Without recycling of some part of activated materials.
[e] Assumed decommissioning schedule: stage1/stage2/stage3.
[f] Assumed decommissioning schedule: stage1/(5~10 years)/stage3.
[g] The lower number is for the safe storage period of 10 years, while the higher estimate is for 51.4 years of safe storage; includes contingency at 25%.
[h] Assumed decommissioning schedule: stage1/30-year storage/stage3.
[i] Assumed decommissioning schedule: stage2/100-year storage/stage3.
[j] This assessment does not include the costs of final unit demolition.

TABLE XXVI. POTENTIAL COST DRIVERS FOR PWR REACTORS (LONG TERM STORAGE)

No.	Reactor type/Country	Total mass to be handled, t	Mass of contam. wastes, t	Volume of contam. wastes, m3	Labour req., person-years	Labour req., person-years per MW(e)
1	PWR-1225 (Germany) Biblis-A	169 670	3810	3824	1810	1.48
2	PWR-1160 (Japan)	-	11 800	-	-	-

This shows one of the reasons why in many cases long term storage is considered preferable by utilities notwithstanding the higher overnight costs. As with immediate decommissioning, the decommissioning of PWR-450 in Netherlands is noticeably more expensive than the other cases, the high cost of post-shutdown operations [41] being one of the probable reasons.

5.2.2.2. BWR reactors

The review of decommissioning costs for BWR reactors is presented in Table XXVII; typical cost drivers for selected decommissioning projects are presented in Table XXVIII. Estimates are given for the following countries: Finland, Germany, Italy, Japan, the Netherlands, and the USA. Reactor units in the capacity range of 60–1300 MW(e) are considered. The following general observations can be made on the basis of Tables XXVII–XXVIII:

- With the exception of a small BWR-60 in the Netherlands, decommissioning costs for the considered BWR reactors range between 150 and 600 $US/kW(e). The mentioned small BWR-60 has the cost of about 4000 $US/kW(e) illustrating that at such small capacity the scaling effect exists.

- The relation between the cost of immediate decommissioning and decommissioning with long term storage is the same as for PWR reactors: undiscounted costs of decommissioning with long term storage are higher than the costs of immediate decommissioning, but the situation for discounted costs is likely to be on the reverse.

- Decommissioning costs in Germany are noticeably higher than in Finland and the USA. One of the reasons for differences is the difference in the estimation of labour requirements, see Table XXVIII.

TABLE XXVII. DECOMMISSIONING COSTS FOR BWR REACTORS (LONG TERM STORAGE)

				Assessment 1		Assessment 2		Assessment 3 (reference assessment)		
No.	Country	Reactor	Gross (or net if noted) capacity, MW(e)	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Specific Cost, $US1997/kW(e) (gross)
1	Finland	BWR-735 (Olkiluoto)	735	383 [a] (FIM-84 [4])	140	397 [b] (FIM-90 [5])	101	420[b] (FIM-90 [48])	107	146
2	Germany	BWR-806 (Brunsbüttel)	806	330 [b] (DM-84 [4])	311	535 [c] (DM-93 [50])	392	690 (DM-94 [41])	486	603
3	Italy	BWR-160	160					65000 [d] (L-89 [5])	65	406
4	Japan	BWR-1100	1100					31400 [e] (YEN-84 [5])	339	308
5	Netherlands	BWR-60	60					392 (G-95 [41])	239	3983
6	USA	BWR-1155	1155			125 [b]-165 [f] $US-84 [4]	188–249			
7	USA	BWR-1129 (WNP-2)	1129					303 [g] $US-93 [59,61]	334	297

[a] Assumed decommissioning schedule: stage1/31-year storage/stage3.
[b] Assumed decommissioning schedule: stage1/30-year storage/stage3.
[c] Assumed decommissioning schedule: stage1/stage2/stage3.
[d] Assumed decommissioning schedule: stage1.
[e] Assumed decommissioning schedule: stage1/(5~10 years)/stage3.
[f] Assumed decommissioning schedule: stage2/100-year storage/stage3.
[g] This assessment does not include the costs of final unit demolition.

TABLE XXVIII. POTENTIAL COST DRIVERS FOR BWR REACTORS (LONG TERM STORAGE)

No.	Reactor type/Country	Total mass to be handled, t	Mass of contam. wastes, t	Volume of contam. wastes, m3	Labour req., person-years	Labour req., person-years per MW(e)
1	BWR-735 (Finland) Olkiluoto	-	5600	14 650	780	1.06
2	BWR-806 (Germany) Brunsbuttel	215 000	4940	5330	1967	2.44
3	BWR-160 (Italy)	-	-	-	306	1.91
4	BWR-1100 (Japan)	-	11 300	-	-	-

5.2.2.3. WWER reactors

The review of decommissioning costs for WWER reactors is presented in Table XXIX; typical cost drivers are presented in Table XXX. Estimates are available for Bulgaria, the Czech Republic, Germany, the Russian Federation and Slovakia. Reactor units are of the capacity of about 440 MW(e) (WWER-440 in the 440/230 and 440/213 modifications).

The following observations can be made on the basis of Tables XXIX–XXX:

- The collected costs for WWERs differ very much for the cases considered: from 120–130 $US/kW(e) for the minimum estimate in the Russian Federation through 350–430 $US/kW(e) in Slovakia up to about 1400 $US/kW(e) in Germany. While some simple reasons can be suggested (as usually, the high labour cost in Germany, the assumed low labour rate in the Russian Federation for the assessment in [17]), it is doubtful that they account for the whole difference, the more so that there are significant differences in the available cost drivers, too, see Table XXX.
- As for PWRs and BWRs, decommissioning with long term storage is more expensive than decommissioning with immediate dismantling. However, the difference between the two is relatively small for Slovakia, the reasons being [73] 1) the relatively long duration of the long term storage (70 years); 2) limited extent of the long term storage (in the case of V2-NPP the reactors with their shafts only are stored); and 3) the fact that some significant cost items (e.g. the demolition cost) are practically identical for the both mentioned decommissioning options.

5.2.2.4. HWR reactors

The three available assessments of decommissioning costs for Canadian units with HWR reactors are presented in Table XXXI; some potential cost drivers are given in Table XXXII.

The following remarks can be made on the costs for HWRs:

- There is a very large difference between two assessments for units of almost equal capacity (lines 1–2 in Table XXXI). This may reflect the change of decommissioning estimations with time, because the second (and higher) assessment is made several years later than the first one.
- For some Canadian HWRs, decommissioning with long term storage is cheaper than decommissioning with immediate dismantling even in undiscounted costs. (As was already noted in [4, 5].) It is not clear what the reasons are.

TABLE XXIX. DECOMMISSIONING COSTS FOR WWER REACTORS (LONG TERM STORAGE)

				Assessment 1		Assessment 2		Assessment 3 (reference assessment)		
No.	Country	Reactor	Gross (or net if noted) capacity, MW(e)	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Specific Cost, $US1997/kW(e) (gross)
1	Bulgaria	WWER-440/230 (Kozloduy 1,2)	2 × 440					13984 (BGL-96 [44])	257	292
2	Czech Republic	WWER-440/213 (Dukovany)	4 × 440					12520 a) (CK-97 [45])	461	262
3	Germany	WWER-440/230 (Greifswald)	440					720 b)-750 c) (DM-90 [49])	597–622	1357–1414
4	Russian Federation	WWER-440/230	440	162 ($US-94 [55])	174	108 d)-124 e)) ($US-94 [17])	116–133	197 f) g) ($US-94? [56])	212	482
5	Slovakia	WWER-440/230 (Bohunice 1–2)	2 × 430					12729 h) (SK-96 [58, 74, 75])	366 i)	426
6		WWER-440/213 (Bohunice 3–4)	2 × 430					10290 (SK-96 [58, 74, 75])	296 i)	344

a) In accordance with [1], the assumed conversion rate from CK to $US of 1997 is 27.15.
b) With Konrad-type containers making use of some part of activated steel.
c) Without recycling of some part of activated materials.
d) Minimum assessment, i.e. for the 2nd and other units on site.
e) Maximum assessment, i.e. for the 1st unit on site.
f) The total cost contains technical (175 M$US) and socio-economic (22 M$US) costs.
g)

TABLE XXX. POTENTIAL COST DRIVERS FOR WWER REACTORS (LONG TERM STORAGE)

No.	Reactor type/Country	Gross capacity, MW(e)	Total mass to be handled, t	Mass of contam. wastes, t	Volume of contam. wastes, m3	Labour req., person-years	Labour req., person-years per MW(e)
1	WWER-440/230 (Russian Federation)	440	-	13 500 a)	15 10 b)	4 571 c)	10.4
2	WWER-440/230 (Slovakia) Bohunice 1–2	2×430	382 000	9807	-	1457	1.69
3	WWER-440/213 (Slovakia) Bohunice 3–4	2×430	830 000	10 398	-	1198	1.39

a) Taken from [56]; includes concrete (9000 tonnes),metal (500), and equipment (4000).
b) Taken from [56]; includes bituminised solidified wastes (390 m^3), cemented solidified wastes (520) and solid wastes (600).
c) Taken from detailed cost tables in [66].

TABLE XXXI. DECOMMISSIONING COSTS FOR HWR REACTORS (LONG TERM STORAGE)

				Assessment 1		Assessment 2 (reference assessment)		
No.	Country	Reactor	Gross (or net if noted) capacity, MW(e)	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Specific Cost, $US1997/kW(e) (gross)
1	Canada	HWR-542	542			53 a) ($CAN-84 [4])	55	101
2	Canada	HWR-600	600			264 b) ($CAN-89 [5])	228	380
3	Canada	HWR-1300	1300			146 a) ($CAN-84 [4])	149	115

a) Assumed decommissioning schedule: stage1/30-year storage/stage3.
b) Assumed decommissioning schedule: stage1/32-year storage/stage3.

TABLE XXXII. POTENTIAL COST DRIVERS FOR HWR REACTORS (LONG TERM STORAGE)

No.	Reactor type/Country	Total mass to be handled, t	Mass of contam. wastes, t	Volume of contam. wastes, m3	Labour req., person-years	Labour req., person-years per MW(e)
1	HWR-600 (Canada)	-	8 342 a)	17 500	1 115	1.92

a) Including packaging.

5.2.2.5. LWGR (RBMK) reactors

The review of decommissioning costs for LWGR (RBMK) reactors for the option of long term storage is presented in Table XXXIII; the few typical cost drivers found are presented in Table XXXIV. Of the three countries that currently operate LWGRs, estimates for this option were found for Ukraine and the Russian Federation.

One should note that due to certain design features (large amount of graphite in the core, uncertainty related to the technologies of handling irradiated graphite after reactor dismantling, etc.), decommissioning with long term storage appears to be more feasible for LWGRs than decommissioning with immediate dismantling.

The following observations can be made on the basis of LWGR cost data in Tables XXXIII–XXXIV:

- Contrary to the conclusion made in the section for LWGR immediate dismantling (Section 5.2.1.5), most assessments for long term storage of LWGRs are higher (in $US/kW(e)) than assessments for other reactor types and are, with the exception of two estimates for the Russian Federation, in the range of 520–600 $US/kW(e). For decommissioning costs, this is a rather good correspondence.

- The cost estimate for Russian LWGRs in [17] substantially differs from the other estimates. As with other data from [17], this may be a result of the assumed low labour rates. As the same methodology of cost conversion as in [17] was also used in [57, 67] (the assessment given in the second line of Table XXXIII), it can explain the rather low level of that estimate, too.

5.2.2.6. GCR and AGR reactors

Gas cooled reactors are found almost exclusively in the United Kingdom, so the assessments are presented for this country and for one old GCR reactor in Spain shutdown in 1990, see Tables XXXV–XXXVI. The capacity range covered is from 60 to 660 MW(e).

Due to certain design features of these reactors, decommissioning with long term storage is clearly preferable over immediate decommissioning, because the opportunity of doing dismantling operations manually following the period of natural decay of radioactive substances gives in the case of GCRs and AGRs much larger advantages than in the case of PWRs and BWRs. Accordingly, only assessments for the long term storage option are presented in this review.

In general, decommissioning costs for gas cooled reactors are noticeably higher than for the other reactor models: 1000–3000 $US/kW(e) for the units of typical sizes (200–600 MW(e)). This can be only partially explained by the smaller size of GCR and AGR units. The design of the reactors with such consequences as larger volumes of radioactive wastes and elevated manpower requirements (see Table XXXVI) should be one of the principal reasons.

TABLE XXXIII. DECOMMISSIONING COSTS FOR LWGR (RBMK) REACTORS (LONG TERM STORAGE)

				Assessment 1		Assessment 2		Assessment 3 (reference assessment)		
No.	Country	Reactor	Gross (or net if noted) capacity, MW(e)	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Specific Cost, $US1997/kW(e) (gross)
1	Russian Federation	LWGR-1000	1000	404 ($US-94 [55])	433	169 [a] -198 [b] ($US-94 [17])	181–213	564 [c) d) e)] ($US-94? [56])	606	606
2	Russian Federation	LWGR-1000 (Leningrad-1)	1000					175 [f) g)] ($US-97 [57])	175	175
3	Ukraine	LWGR-1000 (Chernobyl 1–3)	3 × 1000					1396 [h] ($US-94 [19])	1497	499

a) Minimum assessment, i.e. for the 2nd and other units on site.
b) Maximum assessment, i.e. for the 1st unit on site.
c) The total cost contains technical (542 M$US) and socio-economic (22 M$US) costs.
d) The assessment in [56] is based on [55]. However, several modifications have been made, in particular the addition of 1) the costs of handling the spent fuel during the phase of preparation for decommissioning and 2) the cost of developing the container for dry fuel storage at NPP site.
e) The used publication [56] does not contain the currency base year; 1994 was assumed for the conversion to 1997.
f) This recent assessment does not include the costs of radioactive waste management, i.e. of the processing of the wastes arising from the decommissioning process.
g) This assessment for unit 1 of the Leningrad NPP is presented separately from the other Russian assessments due to the fact that study [67] on which the cost estimation in [57] was based has a more distinct site-specific character than the other Russian studies used.
h) Only for 10 years of decommissioning activities, no dismantling is envisaged.

TABLE XXXIV. POTENTIAL COST DRIVERS FOR LWGR (RBMK) REACTORS (LONG TERM STORAGE)

No.	Reactor type/country	Total mass to be handled, t	Mass of contam. wastes, t	Volume of contam. wastes, m3	Labour req., person-years	Labour req., person-years per MW(e)
1	LWGR-1000 (Russian Federation)	-	53 500 a)	6450 b)	10 410 c)	10.4

a) Taken from [56]; includes concrete (9000 tonnes),metal (500), and equipment (4000).

b) Taken from [56]; includes bituminised solidified wastes (390 m^3), cemented solidified wastes (520) and solid wastes (600).

c) Taken from detailed cost tables in [66].

TABLE XXXV. DECOMMISSIONING COSTS FOR GCR AND AGR REACTORS (LONG TERM STORAGE)

				Assessment 1 (reference assessment)		
No.	Country	Reactor	Gross (or net if noted) capacity, MW(e)	Original cost estimate, national currency unit (n.c.u.) or $US, millions	Cost in M$US of 01/01/97	Specific cost, $US1997/kW(e) (gross)
1	Spain	GCR-500 (Vandellos-1)	500	45000 a) (PES-90 [5])	511	1022
2	United Kingdom	GCR-60	60	105 b) (GBP-89 [5])	229	3817
3		GCR-219	219	317 c) (GBP-90 [5])	694	3169
4		AGR-660	660	301 c) (GBP-90 [5])	658	997

a) Assumed decommissioning schedule: stage1/ stage2/25 years/stage3.

b) Assumed decommissioning schedule: stage1/ stage2/60~90 years/stage3.

c) Assumed decommissioning schedule: stage1/ stage2/90 years/stage3.

TABLE XXXVI. POTENTIAL COST DRIVERS FOR GCR AND AGR REACTORS (LONG TERM STORAGE)

No.	Reactor type/country	Total mass to be handled, t	Mass of contam. wastes, t	Volume of contam. wastes, m3	Labour req., person-years	Labour req., person-years per MW(e)
1	GCR-500 (Spain)	-	14 250	17 000	-	-
2	GCR-60 (United Kingdom)	-	10 172	15 643	641	10.7
3	GCR-219 (United Kingdom)	-	18 893	26 000	2866	13.1

It must be however noted that, notwithstanding the high per kW(e) value of the overnight costs, the decommissioning of GCRs is not necessarily much more expensive in real money terms than for other reactor types. For comparing investment requirements, net present values should be used rather than overnight costs. The discounted costs are not considered in this review, but one should be aware of the difference that their consideration may make for cost comparisons.

5.3. ADDITIONAL INFORMATION AND NOTES ON COUNTRY-SPECIFIC FEATURES

Similar to the presentation of complementary information on the costs of safety upgrades, Annex IV gives more information on the costs of decommissioning in selected countries. This information was obtained both in contacts with relevant countries and in the course of an IAEA consultants meeting of October 29–30, 1998.

Annex IV covers the following countries:

- Bulgaria — IV.1;
- Lithuania — IV.2;
- Russian Federation — IV.3;
- Slovakia — IV.4;
- USA — IV.5;
- Republic of Korea — IV.6.

6. CONCLUSIONS

This section summarises the results obtained during the cost review and discusses possible applications of such cost data. Specifically, the following topics are covered below:

- general observations on the costs collected (Section 6.1);
- applicability of these costs for decision making purposes (Section 6.2).

6.1. OBSERVATIONS ON THE COSTS COLLECTED

The general observation on all the presented costs is that they noticeably vary. With some simplification, one can note four types of variability: the costs vary by country, by reactor type, by unit vintage/age, and, in addition, there are historical changes, i.e. cost assessments change with time. In some cases (safety upgrades) these changes may reflect the process of implementation, in other cases (e.g. decommissioning) cost assessments can change due to the accumulation of knowledge including practical experience from on-going projects.

This variability makes it very difficult, if not impossible, to use generic cost numbers for this or that type of economic analysis involving the costs under consideration. Instead, such analysis should take into account the specific features of the situation, i.e. of the country and reactor type considered. In addition, the cost data should be checked in order to obtain the latest assessment available.

In view of these factors, the cost data presented above should be treated as information suitable for general understanding of the magnitude of the costs and, if necessary, for a first rough estimation of economic effects related to the various continuation options for older nuclear power plants. In certain cases, the difference in similar costs for different countries may reflect, on one hand, underestimation of the required expenditures or, on the other hand, opportunities for cost reduction. In this sense, the presented cost numbers may become an incentive and initial basis for more detailed cost analyses.

These applications of the results of this report are important; however, due caution should be exercised in the generalisation of the presented costs. In particular, possibilities of using generic cost estimates for several countries or of applying cost data for one country to another one are rather limited.

For a more or less complete analysis of the economics of continued operation of older NPPs, more data are needed as well as the application of the technique of power system analysis in addition to the cost numbers reviewed above (see Section 6.2 for more discussion of the subject).

6.1.1. Costs of safety upgrades

The following observations can be made on the costs of safety upgrades reviewed in Section 3.

6.1.1.1. Cost ranges for typical power reactor models

The costs of safety upgrades to be implemented at operating power reactors were found to be of the following order for the typical reactor models:

- WWER-440/230: 30–70 $US-97/kW(e) (assessment of the total remaining costs);
- WWER-440/213: more than 30 $US-97/kW(e) (data insufficient for more definite conclusions);
- WWER-1000: 30–200 $US-97/kW(e) (assessment for the total remaining costs);
- PWR and BWR (US assessments): less than 30 $US-97/kW(e)/year (the given number represents an average annual cost of recent years of upgrades — including safety and non-safety items; on this basis, the costs of safety upgrades for the following years of operation should be anticipated to be lower);
- PWR and BWR (German assessments): less than 30 $US-97/kW(e)/year (the average for last years; as for the US, the actual expenses for safety upgrades for the coming years should be essentially lower because 1) this assessment includes also non-safety modifications; 2) the expenses should decline after the completion of current safety upgrade programmes; 3) the on-going uprating of German NPPs should result in the lowing of per kW(e) cost indicators);
- PWR (experience in the Netherlands): about 500 $US-97/kW(e) (total cost of the completed one-time safety upgrading);
- PWR (Korean assessments): 20–90 $US-97/kW(e) (costs of safety upgrades implemented in Korea from 1978 through 1998 excluding O&M costs and the cost of utility's manpower);
- LWGR (RBMK): 40–100 $US-97/kW(e) (total remaining costs).

