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Nuclear Power Plant Life Management and Longer-term Operation

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NUCLEAR ENERGY AGENCY
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The mission of the NEA is:

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

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

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

FOREWORD

Plant life management for the extended, longer-term operation (LTO) of nuclear power plants is one generally cost-effective means for maintaining or increasing the contribution of nuclear energy to electricity supply. Nuclear energy is an important component of energy mixes in many OECD countries. Policy makers and the public are paying more and more attention to its potential role in reducing the risks of global climate and ensuring better security of energy supply. Properly managing the systems, structures and components (SSCs) of nuclear power plants, and thereby ensuring their safe and reliable LTO, can potentially provide a bridge between the present generation of reactors and advanced energy systems, be they nuclear or non-nuclear.

Safety is of paramount importance in the operation of nuclear power plants. The safety requirements of existing plants were sufficiently stringent at the time they were built to ensure a considerable amount of conservatism in the design. This conservatism, together with feedback from operating experience, improved analytical techniques and training of personnel, allows the safe and reliable longer-term operation of nuclear power plants, though proper regard must be given to the possibility of unknown ageing phenomena.

LTO of existing nuclear power plants offers significant economic advantages. Extending the life of a major generating asset avoids the need for immediate investment in new generating capacity. The capital costs of plant life management activities and plant upgrading for LTO are generally much smaller than those required to build any type of replacement capacity.

The study presents statistics and current trends relating to the extended, longer-term operation of nuclear power plants. It investigates the technical, economic and environmental advantages and challenges associated with nuclear power plant life management and LTO.

Acknowledgements

This study was carried out by an ad hoc group of experts chaired by Dr. Tamás J. Katona, Hungary, and Mr. Eric van Walle, Belgium. The Secretariat would like to acknowledge the efficient leadership of the co-Chairmen and the valuable contributions from the members of the group.

TABLE OF CONTENTS

Appendices:

EXECUTIVE SUMMARY

Many existing nuclear power plants (NPPs) entered operation in the 1970s, most with an originally designed lifetime of up to 40 years. As the end of these original lifetimes has drawn closer there has been increasing interest in the possibility of extending the operating lives of these plants. Such extended operation and the steps taken to prepare for it are termed as plant life management (PLiM) and long-term operation (LTO). The degree of success in achieving LTO with this generation of plants will have a significant impact on installed nuclear capacity during the period from 2010 to 2020 and beyond.

The Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) of the OECD Nuclear Energy Agency (NEA) decided in early 2005 that a report on impact of PLiM and LTO should be prepared, to follow up on the last report on this topic which was issued in 2000. An ad hoc meeting was held to launch the project in April 2005, which resulted in the creation of an ad hoc Expert Group on Nuclear Power Plant Life Management. The Group held three meetings in September 2005, February and May 2006.

The main objective of the study has been to review and analyse the impacts of lifetime extension on fuel cycle and waste management requirements, on the economics of nuclear energy, on knowledge management and preservation, and more broadly on the future of nuclear energy in OECD member countries. Its scope includes technical, economic, social and strategic issues raised by PLiM and LTO in countries planning an extended reliance on nuclear energy, in countries wishing to keep the nuclear option open, and in countries having decided a progressive phase-out of nuclear energy. OECD member countries in each of these categories were represented on the Expert Group, as well as one member country without a nuclear programme.

A questionnaire (see Appendix B) was completed by each participating country to provide the necessary background information for the study. The group found that, while the PLiM and LTO of each plant must be considered individually in the light of its particular condition and economic circumstances, the general conclusion from studies carried out in several member countries is that, for most reactor types, there are no significant technical challenges known which would limit plant lifetime to less than 50 to 60 years.

The Expert Group concluded that in countries where NPPs are in operation LTO has several potential advantages for the owners of NPPs, as well as for the wider society.

The main conclusions are:

- The principal advantages of PLiM for LTO are economic, in that extending the life of a major generating asset avoids the need for immediate investment in new generating capacity. The capital costs of PLiM for LTO will be much smaller than investment in any type of replacement capacity, although there might be a need for some additional investment in plant upgrading. With nuclear fuel costs being generally lower and more stable than fossil fuel costs, this means that LTO can be expected to provide electricity at a lower cost than any other available option, which has a clear benefit to the national economy.
- In addition, LTO of existing NPPs contributes to security and stability of energy supply and to maintaining the diversity of energy sources.
- Furthermore, LTO can provide nuclear energy without the significant environmental impacts that would be created by certain alternative power generation options (notably CO_2 emissions). Most countries with operating NPPs consider that nuclear energy contributes to the sustainability of their overall energy supply system, in that it minimises the long-term and irreversible impacts on the environment of meeting current energy demand.