As is clearly visible from these numbers, the costs are highly variable for at least three important reasons:

(1) The costs are different for different reactor models;

(2) Even for the same model, the costs differ from country to country due to a number of important factors such as technical differences in the basic design, different age/vintage of the plant, the implementation status of safety programmes, differences in the regulatory environment, etc.;

(3) The cost assessments obtained above contain some uncertainty related to the methodological difficulties for obtaining comparable costs.

The last point should be emphasised in order to warn the reader from improper use of the cost numbers given. It was found during the preparation of this report that it is rather difficult to ensure that the costs are really comparable. Very often, the costs contain more than just safety-related upgrades; in some cases, the total costs of the upgrades are available, i.e. both the implemented and the planned upgrades, while other assessments provide either the former or the latter; some countries have published only annual costs without the estimation of the total investment requirements. In addition to these factors, the cost estimation may be strongly influenced by the macro-economic assumptions made: the exchange rate used for the conversion of the costs into the $US, the assumed labour rates, etc. In specific situations, e.g. for countries in the period of economic transition, the effect of the assumed exchange and labour rates may well outweigh all other factors of relevance.

Therefore, as already noted above, one should be extremely careful in using the cost information given. In addition to this report, consulting the background publications referenced here is highly desirable before making any definite conclusions involving the cost estimates of safety upgrades.

6.1.1.2. Absence of quantitative measurement of safety improvements

As another observation of importance, it should be noted that only in rare cases the investments in safety upgrades are assessed in terms of their efficiency, i.e. it is rarely attempted to determine quantitative gains that this or that investment provides.

One of such rare examples in the upgrade of the Borssele plant in the Netherlands. It was estimated for this project that the investment of about 600 $US-97/kW(e) allowed to decrease the core damage probability from 5.6×10^{-5} to 4.5×10^{-6} 1/year. However, such comparisons are made not often due to two main reasons:

– safety requirements are obligatory, so the related investments are also obligatory and their quantitative effect on safety is considered to be of no practical value;

– the quantification of the effect on safety is an extremely difficult task.

While these reasons are to some extent valid, obtaining a quantitative measure for safety upgrades still seems to be an important task. Although safety requirements are obligatory, there is often more than one possible way for meeting these requirements. In selecting the best alternative, quantitative indicators are very helpful. Although there are serious practical difficulties in obtaining an indicator of safety efficiency (sophisticated probabilistic safety assessments are needed), the investments involved are large and an effort in making such estimations may turn out cost-effective. Some efforts in this direction have already been made, see, e.g. [68].

6.1.2. Costs of lifetime extension

For the costs of NPP lifetime extension, the following observations can be made on the basis of Section 4.

6.1.2.1. Relevance of the issue

The issue of lifetime extension is topical in many countries operating nuclear reactors that were commissioned in 70s–80s. For example, Canada, Japan, the Republic of Korea, the United Kingdom, USA explicitly consider the possibility of lifetime extension for their reactors. In the United Kingdom, the licensed operating period for old Magnox reactors has already been extended from the original 30 to 50 years.

One should note that decisions on extended operation of NPPs will depend not only on economic considerations, but on other factors as well such as social/political acceptance of nuclear power, readiness/flexibility of the regulatory environment, availability of other energy resources, development of environmental factors and regulations, etc. However, only the economic side of the problem is considered in this report.

6.1.2.2. Available cost estimates

There are only few cost estimates available for the cost of lifetime extension. The main reasons are, first, the difficulty in the definition of this cost category and distinguishing it from the regular lifetime management costs; and, second, some reluctance of concerned utilities to open such information, because with the opening of the electricity market, the information on the costs of NPP lifetime extension becomes commercially sensitive.

Two estimates for the costs of lifetime extension were found for this review. They are summarised in the two tables below.

Assessment 1: Generic cost estimates for US NPPs (PWRs and BWRs)	
Case	Estimate in $US-97/kW(e)
Optimistic	210
Baseline	420
Pessimistic	840

Assessment 2: Specific cost estimate for Korean PWR-587 Unit 1 of the Kori NPP		
Extension period, years	Extension option[7]	Specific overnight cost, $US-97/kW(e)
10	1	228
	2	361
20	1	433
	2	567
30	1	639
	2	772

[7] Option 1 includes only refurbishment and component replacement, while Option 2 includes, in addition to these, also the estimated costs of safety backfitting and lisensing.

The range of these costs is obviously too large in order to permit for general conclusions on the economic viability of lifetime extension. From the economic viewpoint, the decision to apply for a license for extended operation for a given reactor would depend primarily on two factors: 1) the cost of lifetime extension for this specific reactor based on an in-depth technical feasibility study; and 2) the comparison of the cost of extended NPP operation with the cost of obtaining power from other alternatives. The both factors are highly country- and site-specific, so for definite conclusions it is necessary to consider each situation specifically.

6.1.3. Costs of decommissioning

6.1.3.1. Observations on the costs of decommissioning

The costs of decommissioning are found to be of the following order for the typical reactor models:

- WWER-440: 100–400 $US-97/kW(e) for the option of immediate dismantling and 100–500 $US-97/kW(e) for the option with long term storage (up to 1200–1400 $US-97/kW(e) for the Greifswald NPP in Germany);

- WWER-1000: no cost data found;

- PWR: 150–700 $US-97/kW(e) for the option of immediate dismantling and 200–700 $US-97/kW(e) for the option with long term storage;

- BWR: 170–650 $US-97/kW(e) for the option of immediate dismantling and 150–600 $US-97/kW(e) for the option with long term storage;

- LWGR (RBMK): 80–100 $US-97/kW(e) for the option of immediate dismantling and 200–600 $US-97/kW(e) for the option with long term storage;

- HWR: 100–300 $US-97/kW(e) for the option of immediate dismantling and 100–400 $US-97/kW(e) for the option with long term storage;

- GCR: 1000–3000 $US-97/kW(e) for the option with long term storage (the option of immediate dismantling is not considered).

The shown wide range of the costs confirms the conclusion made in numerous earlier studies that variability is a usual feature of decommissioning costs due to the profound effect of such country- and site-specific factors as the model and design of the plant, selected decommissioning option and its initial and final conditions, amount of radioactive wastes from decommissioning, regulatory environment in the country, etc. Therefore, while being useful for general information, the shown decommissioning costs should not be used for making direct comparisons among countries and reactor types.

It is also important to understand that this report considered only the overnight costs and not the net present values (the application of the calculations including discount rates was considered to be out of scope for this review). As the net present value reflects real financial requirements much more accurately than the overnight cost, it is not possible to deduce direct conclusions from the shown cost ranges, e.g. from the higher per kW(e) values of decommissioning costs for gas cooled reactors.

In some cases, it was observed by comparing decommissioning cost assessments made for the same reactor in different years that the later assessments give a noticeably higher value of decommissioning costs. The factors that cause such development (improved knowledge, changes in the regulatory environment) should be duly analysed and taken into account by relevant utilities and organisations in order not to underestimate the investment requirements for decommissioning.

It was found in the preparation of this review that decommissioning data for "Western" reactor models (PWRs, BWRs) have been studied relatively well in the sense that several in-depth international studies are available that analyse in detail and explain reasons for differences in decommissioning costs from country to country. On the other hand, the situation with "Eastern" models (WWERs, LWGRs) appeared different: while there have been many valuable national cost studies, international comparisons of these studies are rare and reasons for cost differences for the same reactor units are not clearly understood. Moreover, for one reactor model that is widely used in Eastern Europe (WWER-1000) information on decommissioning costs was not found. In this respect, a study aimed at detailed comparison of cost estimates for decommissioning of WWERs and RBMKs could provide important insights for the understanding of the costs and opportunities for their reduction.

6.1.3.2. Possible effect of premature closure on decommissioning costs

Practically all the decommissioning studies considered assess the costs of planned decommissioning, i.e. decommissioning is supposed to occur after a shutdown in accordance with the schedule planned well in advance. However, there may be also cases when decommissioning is required urgently, e.g. due to the decision to discontinue the operation of this or that reactor for safety, political or social reasons. Such cases may involve financial losses due to the fact that the decommissioning fund may have not yet been accumulated by the time of reactor shutdown. In addition, there may be additional costs due to the incompleteness of the preparation of decommissioning, the need to urgently find the replacement capacities for electricity and, sometimes, heat generation and, in certain cases, the need to solve social problems such as the liquidation of the near-plant town and the creation of employment opportunities for the workers laid off as a result of early shutdown.

Such costs are not often addressed. However, they may be noticeable, in particular when the NPP is located in a relatively remote area. For example, a Russian study [55] assesses that the social costs for decommissioning of WWER and LWGR (RBMK) units may be of the order of 10–20% of the total overnight costs of decommissioning.

6.2. APPLICABILITY OF THE REVIEWED COSTS FOR DECISION-MAKING

As noted above, the obtained cost data can be used both for general understanding of the costs and as a basis for more detailed analyses of the considered cost categories. Another important application area for the results is their use in the framework of cost–benefit analyses of continued operation of nuclear units and of their eventual lifetime extension as part of economic inputs for the decision making process. For such purposes, the considered costs are necessary but not sufficient in themselves as discussed below.

6.2.1. Costs of safety upgrades, lifetime extension and decommissioning in the total costs

When assessing the importance of the reviewed costs for decision making in the nuclear power sector, one should note, first of all, that the reviewed costs represent only a part of the total costs required for full operation of an NPP. To obtain the total costs, one should consider costs associated with safety and non-safety upgrades, typical O&M costs of running a plant, fuel costs, administration and various overheads.

Cost experience of different countries shows that the costs of safety upgrades are a noticeable part of the total O&M costs. For example, in the USA the post-operational capital additions (i.e. the costs of safety upgrades plus the costs of equipment replacement) considered in this review represent about 20–25% of the total annual non-fuel operating expenditures [20]. In Germany, the corresponding share is about 1/3 on average [10].

Thus, while being an important expenditure item, the considered costs are not the predominant part. Therefore, to be used for decision making purposes, the costs of safety upgrades, lifetime extension and decommissioning should be considered (with all the necessary cautions noted above) first of all as part of the estimations of the total generation costs of nuclear power plants.

6.2.2. Use of the reviewed costs in assessments of the economic viability of nuclear power

Another aspect of the use of the costs of safety upgrades, lifetime extension and decommissioning for decision making appears due to the fact that economic indicators of nuclear power are not absolute in the meaning, but relative, i.e. the costs of nuclear generation are not important in themselves, but primarily in comparison with other options of serving the demand for electricity. In practice, it means that in order to decide on economic viability of continued nuclear generation or on the economic advantages of NPP lifetime extension, one should compare the costs (or rather the net present value) of this or that nuclear option with the costs of replacement power. As replacement power alternatives, generation on conventional or innovative power sources, power purchases from neighbouring power pools, contracts with independent power producers or demand-side management measures could be considered.

To accurately compare such alternatives, analysis of the whole power system is needed, which usually requires application of corresponding sophisticated computer models such as, e.g. IAEA's WASP [69]. With this analysis, the competitiveness of nuclear power with alternative power sources (in view of the possibility of NPP lifetime extension) could be examined both in the short- and long term perspectives. The technique of such analyses may differ from case to case depending on the level of the study (country level, utility level) and its objectives (development of a least-cost power expansion plan for a country, development of a business plan for a utility, estimation of the perspectives of, e.g. lifetime extension for a given plant, etc.). As examples of such studies, one can cite here the application of optimisation approach at a country level for Lithuania [14] with detailed consideration of the impact of premature closure of the Ignalina NPP, the use of simulation technique for supporting integrated resource planning at a utility level [70] with a multi-criteria consideration of various options, or a mixed optimisation-simulation analysis for determining investment requirements of the Russian power sector [17,18,71]. In any case, such system analysis represents a necessary and important element in the process of using the costs of safety upgrades, lifetime extension and decommissioning for decision making in the power sector, in particular in respect of continued operation and lifetime extension of NPPs of older generations.

ANNEXES I–IV

Annex I

VARIABILITY OF GDP DEFLATORS

As noted in Section 2, cost conversion factors such as GDP deflators, producer or consumer price indices often contain some uncertainty that results from differences in the underlying methodology. Table I.1 below presents GDP deflators for the same countries as in Table I (OECD assessment), but taken from [2] (IMF assessment). Table I.2. summarises the differences between the two sets of GDP deflators.

As one can see, although sometimes the two sources give identical numbers (e.g. for France), in some cases there are significant differences, for instance for the United States and Sweden. Certain differences exist also for Belgium, Canada and Germany.

Apparently, the reason for the differences is a different methodology used. As Table I.2 illustrates, the effect of this factor can be considerable. One can expect similar uncertainties in related cost escalation indicators such as producer or consumer price indices.

The existence of such uncertainties should be kept in mind when using international cost comparisons. It was one of the reasons why this report relies on the most available GDP data instead of using more detailed price escalation indicators such as producer and consumer price indices that are theoretically more suitable for the task but are also more uncertain and less available.

TABLE I.1. . GDP DEFLATORS ACCORDING TO IMF ASSESSMENTS [2, 3]

COUNTRY	GDP Deflators [2], *percent change over previous year; calculated from indices*													Exchange Rates [3], *national currency units per $US of 1996*
	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
BELGIUM	5.1	6.0	3.8	2.3	1.8	4.5	3.3	2.4	3.5	4.1	2.7	...	...	31
CANADA	3.1	2.6	2.4	4.6	4.7	4.8	3.1	2.9	1.2	1.1	0.7	1.5	1.3	1.36
FRANCE	7.5	5.8	5.2	3.0	2.8	3.0	3.1	3.3	2.1	2.5	1.5	1.6	1.2	5.12
GERMANY	2.1	2.1	3.2	1.9	1.5	2.4	3.3	3.7	5.5	3.8	2.3	2.2	1.0	1.5
SWEDEN	7.6	6.7	6.9	5.1	6.0	8.0	8.8	8.2	1.0	2.6	3.1	4.3	...	6.71
UNITED STATES OF AMERICA	4.6	3.8	2.8	2.9	3.5	5.0	4.8	4.0	2.7	2.7	2.2	2.5	2.0	1.0

TABLE I.2. COMPARISON OF OECD [1] AND IMF [2] GDP DEFLATORS

COUNTRY	Difference between the two statistics sources *(IMF value in % — OECD value in %)*												
	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
BELGIUM	-0.1	-0.1	0.2	0.1	-0.3	-0.1	0.2	-0.8	-0.1	-0.1	0.4	...	...
CANADA	0	0	0	-0.1	0.1	0	0	0	0	0.1	0	0	0
FRANCE	0	0	0	0	0	0	0	0	0	0	0	0	0
GERMANY	0	0	0	0	0	0	0.1	-0.2	-0.1	-0.2	-0.1	0.1	0
SWEDEN	0	0.1	0	0.3	-0.5	0	-0.1	0.6	-0.1	0	0.7	0.6	...
UNITED STATES OF AMERICA	0.8	0.4	0.2	-0.2	-0.2	0.8	0.5	0	-0.1	0.1	-0.2	0	-0.3

Annex II

EXCHANGE RATES USED IN OTHER PUBLICATIONS

In some cases, publications used in this review assumed certain values for exchange rates that are different from those in Table I. The tables below summarise such cases giving an opportunity for the reader to check the calculations made.

TABLE II.1. ADDITIONAL EXCHANGE RATES ACCORDING TO OECD [1]

Exchange rates, *national currency units per $US of the given year*							
COUNTRY	***1994***	***1995***	***1996***	**COUNTRY**	***1994***	***1995***	***1996***
BELGIUM	33.46	-	31	JAPAN	-	-	108.8
CANADA	-	-	1.36	NETHERLANDS	-	1.6	1.686
FINLAND	-	-	4.6	SPAIN	-	-	126.7
FRANCE	-	-	5.12	SWEDEN	7.7	-	6.71
GERMANY	1.62	1.43	1.5	UNITED KINGDOM	-	-	0.641
ITALY	-	-	1543	UNITED STATES OF AMERICA	-	-	1

TABLE II.2. EXCHANGE RATES USED IN [17]

Exchange rates, *national currency units per $US of January 1, 1994*	
GERMANY	1.73
SWEDEN	8.3

TABLE II.3. EXCHANGE RATES USED IN [4]

Exchange rates, *national currency units per $US of January 1, 1994*	
CANADA	1.244
FINLAND	5.81
GERMANY	2.72
SWEDEN	8

TABLE II.4. EXCHANGE RATES USED IN [6]

Exchange rates, *national currency units per $US of July 1, 1991*			
BELGIUM	37.28	GERMANY	1.81
CANADA	1.14	JAPAN	137.84
FINLAND	4.28	UNITED KINGDOM	0.62
FRANCE	6.13		

Annex III

ADDITIONAL INFORMATION ON THE COSTS OF SAFETY UPGRADES

III.1. ARMENIA: SAFETY UPGRADE TASKS FOR UNIT 2 OF THE ARMENIAN NPP*

III.1.1. General situation in the Armenian power sector

The energy sector of Armenia is one of the most developed branches of the economy. The main sources of energy are oil products, natural gas, nuclear energy, hydropower and coal. In the period of 1985–1988 the consumption of these energy resources varied between 12–13 million tons per year of oil equivalent. Imported energy sources accounted for 96% of the consumption. During the crisis period of 1993–1995 the consumption dropped to 3 million tons per year.

In 1988 the total installed capacity of the generating stations in Armenia was 3558 MW(e). The annual electricity production was 15.28 billion kW(h). Consumption within the Republic was 12.36 billion kW(h) with 2.92 billion kW(h) exported.

Electricity production by years is shown in Table III.1.1.

TABLE III.1.1. ELECTRICITY GENERATION IN ARMENIA

Type of Power plant	Electricity Generation by Years, billion kW(h)/%				
	1988	1995	1996	1997	1998 (for 8 months only)
Nuclear Power Plant	4.82/32	0.30/5	2.32/37	1.60/27	1.12/37
Hydraulic Power Stations	1.52/10	1.93/35	1.57/25	1.40/23	0.70/23
Thermal Power Stations	8.94/58	3.34/60	2.33/38	3.03/50	1.22/40
TOTAL	**15.28/100**	**5.57/100**	**6.22/100**	**6.03/100**	**3.04/100**

Electricity in Armenia is produced by three thermal, one nuclear, and two major hydroelectric plants together with a number of small hydraulic units.

Hydro power stations (HPS) — installed capacity of 987 MW:

- Sevan-Hrazdan cascade 527 MW,
- Vorotan cascade 400 MW,
- Small HPS 60 MW.

Thermal power stations (TPS) — installed capacity of 1756 MW:

- Hrazdan TPS 1110 MW,
- Vanadzor TPS 96 MW,
- Yerevan TPS 550 MW.

* This material was prepared by A. Gevorgyan, Department of Atomic Energy, Ministry of Energy of Armenia.

Nuclear power plant (NPP) — installed capacity of 815 MW:

– Armenian NPP (ANPP) 815 MW.

The integrated network with the voltage of 330–220–110 kV has an annular structure with high transmission capacity and is able to provide both intra-system transportation and energy transit. Armenian energy system has 6 intersystem connections with all neighbouring countries.

The distribution network 35–10–6 kV is highly developed, has a radial structure and provides power supply to industry, agriculture, and practically to all commercial and residential sectors.

The gas supply system consists of the main and annular distribution networks. There is also underground gas storage capability with the volume of 1.7 million cubic meters. At the maximal pressure of 12.5 MPa, the effective volume of the stored gas is 180 million cubic meters. With a new compressor station in operation, the effective volume can reach 340 million cubic meters.

The gas supply system can be supplied from three directions: Georgia-Alaverdi, Azerbaijan-Ijevan, and Azerbaijan-Karabakh-Goris. At present only the first feeder is in operation.