Safety is of paramount importance in the operation of an NPP. Existing NPPs were designed and constructed according to the requirements and standards of the time. These requirements were sufficiently stringent to ensure a considerable amount of conservatism in the design. Operating experience, improved analytical techniques and training of personnel mean that this conservatism can be allowed for in considering the safety of LTO, though proper regard must be given to the possibility of unknown ageing mechanisms.

Overall, the Expert Group concluded that LTO can potentially provide a bridge between the present generation of NPPs and future generations of power plants – either nuclear or non-nuclear. With 85% of OECD nuclear capacity already over 15 years old, if nuclear capacity is not to decline significantly then LTO of existing NPPs will be necessary to cover the period until new generations of plants can enter operation.

INTRODUCTION

*"Expect the unexpected, vigilance through the monitoring programmes, if something happens, recognise it."**

Nuclear power plants (NPPs) are designed and constructed to achieve very high standards of safety and efficiency when they enter service, in accordance with the state of knowledge and the available technology at the time. Their design, construction and operation are subject to stringent regulation and licensing requirements, which incorporate a considerable degree of conservatism in safety and operating margins. During their operating lifetimes extensive monitoring and maintenance programmes are performed with the aim of ensuring that levels of safety and operational reliability are maintained.

During the years and decades after a plant enters operation there will inevitably be numerous technological advances, and experience will be gained from operation of the plant and of other similar plants. These will allow the plant to be upgraded during the course of its operating life, to enhance safety levels and improve operating efficiency and performance. The latter may include increasing electricity output, reducing operation and maintenance (O&M) costs and fuel consumption, and improving plant reliability (and thus raising capacity factors).

This process of plant life management (PLiM) is also carried out with a view to maintaining and renewing the plant's systems, structures and components (SSCs) to maximise its operating life. PLiM is the integration of ageing management, including obsolescence, and economic planning over the remaining operating term of a nuclear power plant to optimise the operation, maintenance, reliability and service life of SSCs, maintain acceptable levels of

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* David Norfolk.

performance, and maximise return on investment, while maintaining safety. In this context:

- *Ageing* is defined as the continuous time dependent degradation of SSC materials due to normal service conditions, which include normal operation and transient conditions (postulated accident and post-accident conditions are excluded).
- *Ageing management* (AM) is defined as engineering, operation and maintenance actions to ensure ageing degradation of SSCs remains within acceptable limits.
- *Ageing management programme* (AMP) is defined as any programme or activity that adequately manages the effects of ageing on SSCs (e.g. maintenance programme, chemistry programme, inspection or surveillance activities, etc.).

For many operating nuclear power plants, it has been demonstrated to the satisfaction of the relevant regulators that they are capable of safe and efficient operation for a significantly longer period than was envisaged when they were designed, with lifetimes of 50 to 60 years being likely in many cases. Such long term operation (LTO) can be defined as operation beyond the initial time frame set forth in the design, standards, licence, and/or regulations, which is justified by safety assessments considering life limiting processes and features of SSCs.[1]

With many existing nuclear plants having entered operation in the 1970s, often with an originally designed lifetime of 30 or 40 years, there has been increasing interest in the extent to which LTO will become a reality for plants of this generation. With relatively few new nuclear plants having entered operation in the 1990s and later, a significant proportion of existing nuclear capacity will become 40 years old between 2010 and 2020. The degree of success in achieving LTO with these plants will have a significant impact on installed nuclear capacity over this period.

This indicates the importance of PLiM of existing nuclear plants for LTO. A sharp fall in nuclear generation over the next 10 to 15 years would require large scale additional investment in replacement generating capacity. This would clearly impact national electricity markets, but it would also have a wider impact on fossil fuel markets. It could be expected to increase demand for natural gas and coal in particular, as generation from these sources would be

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[1] International Atomic Energy Agency (2006), “Extrabudgetary Programme on Safety Aspects of Long Term Operation of Water Moderated Reactors”, IAEA-EBP-LTO-03, Standard Review Process.

among the most likely replacements for nuclear power within this timeframe. LTO of existing nuclear plants could thus help limit the demand for fossil fuels and the consequences of their use, including CO_2 emissions.

The Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) of the OECD Nuclear Energy Agency (NEA) established an Expert Group on Nuclear Power Plant Life Management to prepare this report on the status of PLiM programmes in OECD countries and the issues which will affect LTO of existing nuclear plants. It is intended that this will provide an up-to-date account for the use of national policy makers based on a consensus view of technical experts drawn from NEA member countries. This includes countries already implementing PLiM programmes for LTO, those where such programmes are still under consideration, and also one country with no NPPs.

It should be noted that there are certain pre-conditions which must exist before a PLiM programme leading to LTO can be considered as an option for any NPP. These include meeting all applicable safety and environmental requirements, as well as being able to operate in an efficient and economic manner in the prevailing electricity market. The report does not discuss these aspects in detail, but rather focuses on the specific issues which must be considered for PLiM programmes leading to LTO.

1. THE POTENTIAL AND VALUE OF PLANT LIFE MANAGEMENT

1.1 Safety aspects of PLiM

In the operation of nuclear power plants (NPPs), safety always has to be the prime consideration. Plant operators and regulators must always ensure that the high level of safety of NPP is maintained, and where possible enhanced, during the plant operating lifetime.

The design and construction processes for NPPs include extensive licensing requirements to ensure that plants entering operation have the highest levels of safety consistent with current technology and knowledge at the time. Over the lifetime of a plant, there will of course be technological advances and improved techniques in, for example, fully-qualified in-service inspection, on-line monitoring systems and qualification of equipment. In addition, experience will be gained from operating the plant and from exchanges with operators of similar units.

Both these effects allow further safety improvements to be made by means of backfitting systems and replacing components during the operating lifetime. In some cases these upgrades may be required by regulators. For example, after the accident at the Three Mile Island NPP, the US Nuclear Regulatory Commission (NRC) required all NPPs in the United States to implement upgrades, and these were also required by regulators in other counties. In other cases, upgrades may be made in the course of repairs and maintenance carried out by the operator under its own programmes, including upgrades following a periodic safety review (PSR).

PLiM programmes are designed to maintain a high level of safety, optimise the operation, maintenance and service life of SSCs, and maintain an acceptable level of performance. The upgrading of SSCs with more up-to-date technology and processes will often result in improved performance and therefore enhanced safety levels. The considerable advances in computer technology over recent decades, for example, have resulted in the availability of enhanced instrumentation and control systems for NPPs.

One of the principal aims of PLiM is to extend the operating lifetime of the plant, while ensuring that it meets safety requirements. Existing NPPs were generally designed and built with a considerable degree of conservatism in the safety and operating margins, in accordance with the state of knowledge at the time (there was then little or no experience of the longer term operation of large NPPs). Operating experience, coupled with improved analytic techniques developed as a result of technological advances (particularly in computer technology), has allowed the extent of the conservatism in operating margins to be better assessed, which provides the possibility for LTO. However, it must also be recognised that operating margins also contribute to safety, and that there are always uncertainties and the possibility of unexpected events.

Another important aim of PLiM programmes is to improve the operating performance of NPPs. This can result from increasing the power output, which may be partly achieved by re-assessing the plant's operating margins, while ensuring continuing compliance with all licensing and regulatory requirements.

In Sweden, for example, all operating NPPs are undergoing a programme to increase their power output by a variety of different methods. At the same time, the regulator SKI is requiring safety levels in the older plants (which are over 30 years old) to be upgraded to more modern standards, making specific provision for their extended lifetime to 50 years or more.

Power uprating under PLiM programmes may also make additional investments to extend the life of the plant more attractive. However, in order to operate the reactor at a power level higher than originally licensed, permission will be required from the reactor licensing authority, as well as from the relevant environmental authorities. In addition, the possibility of degradation of SSCs from power uprating should be assessed to facilitate understanding of the impacts before such uprating is implemented. It is possible that power uprating could result in accelerated ageing of some components, some of which would then require earlier replacement. To avoid conflicts between power uprating and extension of operating life, in some cases a balanced solution will need to be found. This will need to take into account economic aspects, while recognising that safety is the first priority.

The main concerns for safety in the context of extending the lifetime of NPPs occurs with those few critical components which cannot or will not be replaced. To establish the possibility of extending the lifetime of an existing plant beyond the original design lifetime, it must be demonstrated that these components will be able to meet the safety requirements for the extended life which is envisaged. An important part of PLiM related research and development work is aimed at managing and slowing down the ageing process in these components. This is discussed further in Section 1.2 below.

On the other hand, some major components which were not originally expected to require replacement during the operating lifetime (notably steam generators) have in fact needed replacing in a significant number of plants. This has required replacement techniques to be developed for components originally considered non-replaceable, thus helping to open the way to the refurbishment of plants for longer lifetimes.