Another source of energy is mazut (residual oil), the transportation of which is difficult because of interference with railway communications in the Caucasus. The power generation system has an oil storage capacity of 358000 tons.

The fuel-energy sector of the Republic has become obsolete in spite of the fact that the Ministry of Energy tried its best to support the basic funds. Within 6–7 years all power equipment, especially at thermal power stations, will have to be totally updated.

III.1.2. Safety level upgrading in nuclear energy

The technical and financial help of the Russian Federation made is possible, after 6.5 years' outage, within the 2.5 years' period to prepare and restart the Unit 2 of ANPP in November 5, 1995, with the safety level prescribed by the "Starting Concept" and exceeding the designed one.

The total cost of the restoration, commissioning and safety upgrading complex measures for Unit 2 of Armenian NPP has been estimated at about 157 million $US 53.5 million $US have been spent on the Unit 2 commissioning work.

To ensure safe operation of Unit 2 of ANPP instead of the "Programme of Safety, Reliability and Operational Culture Upgrading of Unit 2 of the Armenian NPP for the Period of 1997–2000" the "list of for safety upgrading activity of unit 2 of the Armenian NPP for the period 1998–2004" was developed. The total cost of the list operations is approximately estimated at 63 million $US. It has been presented to different international organizations and donor countries for the attraction of financial means.

The list includes the following:

(1) conduction of relevant scientific research and design activity;

(2) purchase, installation and arranging of special technological equipment;

(3) improvement of the control and management systems of the power Unit;

(4) modernisation of the station electrical systems;

(5) enhancement of the level of operation;

(6) construction of a full-scale simulator for the operating staff training;

(7) improvement of the complex of utilisation and storage of the nuclear wastes;

(8) modernisation of the fire prevention system.

For the implementation of the list agreements with the Governments of the Russian Federation, the USA, France and the European Union have been reached.

In accordance with the list during 1996–1997 the measures on the sum of 2 million $US were fulfilled. The realisation of the sum of 42.5 million $US is under way.

Since its restart until now the ANPP has produced electrical energy of approximately 5.7 billion kW(h). It has allowed the country to overcome the energy crisis and to provide for its socio-economical development. The ecological background of Armenia has much improved. The process of taking water from the Sevan Lake for energy needs has been terminated.

During this period 23 incidents were registered at the ANPP, 17 of which were evaluated as level "O" according to the INES (International Nuclear Event Scale), and 6 — as level "1". More specifically, the annual record of incidents is as follows:

- In 1995 — 6 incidents of level "O";
- In 1996 — 7 incidents of level "O" and 1 incident of level "1" ;
- In 1997 — 3 incidents of level "O" and 2 incidents of level "1";
- In 1998 — 1 incident of level "O" and 3 incidents of level "1".

Since 1994 the construction of a new cooling system for important systems of the primary circuit of ANPP Unit 2, which is financed from the State Budget, has been under way. Its projected cost is estimated at 12 million $US. Between 1994 and 1997 5.5 million $US of this sum were spent by the Government on the project. The further sum of 1.4 million $US is allocated for this purpose from the State Budget in 1998. However the allocated funds are inadequate, therefore loans from the Russian Federation and an assistance fund of the US Government have to be used.

In 1997 the Government of the Russian Federation allocated a credit worth million of new Russian Rubles to be used for the purchase of the nuclear fuel, and the fulfilment of the safety upgrade measures for Unit 2 of ANPP. From this sum 92 million of new Russian Rubles will be used to fulfil the list, and, in particular, 10 million of new Russian Rubles will be spent on purchasing new equipment and materials for the new cooling system.

In view of the inflation of the Russian Ruble these sums will not be sufficient for the planned measures to be fulfilled.

The US Government allocated 12 million $US in total for technical and financial help in 1996–1998 for the fire protection systems, equipment for the new cooling system, computerization of the safety system, procurement of fast-acting main steam isolation valves. It will also allocate the aid fund to be spent in 1999 on the realisation of other measures from the list.

The French Government allocated a credit of 24.5 million FF and technical assistance of 15.5 million FF for the construction of the first stage of the spent fuel dry storage system. The work on the construction started in July 1996. Up to the present the construction-mounting of the spent fuel storage has been completed, the necessary equipment has been delivered from France, and it is expected that by the end of 1998 the license for the storage operation will be obtained. It will be necessary to construct the second stage to store the spent fuel during the whole unit's lifetime.

The European Union in 1996 has started the implementation of a programme for the modernisation of the technological equipment, the construction of a multifunctional simulator, technical assistance for upgrading the standards of operation and operational culture, etc., with the budget of 10 million ECU. In particular, it is proposed that:

- the safety valves of the steam generators and the pressurizer be substituted;
- the modem electromechanical and electrical equipment from the Greifswald NPP be imported;
- the control and operating system of Unit 2 be modernised;
- the ANPP seismic resistance research activity be continued.

Unfortunately the implementation of these programmes is delayed.

Negotiations with the German Government are under way, through the framework for technical assistance, on the supply of thermal, electromechanical and electrical equipment from the Greifswald NPP. The negotiations started in May 1996, but have not yet been fruitful.

Along with the above, it is necessary to conduct research activity and to undertake complex technical measurements to ensure the safe standstill of Unit 1 of the Armenian NPP.

As to the program for the decommissioning of ANPP, up to the present it has not yet been developed. A certain part of the assistance fund allocated by USA for 1999 will be spent on the development of the method of decommissioning approach. We also would like to ask the IAEA to involve Armenian specialists more actively into the process of consideration of such problems and to provide us with relevant information.

III.2. BULGARIA: ALTERNATIVES FOR OPERATION OF EXISTING NUCLEAR REACTORS*

III.2.1. Background

Over the last few years the problem with the alternatives for safety upgrades, lifetime extension and decommissioning of the existing nuclear units in Bulgaria has become of intense interest. The main reasons for that fact are the following:

- The first two units have been in operation for more than 20 years;
- These units do not have a containment;
- There is an agreement between the former Bulgarian Government and the European Bank for Reconstruction and Development (EBRD) signed in 1993 for earlier shutdown of the first four nuclear units. For the compensation of this action EBRD has allocated 30 million US dollars;
- There are some protests from the Governments of several countries of the European Union based on the opinion that the Bulgarian nuclear units are the most dangerous in Europe.

That is why in 1996 three independent expertises were made by Siemens (Germany), Westinghouse (USA) and Gidropress (Russian Federation) for inspections of the metal from the inner side of the reactor of the oldest unit 1, which has been in operation since 1974. The results from all three expertise showed that the remaining lifetime of the old Bulgarian reactors was not less than 10 years.

* This material was prepared by D. Kanev, Bulgarian National Electric Company (NEK).

On the basis of these results the current Bulgarian Government makes large efforts to change the opinion of EBRD and West European institutions concerning the need for earlier shutdown of old nuclear units 1–4 at the Kozloduy NPP. Another argument of the Government is that during the last few years about 200 million US dollars were spent for safety upgrades of these units and now the units satisfy most of the international safety standards.

In this paper a brief comparison is made between the two alternatives for the operation of the old Bulgarian nuclear units — 1) earlier shutdown and 2) operating till the end of their design lifetime.

III.2.2. Current status of the Bulgarian power sector

Electricity generation and consumption in Bulgaria for the last six years in GW(h) was as follows:

Year	1992	1993	1994	1995	1996	1997
Produced by NEK*	30887	33141	33605	37443	38125	38136
out of which-**NPP**	**11552**	**13896**	**15334**	**17261**	**18062**	**17751**
-TPP	17271	17303	16762	17675	17060	17457
-HPP	2063	1941	1509	2507	2984	2928
Other producers	4683	4764	4571	4560	4676	4684
Import	3271	1634	1173	1961	1803	785
Total resources	38841	39539	39349	43964	44604	43605
Export	566	1518	1245	2121	2252	4335
Gross domestic demand	38275	38021	38104	41843	42352	39270
Auxiliaries	4082	4254	4173	4293	4281	4396
T&D losses	5206	4992	5070	6083	6090	6339
Electricity for distribution	28987	28775	28861	31467	31981	28535

* NEK-National Electricity Company of Bulgaria.

The share of electricity generated by nuclear units is about 40% of the total electricity generated in the country.

As already mentioned, during the last few years over 200 million US dollars were spent for safety upgrades of the old nuclear units in Kozloduy and now their level of safety is close to that of the existing PWR units in Europe and USA. The strategy for the development of the Bulgarian power sector is based on the following guidelines:

- stimulation of more effective electricity consumption;
- extension of the life period of the existing power plants due to reasonable modernisation and rehabilitation;

- optimum utilisation of the cheap domestic coal and nuclear energy as a base load, which will ensure the energy independence of the country and give a possibility for an active export policy;
- adequate development of the peak and near-peak power generating units for a stable and sure power supply based on the international standards;
- reaching a higher safety level in the nuclear power sector corresponding to the international standards;
- attention to environmental issues in power generation and a decrease in the thermal plant emissions to a level and standards adequate to the international obligations of the country.

III.2.3. Developed scenarios

Two scenarios for the development of the Bulgarian power sector were prepared under the following assumptions:

- **Scenario 1:** Shutdown of units 1&2 in Kozloduy at the end of the year 2001, i.e. before the end of their planned lifetime;
- **Scenario 2:** Shutdown of units 1&2 in Kozloduy at the end of the year 2005, i.e. after the end of their planned lifetime.

The latest gross demand forecast developed by NEK experts is structured as two scenarios — maximum and minimum. The quantities in GWh are as follows:

Year	2000	2005	2010	2015
Maximum scenario	42 660	51 980	57 000	59 030
Minimum scenario	47 620	56 500	61 700	64 630

The both expansion plans considered below as Scenario 1 and Scenario 2 are made for the minimum demand forecast.

III.2.4. Summary of main results

The additions and retirements plans for the developed scenarios are shown in Tables III.2.1 and III.2.2. The production system cost and the average electricity price are shown in Table III.2.3. The costs for safety upgrades of the old nuclear units are shown in Tables III.2.4 and III.2.5.

It can be seen from Table III.2.3 that for the whole study period scenario 2, in which shutdown of units 1&2 in 2005 is assumed, has a lower total production cost by 704 million US dollars in comparison with Scenario 1, in which units 1&2 in Kozloduy are assumed to shutdown at the end of 2001. Also, the average electricity price in Scenario 2 is lower by 5–6% in comparison with Scenario 1 for every year of the study period.

TABLE III.2.1. ADDITIONS AND RETIREMENTS PLAN TO YEAR 2015 — SCENARIO 1

	ADDITIONS		RETIREMENTS	
Years	Plant	Capacity, MW	Plant	Capacity, MW
1999	Pumped Storage Chaira	2 × 210		
2001			Maritsa 3	80
2001			NPP Kozloduy — unit 1&2	2 × 440
2002	Combined Cycle	1 × 450	Maritsa East 1	180
2003	Substituted Capacity in M. East	1 × 300		
2005	Substituted Capacity in M. East	1 × 300		
2006	New Nuclear Unit	1 × 600		
2008	Substituted Capacity in M. East	1 × 300		
2010	New Nuclear Unit	1 × 600	NPP Kozloduy — unit 3	1 × 440
1999–2010		**2970**		**1580**
2011	HPP Gorna Arda	1 ×156		
2012	New Nuclear Unit	1 × 600	NPP Kozloduy — unit 4	1 × 440
2012	HPP Sredna Vacha	1 × 120		
2014	New TPP — Imported Coal	1 × 300	Bobov Dol	1 × 215
2015			Bobov Dol	1 × 215
2015			Maritsa East 2	1 × 160
2011-2015		**1176**		**1030**
Total		**4146**		**2610**

TABLE III.2.2. ADDITIONS AND RETIREMENTS PLAN TO YEAR 2015 — SCENARIO 2

	ADDITIONS		RETIREMENTS	
Years	Plant	Capacity, MW	Plant	Capacity, MW
1999	Pumped Storage Chaira	2 × 210		
2001			Maritsa 3	80
2002			Maritsa East 1	180
2003	Substituted Capacity in M. East	1 × 300		
2004	Substituted Capacity in M. East	1 × 300		
2005	Substituted Capacity in M. East	1 × 300		
2006	New Nuclear Unit	1 × 600	NPP Kozloduy — unit 1&2	2 × 440
2008	HPP Gorna Arda	1 × 156		
2009	HPP Sredna Vacha	1 × 120		
2010	New Nuclear Unit	1 × 600	NPP Kozloduy — unit 3	1 × 440
1999–2010		**2796**		**1580**
2012	New Nuclear Unit	1 × 600	NPP Kozloduy — unit 4	1 × 440
2013	Combined Cycle	1 × 450		
2014	New TPP — Imported Coal	1 ′ 300	Bobov Dol	1 × 215
2015			Bobov Dol	1 × 215
2015			Maritsa East 2	1 × 160
2011–2015		**1350**		**1030**
Total		**4146**		**2610**

TABLE III.2.3. PRODUCTION COST IN ELECTRICITY SYSTEM AND AVERAGE ELECTRICITY PRICE

Year	Scenario 1		Scenario 2	
	Prod.Cost,Mln.US dollars	Elec.Price,USc/kW(h)	Prod.Cost,Mln.US dollars	Elec.Price,USc/kW(h)
1998	612.05	3.9	599.07	3.86
1999	671.79	3.98	662.08	3.95
2000	722.88	4.02	713.4	3.98
2001	827.23	3.99	810.43	3.96
2002	898.05	4.24	881.91	4.01
2003	918.18	4.38	862.98	4.18
2004	984.9	4.47	887.62	4.21
2005	1001.33	4.4	919.34	4.17
2006	1039.02	4.58	994.01	4.44
2007	1142.04	4.79	1059.35	4.53
2008	1117.67	4.91	1074.81	4.66
2009	1183.15	5.11	1128.37	4.84
2010	1270.47	5.51	1194.17	5.18
2011	1254.17	5.37	1214.71	5.13
2012	1284.04	5.1	1254.84	4.89
2013	1358.26	4.89	1347.28	4.79
2014	1415.27	5.02	1403.96	4.91
2015	1516.07	5.18	1504.43	5.05
Total	19216.57	-	18512.76	-

TABLE III.2.4. COSTS OF SAFETY UPGRADES AND REHABILITATION FOR EXISTING UNITS AT NPP KOZLODUY, MILLIONS US DOLLARS — SCENARIO 1

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
Unit 1 and 2	1.0	1.0	1.0	1.0															**4.0**
Unit 3 and 4	1.0	25.0	25.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5					**61.5**
Unit 5 and 6	85.0	85.0	85.0	85.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	**382.0**
Simulator	0.5																		**0.5**
Total	**87.5**	**111.0**	**111.0**	**87.0**	**4.0**	**4.0**	**4.0**	**4.0**	**4.0**	**4.0**	**4.0**	**4.0**	**4.0**	**3.5**	**3.0**	**3.0**	**3.0**	**3.0**	**448.0**

TABLE III.2.5. COSTS OF SAFETY UPGRADES AND REHABILITATION FOR EXISTING UNITS AT NPP KOZLODUY, MILLIONS US DOLLARS — SCENARIO 2.

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
Unit 1 and 2	1.0	25.0	25.0	1.0	1.0	1.0	1.0	1.0											**56.0**
Unit 3 and 4	1.0	25.0	25.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5					**61.5**
Unit 5 and 6	85.0	85.0	85.0	85.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	**382.0**
Simulator	0.5																		**0.5**
Total	**87.5**	**135.0**	**135.0**	**87.0**	**5.0**	**5.0**	**5.0**	**5.0**	**4.0**	**4.0**	**4.0**	**4.0**	**4.0**	**3.5**	**3.0**	**3.0**	**3.0**	**3.0**	**500.0**

III.3. REPUBLIC OF KOREA: DISBURSEMENT SCHEDULE FOR SAFETY UPGRADES IMPLEMENTED*

To complement the information on the costs of safety upgrades for Korean NPPs (Section 3.3.4.4), the table below presents the annual upgrade costs for the 7 Korean units considered in this report. The costs are given for the period from 1979 (i.e. from the start of the first Korean nuclear unit) through 1998. Forecast for the future is not available at the moment.

TABLE III.3.1. COSTS OF SAFETY UPGRADES FOR KOREAN REACTORS IN THE PERIOD 1979–1998 [13]

No.	Unit name and type	Gross capacity, MW(e)	Start of commercial operation, year	Total costs of the upgrades, million Korean Won of 1997	Total costs of the upgrades, M$US of 1997	Specific costs of the upgrades, $US-97 per kW(e)	1979	1980	1981	1982	1983
1	Kori 1, PWR	587	1978	49346.6	51.9	**88**	0.1	0.0	4.6	1.4	0.0
2	Kori 2, PWR	650	1983	22448.5	24	**37**					0.0
3	Kori 3, PWR	950	1985	20873.7	22	**23**					
4	Kori 4, PWR	950	1986	20841.5	21.9	**23**					
5	Yonggwang 1, PWR	950	1986	18496.9	19.4	**20**					
6	Yonggwang 2, PWR	950	1987	18496.9	19.4	**20**					
7	Wolsong 1, CANDU	679	1983	45126.8	47.5	**70**					0.1

No.	Unit name and type	Annual costs of safety upgrades, M$US-97														
		1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
1	Kori 1, PWR	1.1	0.0	0.1	0.0	0.3	0.0	0.1	0.8	3.5	7.1	3.7	1.2	3.5	2.5	21.9
2	Kori 2, PWR	0.0	0.0	0.6	0.8	0.0	0.0	0.1	0.2	3.5	7.6	2.5	0.1	2.8	2.0	3.4
3	Kori 3, PWR		0.0	0.0	0.0	0.0	0.0	0.0	3.2	2.6	3.5	2.0	0.8	0.5	1.5	7.8
4	Kori 4, PWR			0.0	0.0	0.0	0.0	0.0	3.2	2.6	3.5	2.0	0.8	0.5	1.5	7.8
5	Yonggwang 1, PWR				0.0	0.0	0.0	0.2	5.3	3.5	4.1	3.1	0.9	0.0	1.8	0.5
6	Yonggwang 2, PWR					0.0	0.0	0.2	5.3	3.5	4.1	3.1	0.9	0.0	1.8	0.5
7	Wolsong 1, CANDU	0.4	0.1	0.3	0.4	2.3	1.3	0.1	0.2	15.7	4.7	7.4	12.8	0.5	0.0	1.2

* This material was prepared by I.-S. Jeong, Korea Electric Power Research Institute.

III.4. LITHUANIA: COST ESTIMATES FOR SAFETY UPGRADES AT THE IGNALINA NUCLEAR POWER PLANT*

III.4.1. Introduction

The Ignalina NPP consists of two RBMK-1500 reactors. This is the most advanced version of the RBMK reactor design series. Compared to the Chernobyl NPP, the Ignalina NPP is more powerful and is provided with an improved accident confinement system. (However, for safety reasons the capacity of the Ignalina NPP is derated to 2600 MW(e), i.e. 1300 MW(e) for each reactor). In most other respects, the plant is quite similar to its predecessors. It has two cooling loops, a direct cycle, fuel clusters are loaded into individual channels, and the neutron spectrum is thermalised by massive blocks of graphite.

Although Lithuania declared its independence in March of 1990 the Ignalina NPP remained factually in the jurisdiction of the Former Soviet Union (FSU) until August 1991. Supervision was carried out by the State Atomic Supervision of the FSU. After the formal collapse of the FSU Ignalina NPP finally came under the authority of the Lithuanian Republic. At that time Lithuania had not much of an infrastructure necessary for operation of nuclear power plants and all know-how connected with the design was concentrated in Russia. The Ignalina NPP was a pure operational organisation not having the full responsibility for the safe operation of the plant. Seeking to ensure further operation of the Ignalina NPP it was necessary to:

- create a state regulatory body;
- create the necessary legal framework;
- sign international treaties and conventions;
- prepare an in-dept safety assessment of the Ignalina NPP;
- prepare a detailed least-cost power sector development programme;
- create the Ignalina Safety Analysis group;
- organise the management of radioactive waste.