1.2 Technical limitations

The great majority of SSCs in any NPP are capable of being replaced. Some may be replaced routinely during normal maintenance procedures. The replacement of others may involve significant investment and extended plant outages, and may be expected to take place only once (if at all) during a plant's lifetime. For the purpose of managing the lifetime these SSCs they can be further classified as those which are "critical" and "non-critical" for continued safe and efficient operation of the plant.

Non-critical SSCs are those which can be allowed to fail without causing concerns for safety or reliability of the plant. In most cases, they can simply be replaced or repaired when a fault is detected.

Critical SSCs, on the other hand, include those which would cause safety or reliability issues if they were to fail, leading to an unplanned outage. Preventive and predictive maintenance programmes are designed to ensure that such SSCs are replaced or repaired before they fail.

However, there are a few major critical SSCs the replacement of which is expected to be unfeasible for technical or economic reasons. That is, it would either present too great a technical challenge, and/or it would simply be too costly to be justified by the remaining economic value of the plant (in terms of future electricity production). These latter situations will ultimately limit the plant's operating lifetime.

Critical SSCs generally include the reactor pressure vessel, and may also include some reactor vessel internal components, parts of the primary coolant circuit, and some containment structures. Although the replacement of some of these SSCs may be possible from a technical point of view, for an older plant it may not be justified economically.

Indeed, for any given plant, the number of items considered economically unfeasible to replace will tend to increase as the plant ages. This is because the feasibility of replacement depends on the expected remaining lifetime of the NPP after the replacement. As this remaining lifetime becomes shorter, the period available to recoup the investment in the replacement will at some point become too short. For many plants, steam generator replacement will be in this category.

However, it should also be noted that technological advances and the development of new engineering techniques have resulted in the re-classification of some components which were previously considered non-replaceable. These advances have made the replacement of almost all components apart from the pressure vessel and some containment structures at least technically feasible for many plants. In this respect, there may be significant differences between different reactor designs.

In developing PLiM programmes, plant owners generally categorise all SSCs in one of the categories described above (non-critical, critical and replaceable, or critical and non-replaceable). A different approach needs to be taken for each category.

For SSC items in the critical and replaceable category, PLiM programmes include studies to optimise the maintenance and replacement process to ensure that the plant operates at a high level of safety and reliability. This includes ageing management where appropriate. The priority for research and development has generally been given to those items which most directly impact safety levels. However, attention is also focussed on those items which have more bearing on the reliability of plant operation, as these may directly affect load factors and hence the plant’s economic performance.

For the non-replaceable SSCs, the emphasis is on ageing management, to ensure that the components continue to meet safety and reliability standards for the desired lifetime of the plant. Clearly, the premature ageing of any such component could put the future of the entire plant at risk.

Ageing management of non-replaceable components has been the subject of considerable research and development efforts for many years, and this effort is continuing. Much of this work has taken place in the framework of international cooperative programmes, which are discussed further in Chapter 5.

A previous NEA report on PLiM[1] noted the following topics which were the subject of research and development relevant to PLiM:

- Preventive and corrective maintenance (e.g. water chemistry, pressure vessel annealing, replacing core internals and the reactor vessel head).
- Ageing and degradation mechanisms and evaluation (e.g. irradiation embrittlement, the effects of corrosion, erosion, fatigue and stress, including synergy effects).
- Monitoring, surveillance and inspection (e.g. fatigue monitoring, non-destructive testing).
- Maintenance optimisation (e.g. risk-based analysis).

The ageing of non-replaceable critical SSCs represents the main limitation on the extension of NPP operating lifetime. When a plant owner/operator is considering the feasibility of extending its operating lifetime, the crucial question is whether the non-replaceable SSCs will (with the use of existing ageing management techniques) remain within the necessary margins for safe and reliable operation for the lifetime envisaged.

Studies which have been carried out in several NEA member countries have indicated that, for most designs, reactor pressure vessels can remain in safe operation for a period of at least 50 to 60 years. For a few specific VVER plants annealing has been implemented (e.g. Loviisa in Finland) or may be considered (e.g. Paks unit 1 in Hungary), to reduce the brittle fracture transition temperature.

Indeed, the general conclusion from studies that have been carried out under PLiM programmes in several NEA member countries is that, for most reactor types, there are no significant known technical challenges which would prevent nuclear plant lifetimes being extended to 50 or 60 years.

However, it must always be recognised that there is the possibility of unknown ageing mechanisms, as well as the unexpected development of known ageing mechanisms, emerging during LTO. Provisions in safety margins should be kept to cover such possibilities. In addition, the impact of changes in operating conditions (e.g. due to power uprating), which may cause unanticipated cliff-edge effects, needs to be considered carefully.

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[1] NEA (2000), "Status Report on Nuclear Power Plant Lifetime Management", NEA/SEN/NDC(2000)6, OECD, Paris.

Operators and regulators need to be prepared for such developments, and to ensure that systematic monitoring of the degradation of critical components and re-assessment of the associated risks continues throughout the period of extended operation. Changes in inspection and risk assessment methods should also be considered. Power uprates may lead to reduced intervention time frames in the case of beyond design basis accidents, which may require additional mitigation measures. Ageing processes resulting in cumulative and synergetic effects should be carefully analysed.

1.3 Implications for nuclear capacity assets

Nuclear power plants have low operation and maintenance (O&M) costs compared with other source of power generation, but they are more capital-intensive than other power plants. Since NPPs represent major capital assets, PLiM programmes which can maximise power output throughout their operating life, and which can also result in that lifetime being extended, can be especially attractive for plant owners. PLiM is essentially a process of maximising the return on the initial investment in the plant.

At any point in its operating life, a nuclear plant can be valued according to the expected electricity output from its remaining years of operation, less its future O&M costs (including fuel costs) and the costs of any required safety upgrades and replacement of obsolete or worn-out equipment. So long as a plant retains a positive value it remains an asset to its owners, and operation is likely to continue. Of course, LTO also has wider benefits to the economy and society as a whole, in the context of a national energy strategy.

The introduction of PLiM programmes in several NEA member countries over recent years has resulted in improved performance by many nuclear plants (evidenced by improved availability and load factors), as well as power uprates and extensions in expected operating lives. This has greatly enhanced the value of nuclear capacity assets in many cases. From 1990 to 2004, global nuclear electricity production increased from 1 901 to 2 619 TWh (an increase of almost 40%). As shown in Figure 1, of this growth, 57% came from increased availability of NPPs.

At present, there are 349 nuclear power plants in operation in OECD member countries. The age distribution of these plants is rather uneven. There are 135 operating plants (39%) which are over 25 years old. On the other hand, only 44 plants (13%) are 15 years old or less (Figure 2). This means that nearly half of existing NPPs entered operation within one decade (the 1980s) and are now (in 2005) in the range of 16 to 25 years old.

Figure 1. Contributions to nuclear electricity generation growth 1990-2004

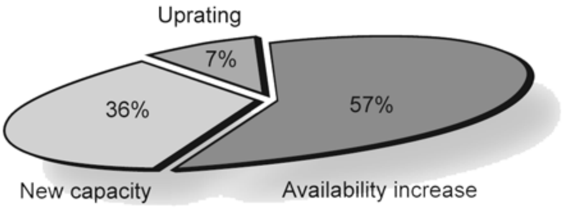


Figure 2. Number of reactors by age

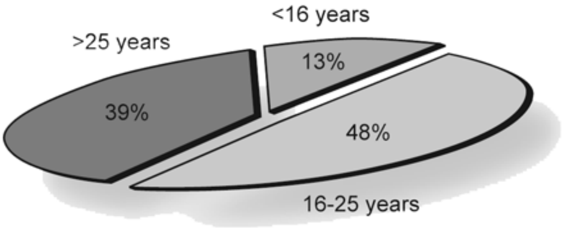
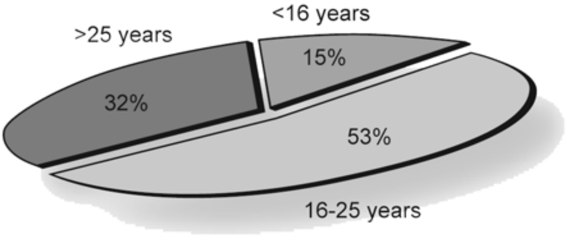


Figure 3. NPP capacity by age



As the older plants generally have lower generating capacities than later units, the situation is slightly different when we look at the age distribution of nuclear capacity. About 165 GWe (53%) of the present OECD total nuclear generating capacity of 315 GWe is attributable to plants which entered operation in the 1980s, while a further 99 GWe (32%) is from plants over 25 years old. Only 15% of OECD nuclear capacity is 15 years old or less (Figure 3).

This situation is even more acute in the case of some individual countries. Both the United Kingdom and the United States have over 40% of their nuclear capacity over 25 years old, while Finland has 50% and Switzerland 64% in this age bracket. Several countries have no capacity at all which is less than 16 years old. Of the major nuclear countries, only Japan and Korea have a relatively balanced age distribution. A breakdown of the figures for each country is shown in Table 1.