The Ignalina NPP is now controlled administratively by the Lithuanian Ministry of Economy. The Lithuanian State Atomic Energy Safety Inspectorate (VATESI) exercises regulatory control. Lithuania signed all the most important international treaties and conventions related to nuclear energy. Other important components (mentioned above) in the total structure of Lithuanian nuclear energy are created also.

III.4.2. Existing power plants and role of the Ignalina NPP

Before Lithuania re-established its independence, its power system was an integrated part of the North-Western United System of the FSU. The largest power plants, the Lithuanian Thermal Power Plant (TPP), the Ignalina NPP and the Kruonis Hydro Pumped Storage Plant, were designed to satisfy regional rather than just domestic needs for electricity. The total installed capacity of the Lithuanian power plants is 6526 MW. The characteristics of the Lithuanian power plants as of July 1998 are given in Table III.4.1.

Until 1991, significant amounts of the electricity generated in Lithuania were exported to Belarus, Latvia and the Kaliningrad region (the Russian Federation). As a consequence of deep economic crisis, the electricity demand within the country decreased sharply in 1992. Economic

* This material was prepared by V. Miskinis, Lithuanian Energy Institute.

recession in neighbouring countries and problems with payments reduced the demand for electricity export. The electricity export to Belarus was even stopped when debts for electricity supply remained unpaid. The Kaliningrad region was supplied from Russia through the Lithuanian power grid. These changes of electricity production and consumption within the country are shown in Fig. III.4.1.

TABLE III.4.1. CHARACTERISTICS OF THE LITHUANIAN POWER PLANTS

Power plant	*Fuel*	*Capacity, MW*	
		installed	*available*
Lithuanian Thermal Power Plant	Heavy fuel oil, natural gas	1800	1800
Vilnius Combined Heat and Power	Heavy fuel oil, natural gas	384	364
Kaunas Combined Heat and Power	Heavy fuel oil, natural gas	178	178
Mazeikiai Combined Heat and Power	Heavy fuel oil	194	99
Klaipeda Combined Heat and Power	Heavy fuel oil, natural gas	11	11
Hydro power plants		108	108
Kruonis Hydro Pumped Storage Plant		800	760
Ignalina Nuclear Power Plant	Nuclear energy	3000	2600
Other power plants	Heavy fuel oil, natural gas	51	51
Total		6526	5971

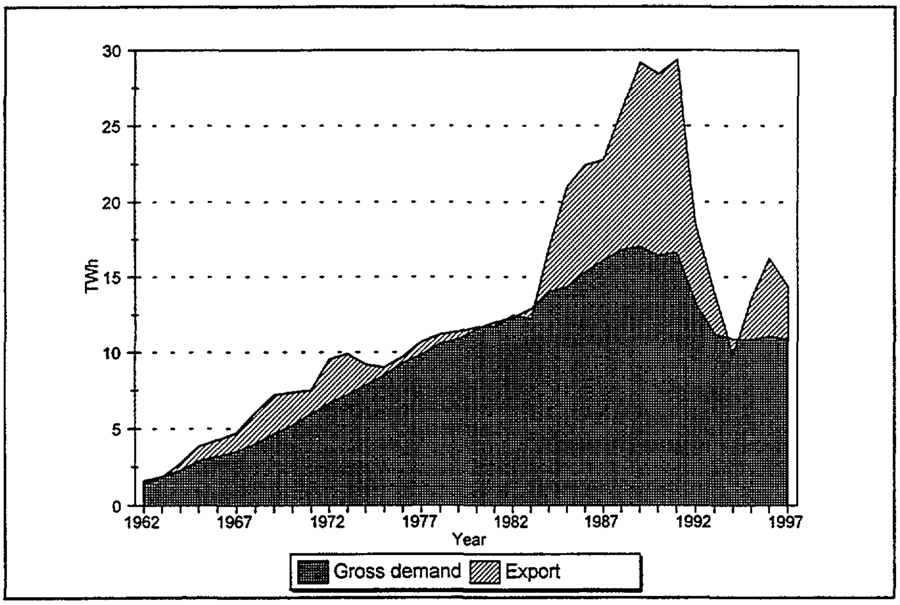

FIG. III.4.1. Changes of electricity production and consumption.

The Ignalina NPP plays especially important role in the Lithuanian power sector. Although its share in the balance of available capacities is only 43.5%, share of electricity produced by this power plant has been increasing since the beginning of its operation and lately it produces more than 85% (Fig. III.4.2). At the same time the share of electricity generated at the Lithuanian TPP decreased from 55.2% in 1994 to 4.1% in 1995.

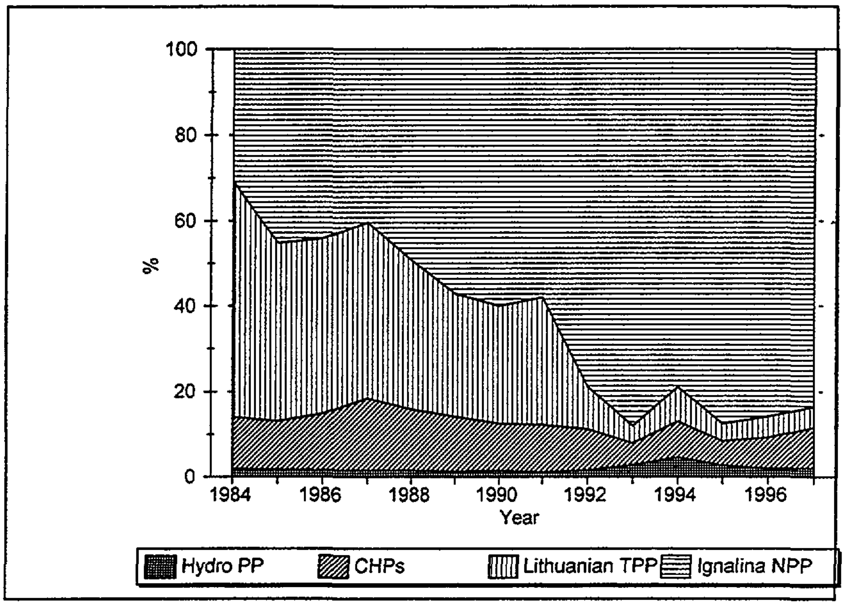

FIG. III.4.2. Structure of electricity production.

III.4.3. Role of the Ignalina NPP for the power sector development

It is expected that in 1999 unit 1 of the Ignalina NPP will receive a license for continued operation, which will be in line with the international standards and experience. Until this work is finished and research work of fuel channels and graphite is carried out (to be completed in 1999), it is impossible to make the final decision about the real dates of the Ignalina NPP closure. It was stipulated in the Nuclear Safety Account Grant Agreement that fuel channels will not be replaced after the end of their lifetime. However, this pre-condition was made on the ground of limited information about the Ignalina NPP safety available in 1993.

In the last years after thorough safety analyses, and a large number of important safety improvement measures being introduced, this situation has changed radically, and further investments into safety improvements satisfy the criterion of least cost power sector development [III.4.1]. The available preliminary information about the state of fuel channels enables to make predictions that in unit 1 they can serve till 2005 and in the unit 2 — up to 2010. Possible inaccuracy might reach one or two years, which has no essential influence on the development of the power sector.

Therefore in the National Energy Strategy [III.4.2] two scenarios have been chosen for the evaluation of the Ignalina NPP. Those two scenarios are considerably different seeking to compare economic social and other consequences related to an early or late closure of the Ignalina NPP: 1) unit 1 of the Ignalina NPP will be shut down in 2005, unit 2 — 2010, i.e. at the end of allowable lifetime of the fuel channels. At those dates a half of the designed technical lifetime of the Ignalina NPP will have elapsed; 2) fuel channels will be replaced by new fuel channels according to the design criteria for this type of RBMK reactors. In this case the Ignalina NPP will be kept in operation during the whole period analysed in the National Energy Strategy.

Because the Ignalina NPP produces electricity considerably cheaper in comparison with other available power plants in Lithuania or probable new power plants, in the case of early closure Lithuania will suffer huge losses. The preliminary studies have indicated that these losses would amount to US $ 1.3–2.2 billion in energy sector [III.4.3, III.4.4] and to US $ 3.3–3.9 billion in the whole economy [III.4.5] for the 2005–2025 year period. These losses were defined as the net value for lost production plus capital losses in the Ignalina NPP area without evaluation of the profit that would be received from the export of all surplus energy. Longer operation would help to accumulate the means necessary for the Ignalina NPP closure, nuclear waste management, and spent nuclear fuel final disposal. These costs may reach US $ 2.5 billion [III.4.6]. In the case of re-channelling undesirable social problems related to finding of new work places for the discharged workers will not appear. Premature closure also will require early capital investments into the whole energy sector development. It will be a heavy burden for the country's economy that just begins to recover.

If the Ignalina NPP is closed and electricity is mainly generated by thermal power plants, the total emissions of harmful substances and CO_2 into the atmosphere in the year 2015 would reach the 1990 level, with a nearly two-times lower electricity production [III.4.7].

In the future Programme of Action of the National Energy Strategy all measures necessary to prepare for the premature closure of the Ignalina NPP must be defined:

- a detailed plan of decommissioning and dismantling, including cost evaluation;
- a plan for nuclear waste and spent fuel management and interim storage;
- a programme for handling social problems related with premature closure;
- a detailed programme for the power sector development in the case of premature closure.

In order to prepare for the probable re-channelling it is necessary:

- to prepare for the fulfilment of the new safety analysis report;
- to carry out the detailed economic analysis of the power sector using the least cost method, to evaluate future prices of nuclear fuel, costs of spent fuel storage, its processing and final disposal and changes in fossil fuel market;
- to prepare the development of infrastructure (administrative, supervision, scientific-technical support, staff training) necessary for the long term safe and economic operation of the Ignalina NPP.

The capacity balance. If the Ignalina NPP operated only a half of its lifetime, the existing capacities would satisfy national demand till 2010 in all cases of demand growth. With upgrading of the Lithuanian TPP by transferring it into combined cycle, the capacity balance over the period concerned (till 2020) would satisfy internal demand only in the case of slow economic growth. If the Ignalina NPP operated till the end of its lifetime and the Lithuanian TPP was upgraded the excess capacity of the Lithuanian power sector would exceed 1.4 GW even without introduction of any new capacities and even in the case of fast economic growth (Fig. III.4.3).

Future power plants. Should new capacities be needed, CHP modules with a diesel engine or gas turbines or new combined cycle gas turbine (CCGT) would be the most attractive source of electricity from the economical point of view (Table III.4.2). The competitiveness of the eventual chain of hydro power plants built on the Neris river and the middle of the Nemunas river becomes obvious. However, the total capacity of these hydro power plants is only 172 MW. Thus, they do not influence the power balance much.

The CHP modules become very attractive for the conditions of Lithuania by implementing them instead of common boiler houses in available district heating systems. The best way to increase efficiency of heat supply systems is to replace large boiler houses by the low capacity thermal power plants. This is the dominating tendency in the power sectors of Western countries. However, the Ignalina NPP could be less efficient than CHP modules only in the case of low discount rate and high value of peak load factor.

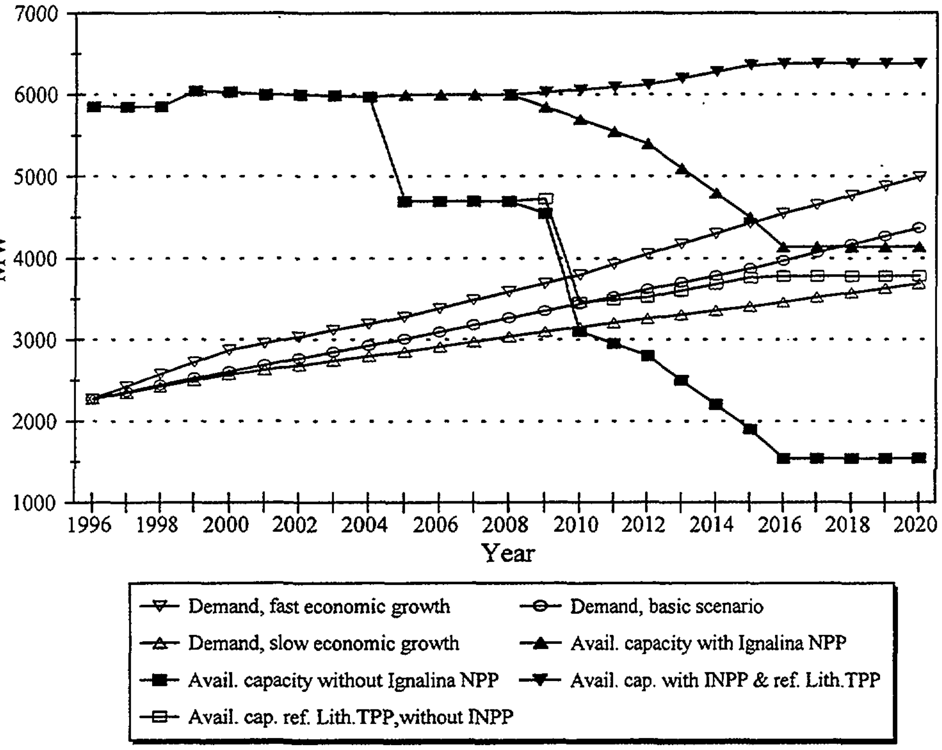

FIG. III.4.3. The balance of capacities of the Lithuanian power sector.

TABLE III.4.2. FORECAST OF ELECTRICITY PRODUCTION COSTS BY POWER PLANTS IN 2010, ct96/kW(h)

Power plant	*Time of maximum capacity utilisation, h*					
	3000	*5000*	*7000*	*3000*	*5000*	*7000*
	With 10% discount rate			*With 5% discount rate*		
Lithuanian TPP, 300 MW	3.7	3.2	3.0	3.6	3.1	2.9
CCGT	4.2–5.0	3.1–3.7	2.7–3.1	3.2–3.7	2.6–2.9	2.3–2.5
Probable HPP on Neris and Nemunas	5.4–7.5	3.3–4.5	2.3–3.2	2.6–3.6	1.6–2.1	1.1–1.5
Modules	3.3	2.4	1.9	2.4	1.8	1.5
New NPP	8.5	5.4	5.4	6.0	3.9	3.0
Ignalina NPP*	2.7	2.2	1.9	2.8	2.2	2.0

* Average in the planning period.

III.4.4. Safety improvement programmes

In order to provide safe operation, a significant programme of safety improvements was established by the plant immediately after the commissioning of the units. After the Chernobyl accident additional measures were implemented concerning the modification of control rods, the introduction of additional absorbers, fast reactor scram system and the upgrading of operating regulations related to core control.

Efforts to upgrade safety of the Ignalina NPP were accelerated since 1990. The first Safety Improvement Programme (SIP-1) has been prepared by the plant with the assistance of Western experts and was approved by the VATESI in 1993. To realize this programme a Grant Agreement was signed in February 1994 between the Lithuanian Government, the Ignalina NPP and the European Bank of Reconstruction and Development (EBRD) on behalf of the Nuclear Safety Account. The grant of 33 million ECU was given to fund short term safety upgrades. As part of the overall safety improvement programme, the EBRD funds were allotted to support 20 projects in three areas: operational safety, technical improvements and services.

An in-depth safety assessment of the Ignalina NPP was undertaken in 1994–1996 and, as a result, a Safety Analysis Report of Western style has been made. It has been reviewed independently by the end of 1996 in the Review of Safety Report. On the basis of both these reports the Ignalina NPP Safety Panel consisting of senior international nuclear experts have made their recommendations to the Government of Lithuania. Thus, no reactors of the RBMK type have been so deeply and in detail analysed using modern western methods as those of the Ignalina NPP. This gives a good basis for the judgement of the safety level as well of the priorities in the different safety improvement projects. On the basis of all these reports a new Safety Improvement Programme (SIP-2) was prepared. The Government of Lithuania has officially declared that all necessary safety improvements will be implemented as soon as practically possible. After implementation of all these improvements the probability (risk) of having a nuclear accident at the Ignalina NPP will be as low as for many Western nuclear power plants of the same vintage.

III.4.5. Costs of the Ignalina NPP safety upgrades

The SIP-1 was curried out during 1993–1996. The original intention of the Lithuanian Government was to contribute to plant improvement about $US 5 million of its own funds. However, at the end of 1993 it was quite clear that Lithuania would not afford to accumulate large financial resources. Thus, the Grant Agreement with the EBRD was a significant Western financial aid for a country in transition. Safety improvement projects funded by the EBRD are presented in Table III.4.3 [III.4.8].

In addition, at that time the Ignalina NPP had on-going bilateral co-operative projects with Sweden, USA, Germany, UK, France, Belgium, Italy, Switzerland, Canada, Finland and Japan. Sweden is most active in Lithuania. The total cost of hardware deliveries and know-how transferred by Swedish consultants until the end of 1997 could be estimated at about $US 28 million.

Initially, nuclear safety investment costs were based on a relevant study prepared for the EBRD in 1993 (Table III.4.4). At that time the cost data were approximate and needed to be revised. These nuclear safety investment costs were used for modelling of scenarios of the Lithuanian power sector development in the studies [III.4.1, III.4.7].

The most important conclusion to be drawn from the modelling results is that it is economic to keep both unit of the Ignalina NPP in operation for as long as this is possible and the necessary license is obtained.

At the end of 1996 as a result of an in-depth safety assessment of the Ignalina NPP the SIP-2 was prepared. Several on-going projects from SIP-1 that were not finished are included into SIP-2. The most recent assessment of investment necessary to implement all safety upgrades are presented in Table III.4.V, and the main sources of investment are shown in Table III.4.6.

TABLE III.4.3 SAFETY IMPROVEMENT PROJECTS AT IGNALINA NPP FUNDED BY EBRD

Project	*Supplier*	*Contract value, millions of $ US*
Steam separator and primary circuit visual inspection equipment	GEC Alsthom (UK)	0.9
Ultrasonic in-service inspection equipment for steam separator, pipes, etc.	Force Institute (Denmark)	0.8
Ultrasonic in-service inspection equipment for reactor channel	MAN Energie (Germany)	1.8
Radiographic inspection equipment	ABB-TRC (Sweden)	0.2
Special tools for maintenance	Furmanite Int. (UK)	0.5
Seal rings for fuel channels	Advanced Products (USA)	0.3
Radioactive release and environment monitoring	SEA (Italy)	2.2
Design documentation upgrading	IVO (Finland)	0.7
Full scope simulator	Atlas (Germany)	7.0
Engineering study of additional shutdown and protection systems	AEA Technology (UK)	0.8
Low flow and low reactivity margin reactor trip systems	Westinghouse (USA)	8.1
Upgrading for the TITAN system	SAIC (USA)	0.5
Seismic upgrading (walkdown)	ISMES (Italy)	0.5
Seismic upgrading (equipment)	-	1.7
Hydrogen monitoring system	Electrowat (Switzerland)	1.8
Safety valves	Sebim (France)	3.4
Motor gate valves	FIAT-AVIO (Italy)	2.9
Fire protection equipment	SVT Brandshutz (Germany)	3.4
Total		37.2

TABLE III.4.4. COSTS OF NUCLEAR SAFETY UPGRADING

Measures	*Millions of $ US 1994*	*Remarks*
Urgent safety upgrades	104	To be implemented until 1998
Short term safety upgrades for unit 1 (if not closed in 1998) and unit 2	81	To be implemented until 2003
Long term safety upgrades for unit 2	58	To be implemented in 2003–2008

TABLE III.4.5. TOTAL COSTS OF SAFETY IMPROVEMENT PROGRAMME, MILLIONS OF US DOLLARS

	Total	*1997*	*1998*	*1999*	*2000*	*2001*
Planned costs	168	28	22	19	27	72

TABLE III.4.6. SOURCES OF INVESTMENTS, MILLIONS OF US DOLLARS

	Including				
	Own funds	*State budget*	*Credit*	*EBRD*	*Foreign aid*
1997 actual costs	6.6		7.9	11.6	2.0
1998 actual costs	6.2	5.0	2.9	0.1	7.7
1999 planned costs	5.8	10.5	1.2	1.5	

REFERENCES TO ANNEX III.4

[III.4.1] Lithuania. Least Cost Power Sector Development Programme, Interim Analysis, November 1997.

[III.4.2] National Energy Strategy. Draft. October 1998.

[III.4.3] VILEMAS, J., GALINIS, A., Safety of the Ignalina NPP and future scenarios of the Lithuanian power sector development (Proc. Baltic Regional Forum on Energy Strategies in the Baltic States: from Support to Business, Riga (1997) 65–73.

[III.4.4] Evaluation of Economic Expediency of the Replacement of Technological Channels of Ignalina NPP, Kaunas, 1996 (in Russian).

[III.4.5] A Study on Cost of Closure of Ignalina Nuclear Power Plant in Lithuania, Defined as Opportunity Loss, Grufman Reje & Partners AB Managementkonsulter, Stockholm (1998).

[III.4.6] Radioactive Waste Management in Lithuania. Preliminary Assessment of Costs for the Nuclear Back-End, SKB Report, Stockholm (1995).

[III.4.7] REPUBLIC OF LITHUANIA, Least-cost Power Development Programme, LEI with Assistance of the EU Phare programme, Kaunas (1996).

[III.4.8] ALMENAS, K., KALIATKA, A., UZPURAS, E. Ignalina RBMK-1500. A Source Book. Extended and Updated Version, Kaunas (1998).

III.5. USA: HISTORICAL BEHAVIOUR OF O&M COSTS AND THEIR COMPONENTS

In addition to the costs of capital additions in the USAS given in Section 3.3.4.1, two more interesting phenomena of the O&M costs in the USAS are discussed in the used analytical study [20]: the historical behaviour of the O&M costs and the share of capital additions in the total O&M costs. As these two phenomena are of certain relevance to the subject of this review, their short characterisation is given below.

The table below shows both the historical behaviour of the O&M costs and the share of capital additions in the total O&M costs. The table illustrates how the O&M costs of NPPs in the USA escalated during the period from 1974 to 1993 — the total non-fuel costs roughly tripled by the end of the period. Simultaneously, the share of capital additions gradually decreased from about 40% in 1974 to some 20% in 1993 showing that the role of capital additions (i.e. roughly safety upgrades plus equipment replacement) has diminished while the role of "regular" O&M costs has correspondingly increased. The decrease of the capital additions may simply mean that the reached safety level at USS NPPs is in general sufficient, so the amount of new investments in plant safety gets lower and lower. Apart from this consideration, this decrease may also have for reasons, as discussed in [20], NRC's steps to control the number of new regulations requiring design modifications, learning experience of the industry and possibly the lack of operator's desire to invest for improving NPP performance.

Year	Total O&M costs		Post-operational capital expenditures		Total non-fuel expenditures,
	$US-93/kW(e)	% of total	$US-93/kW(e)	% of total	$US-93/kW(e)
1974	22.49	61	12.13	39	36.76
1975	25.11	63	10.66	37	39.71
1976	27.38	57	17.62	43	47.68
1977	29.96	51	26.44	49	58.65
1978	34.36	62	20.23	38	54.95
1979	40.83	64	22.77	36	63.46
1980	52.92	61	34.85	39	86.99
1981	54.31	54	45.58	46	101.10
1982	63.68	59	41.02	41	107.28
1983	67.43	59	46.21	41	113.98
1984	79.17	56	62.24	44	140.37
1985	74.09	65	35.44	35	113.54
1986	83.06	65	42.14	35	127.26
1987	89.27	67	39.73	33	132.26
1988	92.17	71	37.79	29	130.56
1989	93.65	72	34.62	28	129.32
1990	94.01	81	20.48	19	116.29
1991	95.24	74	33.63	26	129.53
1992	97.30	81	20.81	19	119.98
1993	96.43	77	28.67	23	125.56

Annex IV
ADDITIONAL INFORMATION ON DECOMMISSIONING COSTS

IV.1. BULGARIA: APPROACH TO DECOMMISSIONING OF UNITS 1&2 OF KOZLODUY NPP*

The first two units at Kozloduy NPP were put in operation in 1974 and 1975. The planned closure of these units has to occur in 2005 and 2006, after the expiration of their designed lifetime.

In 1995–1996 DECOM–Sofia completed a feasibility study on decommissioning of NPP Kozloduy units 1&2. The main purpose of the study was:

- to develop a strategy of NPP Kozloduy Units 1&2 decommissioning and evaluate the proposed options;
- to develop a basis for economic assessment of the selected options.

For the definition of the concept for decommissioning units 1&2, the decision making issues are so-called main "active" objects (common for the two units): the reactor building, auxiliary building, laboratory and access building, ventilation stack and related trestles, passage bridges and tunnels attached to them.

The basic approach is postulated in the following items:

- determination of study bases and assumptions;
- description of the NPP site that belongs to units 1&2 after final shutdown;
- definition of the basic options of decommissioning;
- description of "scenario" for all the selected options;
- analysis and assessment of the characteristic parameters for the selected options:
  - ⇒ working time requirements
  - ⇒ personnel requirements
  - ⇒ definition of necessary technological equipment
  - ⇒ radioactive waste production
  - ⇒ non-active waste production
  - ⇒ collective dose equivalent
  - ⇒ environmental impact on surroundings
  - ⇒ cost analysis
- summary of the main characteristic parameters for each option;
- comparison of evaluated decommissioning options based on the main characteristic parameters and further criteria;
- selection of the optimal decommissioning option.

The basic data sources used for the purpose of the study were operational data and design data of NPP Kozloduy units 1&2. In additional to the available date it was necessary to define the initial date and starting conditions:

* This material was prepared by T. Delcheva, Bulgarian National Electric Company.

(1) Units 1&2 will be shutdown after the designed lifetime expiration (30 years) and no accident resulting in the premature shut down has occurred.

(2) The operational radioactive waste are processed before the final shutdown of the units.

(3) All processed low level radioactive wastes (LLW), RPV, activated parts of the reactors and the biological shield will be disposed in the disposals at the NPP Kozloduy site.

(4) Criteria for releasing of dismantled metallic materials to the environment were accepted as follows:
   - surface beta and gamma contamination <0.4 Bq/sq cm
   - surface contamination alpha <0.04 Bq/sq cm
   - mass activity beta and gamma <100 Bq/kg

(5) Spent fuel management is out of scope of this study.

Five decommissioning options were thoroughly developed in the study:

- Immediate dismantling after shutdown to the stage 3 according to the IAEA classification;
- Safe storage for certain parts of the reactor building–hermetic areas for each unit separately;
- Safe storage for the reactor shafts only;
- Safe storage for reactor building;
- Monitored safe storage for all "active" objects.

For all options a complete demolition is projected after the termination of the safe storage period assuming dismantling and storing reactor vessels intact. It is postulated, too, that the nature of the radioactive contaminants of RPV and internals and part of concrete biological shield will not allow the radioactivity to decay to unrestricted release levels within 70 years following reactor shutdown.

All costs are related to the prices level in the beginning of 1996. For all objects destined for demolition, method of partial demolition is applied. It means that the lower underground structures are destroyed up to –1m level.

The process of decommissioning is divided into 3 or 4 basic phases depending on the options:

(1) Phase of final shutdown — for all options;

(2) Phase of preparation to dismantling — for option 1;

(3) Phase of preparation to safe storage — for option 2, 3, 4 and 5;

(4) Phase of safe storage — for option 2, 3, 4 and 5;

(5) Phase of total dismantling — for all options.

The main results of the study including the costs of the options and the duration of decommissioning phases are shown in Table IV.1.1 below.

TABLE IV.1.1. DECOMMISSIONING COSTS FOR NPP KOZLODUY UNITS 1&2

Power unit(s)	Gross capacity, MW(e)	Assumed approach to decommissioning	Total costs of decommissioning		Total duration of decomm., years	Major decommissioning phases and their duration in years				
			in million BGL of 1996	in million US $ of 1996		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
2 × WWER-440/230	2 × 440	1. Immediate dismantling	9650	189.47	25	5	8			12
		2. Safe storage for "hermetic areas" of reactor building	9555	188.12	80–95	5		10–12	60–70	6–8
		3. Safe storage for the reactor shafts	9050	180.9	78–92	5		12–15	60–70	1–2
		4. Safe storage for the reactor building	9367	185.44	77–91	5		6–8	60–70	6–8
		5. Safe storage for all "active" objects	13984	251.38	83–97	5		10–12	60–70	8–10

IV.2. LITHUANIA: APPROACH TO DECOMMISSIONING OF THE IGNALINA NPP*

The Ignalina NPP contains two RBMK-1500 reactors. The first unit of this power plant went into service at the end of 1983, the second unit in August 1987. The future of the Ignalina NPP is determined by 2 main parameters: the safety of operation (plant could be stopped at any time due to safety requirements) and the lifetime of the fuel channels. It is planned that in 1999 the State Nuclear Safety Inspectorate will license further operation of unit 1. The design lifetime of the fuel channels is 15–20 years. However, reactors were out of operation for some period and the actual lifetime could be longer. In the National Energy Strategy two scenarios have been chosen for evaluation. Scenarios are considerably different seeking to compare economic, social and other consequences related to the earlier or later closure of the Ignalina NPP:

(1) Unit 1 will be shut down in year 2005, unit 2 in year 2010 (at the end of the available lifetime of the fuel channels). At those date half of the designed technical lifetime of the two units will have elapsed;

(2) Fuel channels in both units will be replaced according to the design criteria for this type and generation of RBMK reactors. Both units will be kept in operation until at least 2020.

A plan for decommissioning and dismantling, including cost evaluation, is not prepared yet. An approach presented below is based on the assumptions presented in [IV.2.1]. For the decommissioning two different approaches may be considered: 1) decommissioning as soon as possible after shutdown; 2) deferred decommissioning when dismantling activities are postponed for a two decades after shutdown. Both alternatives have advantages and disadvantages. For the first assessment alternative one has been chosen.

TABLE IV.2.1. STRUCTURE OF ASSESSED DECOMMISSIONING COSTS

	%
Short-lived waste	4.0
Interim storage of spent fuel	10.1
Encapsulation and disposal of spent	70.0
Transport of spent fuel	3.2
Decommissioning of the Ignalina NPP	10.6
Central administration and R&D	2.1

According to the Swedish experience five stages of immediate decommissioning could be distinguished:

(1) Shut-down operation (final removal of spent fuel, decontamination of systems, planning of dismantling activities, acquisition of special tools and equipment;

(2) Service operation (such as waste treatment, water supply and sewerage, ventilation, electricity supply, control and surveillance systems, etc.) will have to maintain their functions during the dismantling period;

(3) System dismantling;

(4) Building demolition;

(5) Site restoration.

* This material was prepared by V. Miskinis, Lithuanian Energy Institute.

It is assumed that decommissioning of the two units is accomplished in a sequence-activities in unit 2 will follow years after corresponding activities in unit 1. Seeking to not disturb operation of unit 2 it is assumed that the dismantling of unit 1 will be kept in the "service operation" stage from 2005 until the end of the year 2010 (when unit 2 is foreseen to be shutdown according scenario 1 of the National Energy Strategy). In addition, problem of the waste management should be sólved. Activities related to radioactive storage and final disposal could be the following:

1999–2010:	Interim storage of spent fuel; Repository for short-lived waste.
2011–2015:	Decommissioning of the Ignalina NPP.
2016–2020:	Low activities.
2021–2030:	Preparation and construction of encapsulation station and spent fuel repository.
2031–2045:	Operation of encapsulation station and spent fuel repository.
2046–2055:	Sealing of repository and decommissioning encapsulation station.

It is necessary to note that data on which costs and time schedule (Tables IV.2.2–IV.2.4) are to a great extent uncertain and detailed study should be done. Costs consist of decommissioning of the Ignalina NPP, treatment and disposal of short-lived low and intermediate level waste, interim dry storage of spent nuclear fuel, and encapsulation, transport and disposal of spent fuel. Costs for decommissioning of the Ignalina NPP are based on experience of the Swedish nuclear unit Oskarshamn No.3. In the Swedish study manpower costs dominate and represent about 85% of total decommissioning costs. However, two circumstances were taken into account for assessment of Lithuanian costs: 1) much lower salaries and wages (about one third of the Swedish level); 2) building and materials at the Ignalina NPP are larger (for compensation of this difference a correction factor equal 1.25 was used). Costs for spent fuel interim storage were assessed the most precisely because casks for its storage are partly contracted. However, dominating future costs related to spent fuel disposal are rather uncertain. Total costs in 1995 was assessed 18000 MSEK or about US $ 2.3 billion. The structure of these costs is presented in Table IV.2.1.

REFERENCE TO ANNEX IV.2

[IV.2.1] Radioactive Waste Management in Lithuania. Preliminary assessment of costs for the Nuclear Back-End, SKB Report, Stockholm (1995).

TABLE IV.2.2. TENTATIVE TIME DISTRIBUTION OF THE IGNALINA NPP DECOMMISSIONING STAGES

		2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Unit 1	*Shut-down operation*	■	■														
	Service operation			■	■	■	■	■	■	■							
	System dismantling							■	■	■							
	Building demolition									■	■	■					
Unit 2	*Shut-down operation*							■									
	Service operation								■	■	■	■					
	System dismantling									■	■	■					
	Building demolition											■	■	■			
	Site restoration														■	■	

TABLE IV.2.3. TENTATIVE TIME SCHEDULE FOR A REPOSITORY OF SHORT-LIVED WASTE IN LITHUANIA

	1996	*1997*	*1998*	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*
Concept planning	■	■															
Areas survey		■	■														
Site characterization			■	■													
Site confirmation					■	■											
Design construction						■	■	■	■								
Operation									■	■	■	■	■	■	■	■	
Closure																	■

TABLE IV.2.4. TENTATIVE TIME DISTRIBUTION FOR WASTE MANAGEMENT AND DECOMMISSIONING

	1996–2000	*2001–2005*	*2006–2010*	*2011–2015*	*2016–2020*	*2021–2025*	*2026–2030*	*2031–2035*	*2036–2040*	*2041–2045*	*2046–2050*	*2051–2055*
Encapsulation and disposal of spent fuel												
Preparation			2007			2024						
Construction						2025		2032				
Operation								2033			2047	
Sealing decommissioning											2048	2055
Decommissioning of INPP		2005			2019							

IV.3. RUSSIAN FEDERATION: MAIN PROVISIONS OF DECOMMISSIONING STRATEGY FOR LENINGRAD UNIT 1 WITH FIRST GENERATION RBMK-1000 REACTOR*

IV.3.1. US/Russian joint decommissioning study for Leningrad NPP

A joint USS/Russian study was performed in 1996–1998 to analyse possible decommissioning strategies for the Leningrad NPP Unit 1. The Leningrad NPP site and the Leningrad Unit 1 with first generation RBMK-1000 reactor were chosen as a representative NPP site and a representative RBMK-1000 reactor. This study was performed by a group of Russian and US experts headed up by the Kurchatov Institute for the Russian efforts and by the Pacific Northwest National Laboratory for the USS efforts and overall project.

IV.3.2. Goals of joint decommissioning study

The ultimate goals of the joint USS/Russian decommissioning study to the Leningrad NPP were: 1) to develop the decommissioning strategy to the Leningrad Unit 1, 2) to select the most suitable decommissioning alternative and unit end state, taking into account the socio-economic conditions and the regulatory environment in the Russian Federation and her decommissioning experience, and 3) to provide a preliminary cost estimate for the decommissioning strategy recommended to the Leningrad Unit 1.

This decommissioning study to the Leningrad NPP included two USS/Russian joint study phases: a first (initial) phase, which was carried out in 1996–1997, and a second (current) phase (1997–1998), which is ongoing now and is close to its completion.

The goal of the initial phase was to define a safe, technically and economically feasible decommissioning strategy for the first generation RBMK-1000 Unit 1 at the Leningrad NPP.

The initial phase included a survey and analysis of Russian and US laws and regulations affecting decommissioning, a survey and analysis of Russian and US experience relevant to decommissioning, and the analysis of possible decommissioning alternatives to find a safe, technically feasible, cost-effective decommissioning strategy for the Leningrad NPP Unit 1.

The goals of the second phase of the US/Russian Decommissioning Strategy Study for the Leningrad NPP Unit 1 were: 1) to obtain all the construction, technical and economic data necessary for a preliminary cost estimate, and 2) to perform cost estimation for works associated with the decommissioning strategy and decommissioning alternative recommended in the earlier study phase.

IV.3.3. Specifics of Leningrad NPP influencing the unit decommissioning strategy

The Leningrad NPP is the first of the series of RBMK-1000s built in the former USSR as well as in the Russian Federation. The Leningrad NPP was designed and built in two Phases of two units each. The Phase I units are the first generation Unit 1 and Unit #2, and the Phase II units — the second-generation Unit #3 and Unit #4.

---

* This material was prepared by B. Bylkin and Yu. Zverkov, Russian Research Centre "Kurchatov Institute". The material is based on the results of an ongoing joint US–Russian decommissioning study led by: S.M. Garrett, M.C. Bierschbach (Pacific Northwest National Laboratory, USA), R.F. Lavelle (Brookhaven National Laboratory, USA), B.K. Bylkin, Y.A. Zverkov, T.D. Shepetina, Y.F. Chernilin, (RRC "Kurchatov Institute", Russian Federation), Y.V. Garusov, V.A. Shaposhnikov (Leningrad NPP, Russian Federation)

The design for and construction of the Leningrad NPP complied with the regulatory codes of the 60s and 70s. The time between the commissioning of the units in each phase averages two years. The Phase I units were commissioned in 1973 and 1975, and the Phase II units were commissioned in 1979 and 1981 correspondingly.

In designing and constructing Phase I and Phase II units, the Leningrad NPP used the principle of maximum sharing of equipment and auxiliary systems. Some of the systems and equipment have since been separated for safety reasons, but some of the systems and equipment are common for units of the same Phase.

The Leningrad NPP plays an important role in the electrical supply of both the Leningrad region and the entire Northwest. In addition, the Leningrad NPP is the main source of heat for the Sosnovy Bor industrial zone and the city of Sosnovy Bor, which is 6 km far from the plant.

The Leningrad NPP, which has the status of an independent operating organization, is a state enterprise, but it is completely self-financed and does not receive any financial support from the state, even for reconstruction activity to provide required safety. Because it does not receive budget allocations, the Leningrad NPP should finance capital construction, reconstruction, and re-equipment as well as unit decommissioning basically from its own funds.

IV.3.4. Option recommended for Leningrad Unit 1 decommissioning

Three decommissioning alternatives were evaluated during initial US/Russian joint study:

- The burial of the reactor structures in their regular place (ENTOMB).
- The immediate dismantling of the reactor structures and the unit's associated facilities (DECON).
- The partial dismantling of equipment and systems, isolation of the reactor structures, and their postponed final dismantling at the end of the storage period (SAFESTOR).

These decommissioning alternatives were based on the US Nuclear Regulatory Commission definitions, but modified for Russian conditions.

The decommissioning alternatives were evaluated taking into consideration several factors, including the regulatory and technical requirements, the specific features of the location, construction, operation of the Leningrad NPP Unit 1, nuclear fuel and radwaste management, status of technological support necessary for the decontamination and dismantlement of RBMK-1000 reactors, etc. Problems related to ensuring the safety of personnel, the population, and the natural environment during decommissioning were also considered.

As result of the analysis performed in the initial phase of the US/Russian Decommissioning Strategy Study, the SAFESTOR option was recommended for the Leningrad Unit 1 decommissioning.

The end state for the Leningrad Unit 1 decommissioning was also investigated. Based on the results of the analyses performed during this US/Russian joint study, it was recommended that unit civil rooms be used for construction of a processing and long term storage facility for radwastes. For an obvious reason, this radwaste facility should be available not only for the Unit 1 decommissioning, but for both units in Phase I and all Leningrad NPP units.

Such an end state reduces total decommissioning cost (lower construction cost for radwaste facility and no dismantling of the current unit facilities) and satisfies the requirement for handling and storing wastes on the Leningrad NPP Site.