Table 1. Age distribution of operating nuclear power plants and nuclear power capacity in OECD members countries (as of 2006)*

Name	<16 years		16-25 years		>25 years	
	Number of reactors	Net capacity [MWe]	Number of reactors	Net capacity [MWe]	Number of reactors	Net capacity [MWe]
Belgium			4	4 037	3	1 787
Canada	2	1 762	12	8 307	4	2 530
Czech Rep.	2	1 705	4	1 663		
Finland					4	2 676
France	7	9 930	38	41 520	14	11 913
Germany			10	13 263	7	7 076
Hungary			4	1 755		
Japan	16	17 003	18	15 917	21	14 673
Korean Rep.	11	9 590	8	6 664	1	556
Mexico	1	655	1	655		
Netherlands					1	449
Slovakia	2	810	2	816	2	816
Slovenia			1	656		
Spain			7	7 000	1	446
Sweden			4	4 209	6	4 701
Switzerland			1	1 165	4	2 055
United Kingdom	1	1 188	10	5 970	12	4 694
United States	2	2 245	46	51 296	55	44 604
Total	44	44 888	170	164 893	135	98 976

* Source: IAEA, "Power Reactor Information System", Update 2006.

These figures illustrate the importance of life extension for nuclear power plants. If all plants were assumed to have an operating lifetime of just 40 years, the rate of plant closures and capacity reductions in the decade of the 2020s would be very steep. This would require large-scale construction of new capacity (either nuclear or non-nuclear), which would require huge capital investments. This would be in addition to those investments needed to meet rising electricity demand and to replace older and more polluting fossil-fuel generating plants.

The life extension of a significant proportion of the existing nuclear fleet will allow replacement capacity to be phased in over a longer period, spreading the investments required and allowing additional time for the development of more technologically advanced alternatives (both nuclear and non-nuclear).

The potential of life extension differs between countries, mainly due to differences in reactor types and nuclear plant designs. Some older plants may be less amenable to life extension, because of technical limitations in their design or simply because their generating capacity is too small to justify the additional investment required. Table 2 summarises the present plans for life extension and capacity uprates in selected OECD member countries.

Indeed, a number of the oldest plants have already closed or are expected to close after operating lifetimes of less than 40 years. For example, the oldest operating plant in Spain, a PWR with a capacity of just 160 MWe, was closed in 2006 after 38 years of operation. Meanwhile, plans are being made to extend the lives of larger, newer plants in that country to 60 years. These plans are unaffected by the moratorium on the construction of new nuclear plants in Spain.

Power uprating of an NPP is defined as the process of increasing the licensed power output. A high proportion of NPPs has either completed or is planning power uprating. In most cases this is an economic way of producing more electricity in an NPP, and it has attracted interest due to increased electricity prices (a situation which is expected to remain). Table 2 shows the planned and potential results of power uprating. The increase in the electricity produced in a NPP can be achieved in two main ways (which can be combined in a single plant):

- by increasing the thermal power in the reactor; and
- by improving the thermal power conversion efficiency in the plant by refurbishing or replacing major components.

The specific reactor designs built in the United Kingdom are expected to have shorter lifetimes than the LWRs common in other countries. The remaining Magnox plants are expected to close in the next few years after operating for about 40 years. The later advanced gas-cooled reactors (AGRs), which were at one time considered to have lifetimes of only 25 years, are now mostly expected to operate for 35 years. Further extensions could be considered if technically feasible and economically justified, although there is no certainty that this will be the case.

Table 2. Planned and potential results of power uprating and PLiM programmes for LTO in selected NEA member countries

Country	Capacity uprating	LTO
Belgium	Yes	Phase out policy
Czech Republic	Planned	Planned to 40 years, potentially to 60 years (4 units)
Finland	Capacity increase of 18 MW completed in 2005 for Olkiluoto unit 2, completed in 2006 for Olkiluoto unit 1	Planned lifetime of 60 years for units 1 & 2 and for unit 3 (EPR) at Olkiluoto; planned lifetime for Loviisa (2 units) raised to 50 years
France	No	Lifetime of 40 to 60 years (58 units)
Japan	No	Lifetime of 40 to 60 years
Germany	Yes	Phase out policy
Hungary	Underway for 4 units, capacity increase of up to 150 MWe	Planned to 50 years (4 units)
Republic of Korea	Yes	Lifetime of 40 to 60 years
Mexico	Yes	Lifetime of 40 to 60 years
Slovenia	Yes	Lifetime of 40 to 60 years
Slovak Republic	Underway for 4 units, capacity increase of up to 220 MWe	Planned to 40 years, potentially to 60 years (4 units)
Spain	Completed for 8 units, capacity increase of 550 MWe	Planned, possibly to 60 years (8 units)
Sweden	Underway for 8 units, capacity increase up to 1 296 MWe	Planned, up to 60 years or more (8 units)
Switzerland	Yes	Lifetime of 40 to 60 years
United Kingdom	No	Planned to 35 years (5 plants) or 30 years (2 plants), further extensions possible
United States	Continuing for many units, total capacity increase of over 4 000 MWe by 2012	Licence extensions granted to 41 units as of May 2006, for up to 60 years of operation