The following basic decommissioning activities of the recommended strategy are to be done to the SAFESTOR option of the Leningrad Unit 1:

- The partial dismantling of reactor equipment and systems above and below the core,
- Localization of the reactor structures,
- Safe storage of the reactor structures,
- The postponed final dismantling of the reactor structures at the end of storage period.

Analysis of the change in the radioactivity of RBMK-1000 reactor structures as a function of storage time after final reactor shutdown shows that a reactor should be held for 50 to 100 years before its dismantling. In this study the 70 year storage period is chosen. In this case the exterior gamma radiation dose rate near the reactor structures when they are dismantled will permit them to be dismantled practically without specialized equipment.

The recommended Leningrad Unit 1 decommissioning strategy, based on the SAFESTOR option, includes the following stages:

- pre-shutdown preparation (planning for decommissioning)
- preparation for decommissioning
- preparation for long term safe storage
- long term safe storage
- final dismantling of the reactor and associated structures.

The detailed activities, which are to be carried out in decommissioning stages and accounted for the cost estimate of the Leningrad Unit 1 decommissioning, are listed in Table IV.3.1.

However, the following decommissioning activities were not accounted for in the cost estimates:

- The cost estimates did not account for the cost of non-decommissioning activities and, hence, the cost of these activities should be included in the operational costs. These activities include, for example, the unit shutdown and cooling, spent nuclear fuel handling, handling of operational radwastes, operation of site storage for spent nuclear fuel and operational radwastes.

- The activities whose costs are difficult to estimate now were not taken into account, because the research and analysis needed were not covered by this study. Activities in this category include preparation of the cooling ponds and the site storages for spent nuclear fuel, revision and reconstruction of the unit systems and equipment required and the final disposition of radwastes for these activities, sorting and storage of radwastes for limited and unlimited use, personnel training.

- The activities for which costs can be estimated only after the decommissioning project and other required design and working documentation are developed, were also not accounted for. These activities include development of necessary regulations for decommissioning activities, dismantling of structures and systems not used.

- The cost estimates are only approximate for the cost of equipment necessary for constructing a facility for processing and storage of processed radwastes.

- The cost estimates do not include the cost of the radwaste facility dismantling after unit decommissioning, for the cost of graphite handling after the reactor structures are dismantled, and for the cost of final removal of spent nuclear fuel and processed radwastes from the NPP site.

IV.3.5. Cost methodology and computer code

In this study the cost methodology integrated computer calculations and separate spreadsheets, based of Russian estimates of labour costs. The costs from the "cost estimating computer program" (CECP) output and the spreadsheets were combined for the final cost estimate. The final cost estimate of US economic conditions was then converted to Russian conditions using cost conversion factors.

The CECP software developed by the NRC at the Pacific Northwest National Laboratory was the basis of the Leningrad NPP Unit 1 decommissioning cost estimating process.

To produce a complete report of decommissioning costs the CECP calculates unit cost factors and then combines these factors with transportation and burial cost algorithms, burial volumes, person-hours, crew-hours, and exposure person-hours associated with decommissioning. For this purpose the CECP uses a special data base including: 1) labour rates, burial costs, constants; 2) unit cost factors for decontamination; 3) unit cost factors for contaminated systems; 4) decommissioning schedules; 5) site information; 6) special equipment costs; 7) building decontamination costs; 8) contaminated system costs; 9) nuclear steam supply system costs; 10) staffing costs; and 11) undistributed costs.

The BWR CECP version was used in this study, but the version was updated prior with the aim to make it useful for estimating projected costs of decommissioning RBMK-1000 Unit: 1) the code was modified to accept data in metric units, 2) cost factors were updated to 1997 dollars, and 3) burial costs were updated to better reflect current burial charges.

When possible, the Leningrad RBMK systems and equipment were mapped to similar BWR systems and costs by the CECP code. In this case, input data were updated to reflect the RBMK case.

Where equipment or systems are present in a BWR reactor but not in an RBMK, no costs were computer. When there was no similar BWR system or situation as compared to the RBMK, then a separate spreadsheet was used to estimate the cost.

Four major calculations were performed in spreadsheets: reactor dismantling, reactor localization, construction of the radwaste processing and storage facility, and final demolition and site restoration.

IV.3.6. Features of cost methodology and computer code used

The use of the US BWR CECP for calculating decommissioning cost estimates for an RBMK-1000 unit, as well as the input data are associated with the following key features due to differences between designs of equipment and systems and between US and Russian economic conditions.

Equipment and systems of reactor section

Design and technical features of equipment and systems of BWR reactor section are significantly different from the same equipment and systems of RBMK reactor section.

Designs of the coolant circulation systems and a number of other systems of the BWR and RBMK units are also significantly different. However, equipment of the coolant circulation circuits and systems has a lot of similar elements.

One element of RBMK systems added to the CECP data is the drum separators (2 per unit).

Turbine hall

Structures of equipment and systems of the steam turbine circuits of single-circuit NPP units with BWR and RBMK include a lot of similar elements. The differences in the designs for the BWR and RBMK turbine halls are primarily the number of some elements of the systems and equipment as well as to their masses and dimensional parameters. Two new systems were added to the CECP data: bubblers (2 per unit) and deaerators (4 per unit).

Auxiliary systems and other equipment

The design RBMK auxiliary systems and other equipment are similar to corresponding BWR systems and equipment.

Differences in US and Russian economic conditions

Economic conditions in the USA and the Russian Federation are characterized by differences in labour cost, labour productivity, cost of equipment, costs of construction and structural materials, and so on. Therefore, special conversion factors should be used to convert the cost calculations from the "US conditions" to the "Russian conditions" for decommissioning an RBMK.

The following conversion factors developed and used for the Joint Parallel Nuclear Alternative Study (JPNAS) were used in this study to convert the cost estimates from US to Russian economic conditions: 1) Equipment – 0.70, 2) Construction labour – 0.10, and 3) productivity of direct & indirect labour – 2.50.

IV.3.7. Assumptions

Several assumptions, in addition to those mentioned above, were made for the Leningrad NPP Unit 1 decommissioning cost estimate. Some of the assumptions relate only to the US or Russian conditions, while others relate to both conditions.

Assumptions related to both conditions

All costs are assumed in 1997 dollars. The CECP was modified to generate a 1997-dollar estimate. A 3% annual inflation rate was assumed to convert the original 1994 CECP costs to 1997 dollars. The contingency of 25% is taken into account, the discounting is not performed.

Indirect labour costs, including insurance and regulatory costs as well as indirect personnel, are based on the previous BWR analysis.

Socioeconomic costs, spent-fuel storage, and operation and maintenance of the waste processing and storage facility are not included in the costs estimated by this study.

Assumptions related to Russian conditions

The Russian conditions reflect the costs associated with decommissioning an RBMK in the Russian Federation and the infrastructure and economics in place in the Russian Federation.

The major difference between Russian and US conditions is that there is no centralised waste disposal site in the Russian Federation. Waste must be processed and stored onsite for an undetermined period of time. The Russian conditions reflects the construction necessary to modify the Leningrad NPP Unit 1 facilities for waste storage and processing.

Assumptions related to US conditions

The US conditions serve as the reference case. It reflects the costs associated with decommissioning an RBMK as if it were in the USA and reflects the infrastructure and economics in place in the USA. Therefore, US personnel (productivity and wages), and centralized burial are assumed. It was assumed there is no construction for US conditions because burial sites are available.

There are also five decommissioning stages for US conditions. The duration of each stage was assumed to be the same as for the BWR, assumed to be the same as estimated by the Russians, or assumed to be 1/2.5 times the Russian estimate, if it is dependent on productivity.

Stage 1 was assumed the same as that for the BWR analysis (2.5 years), Stages 2, 4 and 5 were assumed 1/2.5 times the Russian estimate (2 years each), and Stage 3 was assumed the same as the Russian estimate because it is not dependent on productivity (70 years long).

IV.3.8. Results of cost estimate

The main cost estimates for the Leningrad Unit 1 decommissioning are listed in Tables IV.3.2–IV.3.5 below both for US and Russian economic conditions. Namely, the following cost estimates are presented:

- Table IV.3.2: total decommissioning costs and duration of decommissioning stages.
- Table IV.3.3: breakdown of total decommissioning costs for decommissioning stages with intergrated radwaste costs for US conditions.
- Table IV.3.4: breakdown of total decommissioning costs for decommissioning stages with separated radwaste costs for US conditions.
- Table IV.3.5: breakdown of main decommissioning activity costs.

TABLE IV.3.1. MAIN ACTIVITIES FOR THE SAFSTOR DECOMMISSIONING OPTION RECOMMENDED FOR THE LENINGRAD NPP UNIT 1*

Stage and Decommissioning Activities	Work schedule (a)	
	Start	End
1. Pre-Shutdown Stage:	-5	0
1. Develop organisational and technical documentation:		
1.1. Develop an overall concept for decommissioning Phase I units		
1.2. Develop a program for a comprehensive survey of the unit		
1.3. Develop unit decommissioning plan		
1.4. Develop specification for development of a unit decommissioning project		
1.5. Create a database of information for unit decommissioning		
2. Start the purchase of special equipment		
2. Preparation for Decommissioning Stage:	0	5
1. Comprehensive inspection of unit and experimental design work to develop a unit decommissioning project	1	3
2. Development and approval of required organisational, technical, and design documentation:	1	5
2.1. Development and approval of the unit decommissioning project		
2.2. Official registration of decommissioning license		
2.3. Development of specification and distribution of orders for manufacturing of required dismantling equipment		

Stage and Decommissioning Activities	Work schedule (a)	
	Start	End
3. Preparation for Safe Storage Stage:	5	10
1. Decontamination work:	5	6
1.1. Standard decontamination and drainage of multiple forced circulation circuit		
1.2. Decontamination and drainage of other process circuits and the nuclear fuel cooling ponds		
2. Localize the reactor in place to prevent radionuclides from escaping	6	8
2.1. Dismantle reactor system elements and structures obstructing reactor localization		
2.2. Localize the other reactor structures		
2.3. Seal ventilation, cable, and pipe runs from the reactor cavity		
2.4. Total localization of the reactor construction space		
3. Bringing unit rooms into compliance with radiological and health requirements so that they can be used as temporary processed radwaste storage facilities	5	6
3.1. Decontaminate reactor section equipment and rooms		
3.2. Organize temporary storage for dismantled equipment in the turbine hall		
3.3. Remove thermal insulation from equipment, piping and structures		
3.4. Dismantle and transport equipment and systems from unit rooms designated for radwaste storage to sites of temporary storage		
4. Construction of the radwaste storage and processing facility:	5	10
4.1. Prepare and refurbish unit civil rooms to store conditioned radwaste		
4.2. Partially dismantle turbine hall equipment to make room for the radwaste processing facility		
5. Operations and maintenance:	5	10
5.1. Regularly inspect, repair and operate required equipment and systems of unit		
4. Long-Term Safe Storage Stage:	10	80
1. Preparation of warehousing and temporary storage of wastes permitted for restricted and unrestricted use.	10	15
2. Construction and installation of the radioactive waste processing facility	10	15
3. Dismantling of equipment and systems outside the reactor localization area	10	20
3.1. Completely dismantle turbine hall equipment		
3.2. Dismantle reactor section equipment and systems (as radioactivity declines)		
4. Conditioning, transportation and disposition of radwastes for their storage	15	20
5. Operations and maintenance:	10	80
5.1. Regularly inspect, repair and operate required equipment and systems		
5. Final Dismantling of Reactor Structures Stage:	80	85
1. Removal from storage and inspection of equipment, systems and structures	80	81
2. Dismantling of reactor structures	82	84
2.1. Install required equipment, power-supply, and dust suppression and gas purification systems		
2.2. Install equipment to dismantle reactor structures		
2.3. Open protective engineering barriers and remove structures obstructing access to reactor		
2.4. Dismantle reactor structure elements		
3. Handling of radwaste created during dismantling	82	85
3.1. Dismantle, complete radiological inspection and sort reactor units, reactor metal structure fragments and graphite		
3.2. Package and remove reactor structure elements		
3.3. Process radwaste		
3.4. Transport processed radwaste to unit rooms prepared for radwaste storage		
4. Cleaning or decontamination of the concrete surface of the reactor cavity (if necessary)	84	85
5. Operations and maintenance	80	85
5.1. Regularly inspect, repair and operate required equipment and systems		
6. Decontamination and dismantling of equipment used in dismantling	84	85
7. Final survey of unit structures and site	84	85

* Table IV.3.I presents only main decommissioning activities which were costed.

TABLE IV.3.2. TOTAL COSTS AND DURATION OF STAGES OF DECOMMISSIONING OF THE LENINGRAD UNIT 1 WITH RBMK-1000 REACTOR

Conditions	Gross capacity, MW(e)	Assumed approach to decommissioning	Total costs of decommissioning, $M	Total duration of decommissioning, years	Main decommissioning stages and their duration in years				
					Stage 1, pre-shutdown preparation	Stage 2, preparation for decommissioning	Stage 3, preparation for safe storage	Stage 4, safe storage	Stage 4, final dimantling (incl. demolition and site restoration
USA	1000	Safe storage	823.1	78.5	2.5	2	2	70	2
Russian Federation	1000	Safe storage	174.7	90	5	5	5	70	5

TABLE IV.3.III. BREAKDOWN OF TOTAL COSTS FOR RBMK-1000 LENINGRAD UNIT 1 DECOMMISSIONING STAGES (WITH INTEGRATED RADWASTE COSTS FOR US CONDITIONS)

Decommissioning Stages	USA conditions, $M (%)	Russian conditions, $M (%)
1. Pre-Shutdown preparation	13.4 (1.6)	5.9 (3.4)
2. Preparation for decommissioning	6.8 (0.8)	2.6 (1.5)
3. Preparation for safe storage	118.2 (14.4)	39.4 (22.5)
4. Safe storage	464.6 (56.5)	86.9 (49.7)
5. Final dismantling	220.2 (26.8)	39.8 (22.8)
TOTAL	823.1 (100)	174.7 (100)

TABLE IV.3.4. BREAKDOWN OF TOTAL COSTS FOR RBMK-1000 LENINGRAD UNIT 1 DECOMMISSIONING STAGES (WITH SEPARATED RADWASTE COSTS FOR US CONDITIONS)

Decommissioning Stages	US Conditions, $M (%)	Russian Conditions, $M (%)
1. Pre-shutdown preparation	13.4 (1.6)	5.9 (3.4)
2. Preparation for decommissioning	6.8 (0.8)	2.6 (1.5)
3. Preparation for safe storage	116.1 (14.2)	39.4 (22.5)
4. Safe storage	250.2 (30.4)	86.9 (49.7)
5. Final dismantling	114.6 (13.9)	39.8 (22.8)
Total without radwaste costs	501.0 (60.9)	174.7 (100)
Radwaste costs (ship & bury)	322.1 (39.1)	-
TOTAL	823.1 (100)	174.7 (100)

TABLE IV.3.V. BREAKDOWN OF MAIN ACTIVITY COSTS FOR LENINGRAD UNIT 1 DECOMMISSIONING

Decommissioning activity costs	US conditions, %	Russian conditions, %
1. Localization and final removal of reactor structures	16.4	9.7
2. Removal of equipment and systems	33.2	8.1
3. Decontamination	2.6	1.8
4. Plant power usage	0.8	0.8
5. Special tools and equipment	0.6	1.9
6. Radwaste facility construction	-	4.9
7. Surveillance and maintenance during safe storage	0.2	0.2
8. Utility and DOC staff	25.2	27.5
9. Demolition and site restoration	6.1	7.2
10. Site termination survey	0.2	0.2
11. Other costs	14.7	37.2
TOTAL, $M	823.1 (100)	174.7 (100)

IV.4. SLOVAKIA: APPROACH TO DECOMMISSIONING OF V1 AND V2 NPP IN SLOVAKIA*

IV.4.1. V1-NPP

The V1 part of the BOHUNICE NPP includes two WWER-440/230 units that started operation in 1980 and 1981 correspondingly. Two decommissioning options have been analysed for these reactors:

– Immediate total NPP dismantling after final shutdown (third stage according to the IAEA classification)
– Safe enclosure (storage) for certain parts of the reactor building ("hermetic area") for each unit separately, followed by dismantling to the "green field". The duration of safe enclosure or storage is 70 years.

Process of V1–NPP decommissioning is divided into three or four basic phases depending on the chosen option:

For immediate decommissioning to stage 3 the phases are:

(1) Phase of final shutdown
(2) Phase of lead time (preparation) to dismantling
(3) Phase of total dismantling.

For decommissioning with long term safe enclosure the breakdown by phases is the following:

(1) Phase of final shutdown
(2) Phase of lead time (preparation) to safe enclosure
(3) Phase of safe enclosure
(4) Phase of total dismantling.

For the both decommissioning options, "pre-shutdown operations (pre-shutdown activities)" should be taken into account, too.

Fundamental activities which are to be carried out in decommissioning phases are introduced in Table IV.4.1.

For the option of safe enclosure, the following technological equipment (systems) of V1–NPP will be subject to safe enclosure during 70 years:

– reactor
– steam generators
– primary circuit piping
– main circulating pumps and main isolation valves of the primary circuit
– pressurizer system
– spraying system
– emergency makeup system of the primary circuit.

* This material was prepared by E. Hladky, DECOM Slovakia, Ltd; Trnava, Slovakia.

TABLE IV.4.1. FUNDAMENTAL ACTIVITIES DURING DECOMMISSIONING PHASES

Phase	Performed activities
Final shutdown	– final unit shutdown (adjustment of fuel charging scheme) – fuel transfer from reactor into a fuel storage pool – drainage of materials in process (particularly coolant from the primary circuit) – primary circuit decontamination – treatment and conditioning of produced radwaste – preparatory adjustment of systems taking into account their limited extent of following operation
Lead time (preparation) to technological system dismantling (option1)	– pre-dismantling decontamination – preparation of auxiliary systems for dismantling – dismantling – post-dismantling decontamination – treatment, conditioning, transport and storage of waste
Lead time (preparation) to safe enclosure (option 2)	– pre-dismantling decontamination of technological equipment and rooms – dismantling of equipment (it depends on a safe enclosure extent) – post-dismantling decontamination – demolition of buildings outside the safe enclosure – realization of auxiliary systems for the safe enclosure – formation of required barriers (adjustment of safe enclosure building) – treatment, conditioning, transport and storage of waste (radioactive and non-active)
Safe enclosure (option 2)	– performance and maintenance of equipment (ventilation, drainage system and so on) – check of barrier state – radiological control
Total dismantling (option 1)	– pre-dismantling decontamination of equipment – dismantling – post-dismantling decontamination – decontamination of building surfaces – demolition of buildings – treatment, conditioning, transport and storage of waste (radioactive and non-active)
Total safe enclosure dismantling (option 2)	– dismantling of equipment – post-dismantling decontamination – decontamination of building surfaces – demolition of buildings – treatment, conditioning, transport and storage of waste (radioactive and non-active)

These technological systems are situated in hermetic areas, which will be re-arranged so that they fulfil the requirement of separate building with a possibility to perform all necessary checks and monitoring during safe enclosure.

In addition, the following specific features of the assumed approach to decommissioning should be noted:

- In the first place technological processes and equipment already in the site will be used for treatment and conditioning of radwaste from V1–NPP decommissioning. Specific character of waste will require additional techniques (high pressure compacting and melting of metallic materials).
- Main part of radwaste from decommissioning could be disposed in the near surface repository for low and intermediate level activity waste at Mochovce.
- Special deep disposal facility construction is envisaged for high level waste.
- Significant amount of radwaste from V1–NPP decommissioning will be suitable for free release into the environment (exemption from control for unrestricted use). The following limits are used for free release of materials:
  - specific activity : <0.1 Bq/g for beta, gamma
  - surface activity : 0.4 Bq/cm^2 for beta, gamma
    0.04 Bq/cm^2 for alpha
- Material with specific activity 0.1–3 Bq/g is envisaged for disposal on a communal controlled storage site.
- Final shutdown after finishing of designed lifetime is supposed (serious accident did not occur and was not a reason of premature shutdown).
- Spent fuel management is out of considered decommissioning activities.
- Price level of 1996 for the costs in Slovak Korunas and 1998 level for the costs in $US are used for cost estimates of single decommissioning phases, discounting is not performed.

IV.4.2. V2-NPP

The V2 part of the BOHUNICE NPP includes two WWER-440/213 units that started operation in 1984 and 1985 correspondingly. Two decommissioning options have been analysed for these reactors:

- Immediate total NPP dismantling after final shutdown (third stage according IAEA classification)
- Safe enclosure (storage) of the reactor cavity with each reactor separately, followed by dismantling to the “green field”. The duration of the safe enclosure (storage) is 70 years.

All major specific features of decommissioning process for V2, i.e. the breakdown by phases, the list of fundamental activities and the background assumptions, are the same as given above for V1. The main quantitative parameters characteristic for V1 and V2 decommissioning are given in Tables IV.7.2–4 below. Namely, the following characteristics are presented:
- Table IV.7.2: total costs of decommissioning and duration of decommissioning phases;
- Table IV.7.3: typical cost drivers for decommissioning;
- Table IV.7.4: decommissioning schedules.

One should note that the decommissioning study for units 3, 4 of Bohunice is much more recent than that on Bohunice 1, 2 completed in 1992. Therefore, data on Bohunice 1, 2 are less reliable than data on units 3, 4. Currently, there is a new decommissioning study on Bohunice 1, 2 in progress that should update earlier estimations of decommissioning costs.

TABLE IV.4.2. DECOMMISSIONING COSTS FOR THE BOHUNICE NPP IN SLOVAKIA

Power unit(s)	Gross capacity, MW(e)	Assumed approach to decommissioning	Total costs of decommissioning		Total duration of decommissioning, years	Major decommissioning phases and their duration in years*				
			in million SK (Slovak Korunas) of 1996	in million $US of 1998		Phase 1, pre-shutdown operations	Phase 2, shutdown operations	Phase 3, preparation for dismantling (for safe storage)	Phase 4, safe storage	Phase 5, total dismantling (incl. demolition) and site release
V1 (2 × WWER-440/230)	2 × 440	1. Immediate dismantling	12 284	353	25	3	6	8	...	16
		2. Safe storage followed by dismantling	12 729	366	95	3	6	14	70	6
V2 (2 × WWER-440/213)	2 × 440	1. Immediate dismantling	10 603	305	18	3	6	8	...	11
		2. Safe storage followed by dismantling	10 290	296	89	3	6	10	70	6

* The total duration of decommissioning is not a sum of decommissioning phases duration, because phases 2, 3, 5 can overlap.

TABLE IV.4.3. TYPICAL DECOMMISSIONING COST DRIVERS FOR THE BOHUNICE NPP

Power unit(s)	Gross capacity, MW(e)	Assumed approach to decommissioning	Labour requirements for decommissioning and labour costs		Characteristics of decommissioning wastes	
			Labour req. in person-years	Labour costs in million $US of 1998	Total amount of mass to be handled during decommissioning, tonnes	Total amount of generated decommissioning wastes to be disposed of, tonnes
V1 (2 × WWER-440/230)	2 × 430	1. Immediate dismantling	1337	101.0	384 000	19 716
		2. Safe storage followed by dismantling	1457	110.0	382 000	9 807
V2 (2 × WWER-440/213)	2 × 430	1. Immediate dismantling	1153	87.0	834 000*	20 879
		2. Safe storage followed by dismantling	1198	90.5	830 000*	10 398

TABLE IV.4.4. DECOMMISSIONING SCHEDULES FOR THE BOHUNICE NPP

Power unit(s)	Assumed approach to decommissioning		Years (t=0: shutdown of the reactor)												
			-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7
V1 (2 × WWER-440/230)	1. Immediate dismantling	Phase 1	■	■	■										
		Phase 2				■	■	■	■	■	■				
		Phase 3					■	■	■	■	■	■	■	■	
		Phase 4													
		Phase 5										■	■	■	■
		Annual costs, M$US	0.4	1.0	2.6	3.7	5.2	8.3	18.5	18.0	10.4	14.5	13.1	19.1	16.4
	2. Safe storage followed by dismantling	Phase 1	■	■	■										
		Phase 2				■	■	■	■	■	■				
		Phase 3								■	■	■	■	■	■
		Phase 4													
		Phase 5													
		Annual costs, M$US	0.4	1.0	2.3	2.9	4.3	6.3	7.1	11.8	14.9	15.3	6.9	9.8	12.3
V2 (2 × WWER-440/213)	1. Immediate dismantling	Phase 1	■	■	■										
		Phase 2				■	■	■	■	■	■				
		Phase 3					■	■	■	■	■	■	■	■	
		Phase 4													
		Phase 5								■	■	■	■	■	■
		Annual costs, M$US	0.4	1.0	2.3	3.2	4.3	9.8	12.5	24.3	13.0	26.2	23.8	38.0	37.7
	2. Safe storage followed by dismantling	Phase 1	■	■	■										
		Phase 2				■	■	■	■	■	■				
		Phase 3						■	■	■	■	■	■	■	■
		Phase 4													
		Phase 5													
		Annual costs, M$US	0.4	1.0	2.3	2.9	3.0	11.9	15.4	24.3	19.2	22.3	17.1	40.6	35.8

TABLE IV.4 (cont.)

Power unit(s)	Assumed approach to decommissioning		years (t=0: shutdown of the reactor)												
			8	9	10	11	12	13	14	15	16	17	18	19	20
V1 (2 × WWER-440/230)	1. Immediate dismantling	Phase 1													
		Phase 2													
		Phase 3													
		Phase 4													
		Phase 5													
		Annual costs, M$US	18.7	18.7	14.3	13.7	22.4	28.6	28.4	28.5	17.0	16.4	11.7	3.4	
	2. Safe storage followed by dismantling	Phase 1													
		Phase 2													
		Phase 3													
		Phase 4													
		Phase 5													
		Annual costs, M$US	14.0	17.9	15.3	22.1	28.4	30.9	21.3	21.6	0.26	0.26	0.26	0.26	0.26
V2 (2 × WWER-440/213)	1. Immediate dismantling	Phase 1													
		Phase 2													
		Phase 3													
		Phase 4													
		Phase 5													
		Annual costs, M$US	32.2	31.2	31.8	8.2	4.8								
	2. Safe storage followed by dismantling	Phase 1													
		Phase 2													
		Phase 3													
		Phase 4													
		Phase 5													
		Annual costs, M$US	31.8	30.6	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06

TABLE IV.4 (cont.)

Power unit(s)	Assumed approach to decommissioning		years (t=0: shutdown of the reactor)									
			21	22	23	24	25	......	75	76	77	78
V1 (2 × WWER-440/230)	1. Immediate dismantling	Phase 1										
		Phase 2										
		Phase 3										
		Phase 4										
		Phase 5										
		Annual costs, M$US										
	2. Safe storage followed by dismantling	Phase 1										
		Phase 2										
		Phase 3										
		Phase 4										
		Phase 5										
		Annual costs, M$US	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
V2 (2 × WWER-440/213)	1. Immediate dismantling	Phase 1										
		Phase 2										
		Phase 3										
		Phase 4										
		Phase 5										
		Annual costs, M$US										
	2. Safe storage followed by dismantling	Phase 1										
		Phase 2										
		Phase 3										
		Phase 4										
		Phase 5										
		Annual costs, M$US	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	1.1

TABLE IV.4 (cont.)

Power unit(s)	Assumed approach to decommissioning		years (t=0: shutdown of the reactor) 79	80	81	82	83	84	85	86	87	88	89
V1 (2 × WWER-440/230)	1. Immediate dismantling	Phase 1											
		Phase 2											
		Phase 3											
		Phase 4											
		Phase 5											
		Annual costs, M$US											
	2. Safe storage followed by dismantling	Phase 1											
		Phase 2											
		Phase 3											
		Phase 4											
		Phase 5											
		Annual costs, M$US	0.26	0.26	0.26	0.26	0.26	2.3	10.5	6.3	15.9	39.2	7.1
V2 (2 × WWER-440/213)	1. Immediate dismantling	Phase 1											
		Phase 2											
		Phase 3											
		Phase 4											
		Phase 5											
		Annual costs, M$US											
	2. Safe storage followed by dismantling	Phase 1											
		Phase 2											
		Phase 3											
		Phase 4											
		Phase 5											
		Annual costs, M$US	2.0	8.0	8.4	8.1	5.3						

IV.5. USA: ADDITIONAL INFORMATION ON US DECOMMISSIONING PROJECTS

IV.5.1. Characteristic breakdowns for US reference decommissioning projects

Usually, decommissioning costs vary from case to case, sometimes without an obvious reason. It was confirmed in this review as well. Recent US cost studies for two reference decommissioning projects illustrate some typical sources of the variability of decommissioning costs, see Tables IV.5.1 and IV.5.2 below*.

TABLE IV.5.1. BREAKDOWN OF DECOMMISSIONING COSTS FOR THE REFERENCE US PWR DECOMMISSIONING PROJECT — THE 1155 MW(E) TROJAN NPP UNIT

Cost Component	DECON Option (Immediate Dismantling)		SAFSTOR** Option (Dismantling after long term storage	
	Burial site: Hanford	Burial site: Barnwell	Burial site: Hanford	Burial site: Barnwell
Labour and Mmaterial	89.9	90.4	149.8	150.3
Energy and transportation	9.2	17.3	9.9	18.1
Waste burial	24.5	110.1	24.1	108.1
Taxes and insurance	9.7	9.7	54.0	54.0
Total	**133.3**	**227.5**	**237.9**	**330.5**

TABLE IV.5.2. BREAKDOWN OF DECOMMISSIONING COSTS FOR THE REFERENCE US BWR DECOMMISSIONING PROJECT — THE 1129 MW(E) WASHINGTON NUCLEAR PLANT 2 (WNP-2) UNIT

Cost component	DECON option (immediate dismantling)		SAFSTOR option (dismantling after long term storage	
	Burial site: Hanford	Burial site: Barnwell	Burial site: Hanford	Burial site: Barnwell
Labour and material	100.8	100.8	205.2	-
Energy and transportation	5.1	11.8	5.7	-
Waste burial	43.2	183.8	42.8	-
Taxes and insurance	9.1	9.1	49.4	-
Total	**158.2**	**305.7**	**303.1**	-

* The costs in these tables differ from the US decommissioning costs presented in the main body of the text for two main reasons: 1) these costs are in $US of 1993 and not of 1997 and 2) the cost estimates for the same reactors in Section 5 contain an adjustment for the demolition costs according to [51] that is not included in the original estimates made in [59, 60].

** In [59, 60], two options of SAFSTOR are considered: SAFSTOR1 and SAFSTOR2. Only the results for SAFSTOR2 are given here as being more representative. The cost of the SAFSTOR1 option that is characterized by lower amount of the disposed radio-active wastes than for SAFSTOR2 is between the costs of DECON and SAFSTOR2.

TABLE IV.5.3. DECOMMISSIONING COSTS FOR SELECTED US NPPs [42]

Reactor code	Reactor name	Reactor type	Capacity, MW(e) gross	Decomm. costs, M$US	Base year for decomm. cost	Decomm. costs, M$US97	Specific decomm. costs, $US97/kW(e)
US -306	PRAIRIE ISLAND-2	PWR	531	245	93	270	508
US -282	PRAIRIE ISLAND-1	PWR	534	207	93	228	427
US -250	TURKEY POINT-3	PWR	699	157	87	215	307
US -251	TURKEY POINT-4	PWR	699	184	87	252	360
US -255	PALISADES	PWR	770	316	89	404	525
US -280	SURRY-1	PWR	820	193	90	237	289
US -281	SURRY-2	PWR	820	242	90	297	363
US -289	THREE MILE ISLAND-1	PWR	834	203	87	278	333
US -348	FARLEY-1	PWR	856	276	93	304	355
US -302	CRYSTAL RIVER-3	PWR	860	293	91	345	401
US -334	BEAVER VALLEY-1	PWR	860	283	92	320	373
US -364	FARLEY-2	PWR	864	302	93	333	385
US -412	BEAVER VALLEY-2	PWR	870	256	92	290	333
US -335	ST. LUCIE-1	PWR	872	187	87	256	293
US -389	ST. LUCIE-2	PWR	882	211	87	289	327
US -269	OCONEE-1	PWR	886	236	85	343	387
US -270	OCONEE-2	PWR	886	142	85	206	233
US -287	OCONEE-3	PWR	886	142	85	206	233
US -338	NORTH ANNA-1	PWR	894	118	83	185	207
US -346	DAVIS BESSE-1	PWR	921	346	93	381	414
US -339	NORTH ANNA-2	PWR	957	236	90	290	303
US -424	VOGTLE-1	PWR	1159	264	90	324	280
US -425	VOGTLE-2	PWR	1163	329	90	404	348
US -382	WATERFORD-3	PWR	1120	320	94	344	307
US -275	DIABLO CANYON-1	PWR	1124	237	88	315	280
US -323	DIABLO CANYON-2	PWR	1137	286	88	380	334
US -272	SALEM-1	PWR	1149	183	90	225	196
US -311	SALEM-2	PWR	1149	273	90	335	292
US -445	COMANCHE PEAK-1	PWR	1161	268	92	304	261
US -446	COMANCHE PEAK-2	PWR	1161	363	92	411	354
US -482	WOLF CREEK	PWR	1181	370	93	408	345
US -413	CATAWBA-1	PWR	1192	179	85	260	218
US -414	CATAWBA-2	PWR	1192	185	85	269	225
US -443	SEABROOK-1	PWR	1200	361	94	388	323
US -483	CALLAWAY-1	PWR	1232	372	93	410	333
US -528	PALO VERDE-1	PWR	1303	358	93	394	303
US -529	PALO VERDE-2	PWR	1303	341	93	376	288
US -530	PALO VERDE-3	PWR	1303	698	93	769	590
US -219	OYSTER CREEK	BWR	632	198	87	271	429
US -220	NINE MILE POINT-1	BWR	635	212	86	298	469
US -321	HATCH-1	BWR	774	236	90	290	375
US -324	BRUNSWICK-2	BWR	782	199	89	255	326
US -298	COOPER	BWR	787	424	93	467	594
US -325	BRUNSWICK-1	BWR	791	216	89	276	350
US -366	HATCH-2	BWR	799	311	90	382	478
US -354	HOPE CREEK-1	BWR	1076	437	90	537	499
US -277	PEACH BOTTOM-2	BWR	1098	254	90	312	284
US -278	PEACH BOTTOM-3	BWR	1098	315	90	387	352
US -410	NINE MILE POINT-2	BWR	1124	228	84	344	306
US -416	GRAND GULF-1	BWR	1190	407	94	437	367
US -440	PERRY-1	BWR	1225	502	93	553	451

As one can see with these tables, a simple change in the burial place for decommissioning low-active wastes can result in almost doubling the total cost of decommissioning. The choice of the place can be influenced by many factors, such as the status of various inter-state agreements on waste disposal, availability of other disposal sites, size of the available depositories, etc. At the moment, the final disposal site is not known and this factor alone can drastically change the cost of decommissioning.

Of course, this situation is specific for the USA, but the same factor is one of the reasons for significant differences in the decommissioning costs in different countries.

IV.5.2. Variability of US decommissioning costs

In view of the above, one cannot expect too much consistency about decommissioning cost estimates at the level of total costs. The costs can vary significantly depending on the year of the estimation, assumptions on the final condition of the unit, number of the units on site, assumed composition of the decommissioning costs, characteristics of the site of waste disposal, etc.

Table IV.5.3 below that combines numerous decommissioning cost estimates for US NPPs and structured by reactor type and capacity, confirms this observation and allows to compare the magnitude of the possible effect of reactor type and capacity with the dominating effect of the mentioned variables.

In addition, one should have in mind that many assessments in Table IV.5.3 were made several years ago. As with years decommissioning cost estimates have some tendency to grow (due to a multitude of reasons, including growing costs of handling low-active wastes), it is possible that earlier estimates underestimate the actual expenses required. This factor adds to the variability of the costs presented below.

IV.6. REPUBLIC OF KOREA: DECOMMISSIONING SCHEDULE FOR KORI-1 UNIT*

To complement the information on the costs of decommissioning for Korean NPPs (Section 5), the tables below present additional cost data for the PWR-587 Kori-1 unit. Table IV.6.1 presents the total costs of decommissioning and the duration of main decommissioning phases while Table IV.6.2 provides an estimation for annual cost disbursements.

For Table IV.6.2 the following notes should be taken into account.

1. Assumptions for the option of immediate dismantling

- All decommissioning activities and site recovery are completed within 8.6 years after shutdown.
- Major dismantling activities are performed in Phase 4.

2. Assumptions for the option of safe storage followed by dismantling

- All decommissioning activities and site recovery are completed within 18.6 years after shutdown.
- 10 years of safe storage period are included.
- No dismantling activities are performed in safe storage period except decontamination and clean-up.

* This material was prepared by I.S. Jeong, Korea Electric Power Research Institute (KEPRI).

- All systems and components are drained and depowered except essential systems and components required to operate during safe storage period.
- The amounts of contaminated systems and materials after the safe storage are assumed to be at the same level as before the safe storage.

3. Assumptions for the calculation of decommissioning costs

- All costs are net overnight costs of January 1, 1995.
- The cutting length of piping is 15 ft.
- The disposal cost of low active radwaste material is 77.8 $US/ft^3.
- Contingency is included at 25%.

For Table IV.6.2 it is important to note the contents of major activities to be performed during the shown decommissioning phases. For the option of immediate dismantling, the main activities are as follows:

Phase 1: Planning and preparation:

- Estimate amount of dismantling materials.
- Submit and getting approval of Safety Analysis Report from the government.
- Prepare storage area.

Phase 2 : Defueling and lay-up

- Removal of RPV internals.
- Chemical decontamination.
- Disposal of concentrated boron solution.
- Survey radiation level.

Phase 3: Spent fuel pool operation

- Preparation of work procedure.
- Decontamination and environment monitoring.
- Selection of contractors.

Phase 4: Dismantling and site recovery

- Removal of NSSS (reactor, piping, pressurizer, steam generator, spent fuel racks, etc.).
- Removal of contaminated plant systems.
- Decontamination of site buildings.
- Site termination and survey.

For the option of long term storage, the following main activities are planned:

Phase 1: Planning and preparation

- Estimate amount of dismantling materials
- Submit and get approval of Safety Analysis Report from the government
- Prepare storage area and equipment

Phase 2: Defueling and lay-up

- Removal of RPV Internals
- Chemical decontamination
- Survey radiation level

Phase 3: Spent fuel pool operation

- Environment monitoring
- Maintenance of structures

Phase 4: Extended safe storage

- Preparation of work procedure
- Selection of contractors
- Safety analysis and survey of plant radiation level
- Spent fuel pool water treatment

Phase 5: Dismantling and site recovery

- Removal of NSSS (reactor, piping, pressurizer, steam generator, spent fuel racks, etc.)
- Removal of contaminated plant systems
- Decontamination of site buildings
- Site termination and survey

TABLE IV.6.1. DECOMMISSIONING COSTS AND PHASES FOR THE KOREAN KORI-1 UNIT

Power unit(s)	Assumed approach to decommissioning	Total costs of decommissioning		Total duration of Decomm., years	Major decommissioning phases and their duration in years						Commercial operation	Shut-down
		in million Won of the 1995	in million $US of the 1995		Phase 1, Planning and preparation	Phase 2, Defuel and lay-up	Phase 3, Spent fuel pool operation	Phase 4, Dismantling and site recovery	Phase 4, Extended safe storage	Phase 5, Dismantling and site recovery	in calendar years	in calendar years
Kori-1	1. Immediate dismantling(DECON)	144948	188	11	-2.5 ~ 0.0	0.0 ~ 0.6	0.6 ~ 6.9	6.9 ~ 8.6	-	-	1978	2008
	2. Safe storage followed by dismantling (Mothballing with delayed dismantling, SAFSTOR)	161910	210	21	-2.5 ~ 0.0	0.0 ~ 0.6	0.6 ~ 6.9	-	6.9 ~ 16.9	16.9 ~ 18.6		

TABLE IV.6.2. DISBURSEMENT OF DECOMMISSIONING COSTS FOR THE KOREAN KORI-1 UNIT

Power unit(s)	Assumed approach to decommissioning		years (t=0: shutdown of the reactor)																
			-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10 ~ 16	17	18	19
Kori-1	1. Immediate dismantling	Decommissioning phase	Phase 1 (-2.5 ~ 0)				Phase 2 (0 ~ 0.6)	Phase 3 (0.6 ~ 6.9)					Phase 4 (6.9 ~ 8.2)						
		Annual costs, M$US	26				39.5	8.8					113.7						
	2. Safe storage followed by dismantling	Decommissioning phase	Phase 1 (-2.5 ~ 0)				Phase 2 (0 ~ 0.6)	Phase 3 (0.6 ~ 6.9)					Phase 4 (6.9 ~ 16.9)				Phase 5 (16.9 ~ 18.6)		
		Annual costs, M$US	26				39.5	7.5					24.9				112.3		

REFERENCES

[1] ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, OECD Economic Outlook, OECD, Paris (1997).