In Canada, pressurised heavy water reactors named CANDU have been built. Although several of the older plants have had to be closed down for extended periods for refurbishment, the successful return to service of some of these plants has shown that they do potentially have operating lifetimes at least as long as LWRs. In fact, unlike LWRs they do not have large non-replaceable pressure vessels, with all core components being replaceable from a technical point of view.

In other countries most plants which entered operation in the 1980s were LWRs, designed with a lifetime of about 40 years in mind. In the majority of cases, these designs incorporated sufficient conservatism in the major non-replaceable components to allow for potential life extensions to a total of 50 or 60 years of operating life. These plants are also on average larger than older plants, which makes it easier to justify the necessary investment to maintain and upgrade them to the standard required for such extended operation.

In some countries like Belgium and Germany, LTO is actually not an option at present as a politically driven phase out scenario is in force, independent of technical considerations concerning the NPPs.

The Soviet-designed VVER-440/213 plants in operation in the Czech Republic, Hungary and the Slovak Republic were originally considered to have a design life of only 30 years. However, technical analyses performed in those countries indicate that those plants are also capable of operating for 50 to 60 years. This follows the completion of significant upgrades of safety-related SSCs and the installation of improved instrumentation and control systems. Again, the original design of the major non-replaceable components included a sufficient degree of conservatism to make this possible. The process of licensing such plants for LTO is already underway.

Of course, the designers of each generation of NPPs have learned from the experience of the construction and early operation of those which went before. It is only more recently, however, that some of the lessons learned during significant operation periods have become available to the designers of new plants. The relatively small number of plants built in the last decade have incorporated some of these lessons, and it has been possible in the latest ("Generation III") models to design the plants for a lifetime of 60 years from the outset. A particular example is the 1 600 MWe European Power Reactor (EPR) design, the first of which is now under construction in Finland (with planned commissioning in 2009); a preliminary decision has also been made to construct a second EPR at Flamanville in France.

This increase in design lifetimes has been achieved by improving the design, material selection and elaboration, and manufacturing techniques of the major SSCs (especially the non-replaceable ones). The design and layout of the plants has also been improved to reduce the impact of ageing effects such as corrosion, fatigue, neutron embrittlement and thermal ageing, and to facilitate the maintenance and eventual replacement of SSCs.

Designs for potential future reactors, often referred to as “Generation IV” and “INPRO” designs, are often radically different from existing designs. Although this can mean that experience with existing plants is less applicable, these designs may provide additional opportunities to “design out” some of the impacts of ageing so as to maximise the design lifetime. For example, it may be possible to avoid having any non-replaceable components at all, meaning that the entire plant can be progressively renewed as necessary throughout its operating life.

In the long term development of nuclear programmes, life extension of the existing nuclear fleet has a vital role to play in maintaining the share of nuclear power in total electricity generation in many countries. With construction of Generation III plants in its early stages and unlikely to reach a significant scale until after the lead plants enter operation, it will take 20 to 30 years before such designs become the mainstay of nuclear power generation. The existing plants will thus need to continue operating for an extended period, if they are not to be replaced by other forms of generation of efficiency measures, and if the capabilities and capacities of the nuclear industry are to be maintained and eventually expanded for the future generations.

2. DRIVERS FOR PLANT LIFE MANAGEMENT

2.1 Economic incentives

For owners of NPPs, the principal considerations in implementing PLiM programmes are likely to be economic ones. A NPP represents a very large and long-term investment, compensated by a relatively low and stable fuel cost. To achieve the maximum return on that investment means keeping the plant operating safely and as efficiently as possible throughout its operating life. As well as meeting all safety and licensing requirements, the plant needs to achieve a high capacity factor.

While the normal O&M costs provide for the routine repair and maintenance of the plant's SSCs, PLiM activities for LTO go beyond this. They are designed to secure the possibility of an extended operating lifetime, as well as of achieving other goals such as increased power output, enhanced safety levels, greater operating efficiency, etc. Thus the costs of such activities can be seen as constituting a new investment in the plant.