[2] INTERNATIONAL MONETARY FUND, International Financial Statistics Yearbook, IMF (1997).

[3] INTERNATIONAL MONETARY FUND, World Economic Outlook, IMF (1997).

[4] NUCLEAR ENERGY AGENCY OF THE ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, Decommissioning of Nuclear Facilities: Feasibility, Needs and Costs, OECD/NEA, Paris (1986).

[5] NUCLEAR ENERGY AGENCY OF THE ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, Decommissioning of Nuclear Facilities: An Analysis of the Variability of Decommissioning Cost Estimates, OECD/NEA, Paris (1991).

[6] NUCLEAR ENERGY AGENCY OF THE ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, Projected Costs of Generating Electricity (Update of 1992), OECD/NEA, Paris (1992).

[7] EUROPEAN BANK FOR RECONSTRUCTION AND DEVELOPMENT, Review of Economic Aspects of Nuclear Generation and Safety Improvements in Eastern and Central Europe, EBRD (1993).

[8] GEVORGYAN, A., "Safety upgrading tasks for unit 2 of the Armenian NPP", paper presented at the IAEA Consultants Meeting on the Review of Cost Estimates of Safety Upgrades and Lifetime Extension of Nuclear Power Plants, October 27–28, 1998, Vienna.

[9] BULGARIAN NATIONAL ELECTRIC COMPANY, Working Report of NEK Experts for the European Bank of Reconstruction and Development (EBRD), NEK (1997).

[10] BILGER, H., WEIS, P., ZIMMER, H.-J., "Serviceleistungen — ein Beitrag zur Wirtschaftlichkeit von Kernreaktoren", Vortrag anläßlich der DAtF-Herbsttagung "High-Serve" in Königswinter am 17. October 1995 (1995).

[11] BRÖCKER, HANSSON, "Vergleich der Instandhaltungskosten von PreussenElektra- und Sydkraft-Kernkraftwerken", Vortrag anläßlich der DAtF-Herbsttagung "High-Serve" in Königswinter am 17. October 1995 (1995).

[12] ALT, M., Analyse der Betriebkosten am Beispiel der Doppelblockanlage GKN, Gemeinschaftskernkraftwerk Nektar GmbH, Nektarwestheim (1998).

[13] JEONG, I.-S., "Safety upgrades and lifetime extension in Korea", paper presented at IAEA Consulants Meeting on the Review of Cost Estimates of Safety Upgrades and Lifetime Extension of Nuclear Power Plants, October 27–28, 1998, Vienna,.

[14] UK KNOW-HOW FUND, Republic of Lithuania Least-Cost Power Sector Development Programme, Report of ERM Energy for the UK Know-How Fund, ERM Energy Ltd (1996).

[15] MISKINIS, V., Lithuanian Energy Institute, "Cost estimates for safety upgrades at the Ignalina Nuclear Power Plant", paper presented at IAEA Consulants Meeting on the Review of Cost Estimates of Safety Upgrades and Lifetime Extension of Nuclear Power Plants, October 27–28, 1998, Vienna.

[16] GRUHL, H.H., KALVERBOER C., Backfitting Borssele, Nuclear Engi. Int., Dec. 1997.

[17] US–RUSSIAN JOINT PARALLEL NUCLEAR ALTERNATIVES STUDY (JPNAS) FOR RUSSIA, Final Report prepared for United States Department of Energy and Ministry of Atomic Energy of the Russian Federation (1995).

[18] US–RUSSIAN JOINT PARALLEL NUCLEAR ALTERNATIVES STUDY (JPNAS) FOR RUSSIA, Appendix I (JEPAS Data Set) to the Final Report prepared for United States Department of Energy and Ministry of Atomic Energy of the Russian Federation (1995).

[19] NIGMATULLIN, R., NULTON, J.D., SHEBERSTOV, A., US/Ukraine Evaluation of Energy Options to Replace the Chernobyl Nuclear Plant, Report approved by GOSKOMATOM of Ukraine, Ministry of Energy of Ukraine, US Department of Energy (1994).

[20] US ENERGY INFORMATION ADMINISTRATION, An Analysis of Nuclear Power Plant Operating Costs: A 1995 Update, Rep SR/OIAF/95-01, US EIA (1995).
[21] INTERNATIONAL ATOMIC ENERGY AGENCY, International Assistance to Upgrade the Safety of Soviet-designed Nuclear Power Plants: Selected Activities in Eastern and Central Europe and the Countries of the Former Soviet Union: An Overview, IAEA, Vienna (1993).
[22] INTERNATIONAL ATOMIC ENERGY AGENCY, The Safety of WWER-440 Model 230 Nuclear Power Plants: An Overview and Major Findings of the IAEA Extrabudgetary Programme on the Safety of WWER-440 Model 230 Nuclear Power Plants, IAEA, Vienna (1992).
[23] INTERNATIONAL ATOMIC ENERGY AGENCY, Ranking of Safety Issues for WWER-440 Model 230 Nuclear Power Plants: Report of the IAEA Extrabudgetary Programme on the Safety of WWER-440 Model 230 Nuclear Power Plants, IAEA-TECDOC-640, Vienna (1992).
[24] WORLD ASSOCIATION OF NUCLEAR OPERATORS, Safety Improvements of Operating WWER-440/230 Plants, WANO (1994).
[25] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power Reactors in the World, Reference Data Series No. 2, IAEA, Vienna (1998).
[26] INTERNATIONAL ATOMIC ENERGY AGENCY, Design Basis and Design Features of WWER-440 Model 213 Nuclear Power Plants: Reference Plant: Bohunice V2 (Slovakia), Report of the IAEA Technical Co-operation Project RER/9/004 on Evaluation of Safety Aspects of WWER-440 Model 213 Nuclear Power Plants, IAEA-TECDOC-742, Vienna (1994).
[27] INTERNATIONAL ATOMIC ENERGY AGENCY, Selected Safety Aspects of WWER-440 Model 213 Nuclear Power Plants: Final Report of the IAEA Project on Evaluation of Safety Aspects for WWER-440 Model 213 Nuclear Power Plants, IAEA, Vienna (1996).
[28] WORLD ASSOCIATION OF NUCLEAR OPERATORS, Safety Upgrading of the WWER-440/213 Reactors, WANO (1994).
[29] WORLD ASSOCIATION OF NUCLEAR OPERATORS, Improvement of WWER-1000 Nuclear Power Plant Safety, WANO (1994).
[30] WORLD ASSOCIATION OF NUCLEAR OPERATORS, Improvement of RBMK Nuclear Power Plant Safety, WANO (1994).
[31] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment of Proposed Improvements to RBMK Nuclear Power Plants: Report of the IAEA Extrabudgetary Programme on the Safety of RBMK Nuclear Power Plants, IAEA-TECDOC-694, Vienna (1993).
[32] US ENERGY INFORMATION ADMINISTRATION, Annual Energy Outlook 1998 with Projections to 2020, Rep. DOE/EIA-0383 (98), US EIA (1997).
[33] NUCLEAR ENERGY INSTITUTE, "Duke Power's decision to extend electricity production at Oconee nuclear station: good news for consumers, environment", press release of July 6, 1998 (1998).
[34] CHEBESKOV, A., Institute of Physics and Power Engineering (IPPE), "Status of nuclear power in Russia", paper presented at the IAEA Consultancy Meeting on Nuclear Capacity Projections, April 22–23, 1998, IAEA, Vienna (1998).
[35] NUKEM Market Report, May 1998 (1998).
[36] INTERNATIONAL ATOMIC ENERGY AGENCY, Methodology for the Management of Ageing of Nuclear Power Plant Components Important to Safety, Technical Reports Series No. 338, IAEA, Vienna (1992).
[38] FOREST, L.R., DEUTSCH, T.R., SCHENLER, W.W., "Cost savings from extended life of nuclear plants", Safety Aspects of the Ageing and Maintenance of Nuclear Power Plants (Proc. Int. Symp. Vienna, –1987), IAEA, Vienna (1988).
[39] HONG, S.-Y., JEONG, I.-S., JIN, Y.E., Recent strategy and progress in Korean nuclear PLIM program, Nuclear Engineering and Design **174** (1997) 25–32.
[40] KOREA ELECTRIC POWER COMPANY, Nuclear Power Plant Lifetime Management Study (1), Rep. TR.92NJ10.96.01, KEPCO (1996).

[41] LUKACS, G., MITTLER, M., Nationale und Internationale Kostenaspekte bei Stillegung und Ruckbau Kerntechnischer Anlagen, paper presented at VDI Conference, September 1996 in Schwerin, Germany (1996).
[42] STONE & WEBSTER WORLDWIDE ENGINEERING, Decommissioning and Radioactive Waste Disposition Feasibility Study: Kozloduy Nuclear Power Plant Units 1–4, National Technical Information Service, US Department of Commerce (1996).
[43] DELCHEVA, T., "Results from the feasibility studies on decommissioning NPP Kozloduy units No. 1&2", paper presented at a Technical Co-operation Workshop on Planning and Management of Decommissioning for WWER-type NPPs, RER/9/034, Balatonfured, Hungary, November 1996 (1996).
[44] DELCHEVA, T., "A short description of approach to decommissioning of Kozloduy NPP — Units 1&2", paper presented at IAEA Consulants Meeting on the Review of Cost Estimates for Nuclear Power Plant Decommissioning, October 29–30, 1998, Vienna.
[45] STEPANEK, L., personal communication (1998).
[46] KUKKOLA, T., "Decommissioning cost estimate of the Loviisa power plant", paper presented at International Seminar on Decommissioning Policies for Nuclear Facilities in Paris, 1991 (1991).
[47] KUKKOLA, T., "Decommissioning cost estimate of the Loviisa power plant", Decommissioning Policies for Nuclear Facilities (Proc. Int. Seminar, 1991), NEA/OECD, Paris (1992).
[48] RYHÄNEN, V., "Policy, technical plan and cost estimate for the decommissioning of the Olkiluoto BWR units", Decommissioning Policies for Nuclear Facilities (Proc. Int. Seminar, 1991), NEA/OCDE, Paris (1992).
[49] PFLUGRAD, K., PETRASCH, P., ROGER, J., "CEC studies on decommissioning costs", Decommissioning Policies for Nuclear Facilities (Proc. Int. Seminar, 1991), NEA/OECD, Paris (1992).
[50] COMMISSION OF THE EUROPEAN COMMUNITIES, Decommissioning Costs of Light Water Nuclear Power Plants in Germany from 1977 to Date, Rep. EUR 14798en, CEC DG XIII, Luxembourg (1993).
[51] ANDERSON, S.O., HEIBEL, R., VARLEY, G., RUSCH, C., An Evaluation of Cost Estimates of Nuclear Power Reactor Decommissioning in Sweden, Germany and the United States, Rep. 95:65, Statens Kärnkraftinspektion (1995).
[52] JEONG, I.-S., "Nuclear power plant decommissioning in Korea", paper presented at IAEA Consulants Meeting on the Review of Cost Estimates for Nuclear Power Plant Decommissioning, October 29–30, 1998, Vienna.
[53] KOREA ELECTRIC POWER RESEARCH INSTITUTE, Establishment of Optimum Decommissioning Plan in Korea and Development of a Site Specific Decommissioning Cost Evaluation Technology, Rep. KEPRI-93N-J03, KEPRI (1995).
[54] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, Radioactive Waste Management in Lithuania: Preliminary Assessment of Costs for the Nuclear Back-End, SKB (1995).
[55] BYLKIN, B.K., ZVERKOV, Yu.A., ZIMIN, V.K., Technical and Economic Assessments of Planned and Early Decommissioning of First-Generation Nuclear Power Plants in Russia, Atomic Energy **78–4** (1995).
[57] BYLKIN, B., ZVERKOV, Yu., "Description of main provisions of decommissioning strategy to Leningrad Unit 1 with first generation RBMK-1000 reactor", paper presented at IAEA Consulants Meeting on the Review of Cost Estimates for Nuclear Power Plant Decommissioning, October 29–30, 1998, Vienna.
[58] HLADKY, E., "Short description of approach to decommissioning of V1 and V2 NPP in Slovak Republic", paper presented at IAEA Consulants Meeting on the Review of Cost Estimates for Nuclear Power Plant Decommissioning, October 29–30, 1998, Vienna.
[59] BIERSCHBACH, M.C., KONZEK, G.J., MCDUFFIE, P.N., SMITH, R.I., Revised Analyses of Decommissioning for the Reference Boiling Water Reactor Power Station, Rep. NUREG/CR-6174, US Nuclear Regulatory Commission (1994).

[60] BIERSCHBACH, M.C., KONZEK, G.J., MCDUFFIE, P.N., SMITH, R.I., Revised Analyses of Decommissioning for the Reference Boiling Water Reactor Power Station, Rep. NUREG/CR-5884, US Nuclear Regulatory Commission (1994).

[61] US ENERGY INFORMATION ADMINISTRATION (US EIA), Nuclear Power Generation and Fuel Cycle Report 1996, US EIA (1996).

[62] INTERNATIONAL ATOMIC ENERGY AGENCY , Decommissioning of Nuclear Facilities: Decontamination, Disassembly and Waste Management. Technical Reports Series No. 230, IAEA, Vienna (1983).

[63] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Nuclear Facilities, IAEA-TECDOC-179, Vienna (1975).

[64] INTERNATIONAL ATOMIC ENERGY AGENCY, Factors Relevant to the Decommissioning of Land-based Nuclear Reactor Plants, Safety Series No. 52, IAEA, Vienna (1980).

[65] HEWLETT, J., US Energy Information Administration, personal communication (1998).

[66] US–RUSSIAN JOINT PARALLEL NUCLEAR ALTERNATIVES STUDY (JPNAS) FOR RUSSIA, Final Report prepared for United States Department of Energy and Ministry of Atomic Energy of the Russian Federation (1995), Appendix C.

[67] BYLKIN, B.K., et al., Report of the Joint US/Russian Study on the Development of a Decommissioning Strategy Plan for RBMK-1000 Unit #1 at the Leningrad Nuclear Power Plant prepared by Pacific Northwest National Laboratory (USA), Brookhaven National Laboratory (USA), Russian Research Centre "Kurchatov Institute" (Russian Federation) for the US Department of Energy and the Ministry of Atomic Energy of the Russian Federation (1997).

[68] EMRIT, R., MILSTEAD, W., PITTMAN, J., RIGGS, R., A Prioritization of Generic Safety Issues, Rep. NUREG-0933, US Nuclear Regulatory Commission (1996).

[69] INTERNATIONAL ATOMIC ENERGY AGENCY, Wien Automatic System Planning Package (WASP): A Computer Code for Power Generating System Expansion Planning. Version WASP-III Plus. User's Manual. Volumes 1–2, IAEA Computer Manual Series No. 8, IAEA, Vienna (1995).

[70] ONTARIO HYDRO, A Strategic Planning Input to 1996—1999 Business Planning. Corporate Integrated Resource Planning, Ontario Hydro (1995).

[71] US–RUSSIAN JOINT ELECTRIC POWER ALTERNATIVES STUDY (JEPAS), An Investment Program for Russia, Final Report prepared for Energy Policy Committee of the US–Russia Joint Commission on Economic and Technical Co-operation (1995).

[72] KALVERBOER, C., EPZ, personal communication (1998).

[73] HLADKY, E., DECOM Slovakia, Ltd., personal communication (December 1998).

[74] HLADKY, E., BLAZEK, J., POLAK, V., TIMULAK, J., "Decommissioning Methods and technologies in the Slovak Republic", paper presented at a Technical Co-operation Workshop on Planning and Management of Decommissioning for WWER-type NPPs, IAEA, Vienna (1995).

[76] INTERNATIONAL ATOMIC ENERGY AGENCY, Applicability of the Leak Before Break Concept: Report of the IAEA Extrabudgetary Programme on the Safety of WWER-440 Model 230 Nuclear Power Plants, IAEA-TECDOC-710, Vienna (1993).

[77] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of the Leak Before Break Concept: Report of the IAEA Extrabudgetary Programme on the Safety of WWER-440 Model 230 Nuclear Power Plants, IAEA-TECDOC-774, Vienna (1994).

ABBREVIATIONS

ANPP	Armenian NPP
BWR	boiling water reactor
CCGT	combined-cycle gas turbine plant
CHP	combined heat and power generating plant
CPI	consumer price index
EIA	Energy Information Administration
GCR	gas cooled reactor
GDP	gross domestic product
HPP	hydraulic power plant
HPS	hydraulic power station
HWR	heavy water reactor
I&C	instrumentation and control
IMF	International Monetary Fund
INES	International Nuclear Event Scale
LLW	low level radioactive wastes
LWGR	light water-moderated, graphite cooled reactor
n.c.u.	national currency units
NEA	Nuclear Energy Agency (of the OECD)
NEK	National Electric Company of Bulgaria
NRC	Nuclear Regulatory Commission (USA)
NSSS	nuclear steam supply system
O&M	operation and maintenance
OECD	Organisation for Economic Co-operation and Development
PLEX	plant lifetime extension
PLIM	plant lifetime management
PPI	producer price index
PSA	probabilistic safety assessment
PWR	pressurized water reactor
RPV	reactor pressure vessel
SG	steam generator
T&D	transmission and distribution
TPP	thermal power plant
TPS	thermal power station
WWER	water cooled, water moderated energy reactor

CONTRIBUTORS TO DRAFTING AND REVIEW

Bertel, E.	OECD Nuclear Energy Agency
Bylkin, B.	Russian Research Centre "Kurchatov Institute", Russian Federation
Davidova, I.	Czech Power Company (ČEZ), Czech Republic
Delcheva, T.L.	National Electric Company (NEK), Bulgaria
Friedmann, P.	SIEMENS AG, Germany
Gevorgyan, A.	Ministry of Energy of Armenia, Armenia
Gueorguiev, B.	International Atomic Energy Agency
Hewlett, J.	Department of Energy, United States of America
Hladky, E.	DECOM Slovakia, Ltd, Slovakia
Jeong, I-S.	Korea Electric Power Research Institute, Republic of Korea
Kalverboer, C.	EPZ, Netherlands
Kanev, D.	National Electric Company, Bulgaria
Kidd, S.	Uranium Institute, London
Kononov, S.	International Atomic Energy Agency
Langlois, L.M.	International Atomic Energy Agency
Laraia, M.	International Atomic Energy Agency
Marjanovic, M.	Université Stendal, France
Miskinis, V.	Lithuanian Energy Institute, Lithuania
Pakan, M.	Atomic Energy of Canada Ltd, Canada
Rogner, H.H.	International Atomic Energy Agency, Vienna
Schricker, W.	SIEMENS AG, Germany
Spiegelberg-Planer, R.	International Atomic Energy Agency
Vera, I.	OECD Nuclear Energy Agency
Yamagata, H.	OECD Nuclear Energy Agency
Zimin, V.	All-Russian Institute of Atomic Power Stations, Russian Federation
Zverkov, Yu.	Russian Research Centre "Kurchatov Institute", Russian Federation

Consultants Meetings

Vienna, Austria: 27–28 October 1998; 29–30 October 1998