Like all investments, the costs of PLiM activities are subject to economic analyses to ensure that they provide an adequate return to the investors. In other words, the value realised in terms of additional electricity output (compared to not making the investment) must be sufficient to justify the required investment.

Such an economic analysis can be complex and depends on numerous factors, some of which are difficult to predict and are outside the control of the plant's owner. The principal uncertainty is likely to be the future price of electricity, which will in turn be determined by various factors including the future supply/demand balance and the production costs of other generators (most importantly, the future price of fossil fuels).

However, with electricity demand expected to continue to increase throughout the OECD member countries, and with the costs and uncertainties involved in constructing new large scale generating plants, it is likely that the future electricity market conditions in most OECD countries will make life extensions economically attractive.

Furthermore, the evidence from the numerous studies of PLiM activities which have been carried out in several OECD countries is that the investment costs for plant life extension are modest (compared to the costs of constructing new generating plants). Given that the original capital investment in the plant will normally have been fully amortised during the original design lifetime, this means that LTO will in most cases be economically attractive, even if some additional investment is required to upgrade the plant. For example in case of Paks NPP in Hungary, during the planned period of LTO a profit of 4.4 times the originally invested capital is expected to be paid to the owners.

Indeed, in many cases it has been shown that preparing for possible life extension does not significantly increase costs beyond those incurred for plant upgrading which might have been undertaken in any case within the originally envisaged lifetime. The use of improved technologies and materials, compared with those available when plants were built 20 or more years ago, can make upgraded systems better than the original systems, with a longer lifetime.

This is particularly true where SSCs are upgraded in order to increase a plant’s power output. The investment in such upgrades can normally be justified in terms of the additional electrical output within the originally envisaged lifetime. However, the upgraded systems will also have the effect of increasing the potential for lifetime extension, for little or no additional cost.

Other upgrades may become necessary during a plant’s life for other reasons, for example, to improve safety levels or to replace obsolete equipment. The plant’s owners can take the opportunity of such upgrades to plan for an extended lifetime by ensuring that the new SSCs meet the requirements for extended operation.

Another important economic consideration when implementing PLiM programmes is the costs of the waste management and decommissioning activities at the end of a plant’s life, after it is permanently shutdown. While LTO will result in some additional operational waste as well as may increase the amount of decommissioning waste considering that structural components will be irradiated for an extended timeframe. However taking into account that the annual costs related to decommissioning fund rising, these costs will be reduced if they are counted for a 10 or 20 years longer time period.

In addition to the benefits of deferring these end-of-life costs, they are also spread over an extended operating period, and thus over a greater lifetime electrical output from the plant, thus reducing further the costs per kWh. Technological progress over the extended lifetime can also be expected to reduce decommissioning costs, and more time will be available for waste management techniques and facilities to be developed (although this could be offset to some extent by increased regulatory requirements).

In Hungary, for example, after the approval of LTO of nuclear power units at Paks, the provision for decommissioning per kWh will be reduced. This will significantly improve the economics of the NPP with immediate effect.

2.2 Security of energy supply

As well as making good economic sense, LTO can also contribute to security of supply. In the first place, PLiM programmes are designed to maintain and improve a plant’s reliability, thus helping to improve the reliability and security of the entire electricity supply system.

In the longer term, a PLiM programme can provide a reasonable degree of assurance that a plant will continue in operation for an extended period. This obviates the need to plan for additional new generating capacity which would otherwise need to be built. The construction of new capacity will generally take longer and cost more than extending the life of existing capacity.

PLiM programmes for NPPs can also help in maintaining the diversity of energy supplies. As NPPs are normally operated as baseload capacity, any replacement capacity would also need to be suitable for such operation. This means that intermittent generating sources would not be suitable as replacement capacity, as they would require expensive back-up generating capacity. Given that there are presently only a few options for conventional base-load plants (principally coal, gas and nuclear), closure of NPPs might well result in increased reliance on coal and/or gas, in many cases resulting in a reduction in the diversity of energy sources.

A further consideration is the geographic distribution of plants within the electricity transmission system, both within each country and among neighbouring countries with shared transmission systems. Major imbalances could arise if NPPs were closed down and replaced with capacity in another region. This could require significant investments to be made in additional transmission capacity, which could have environmental impacts; transmission losses might also be increased.

In countries with liberalised electricity markets, responsibility for security of supply generally does not lie with the individual generating companies. However, at the energy policy level, security of supply remains an important issue. It provides an important motivation for governments to facilitate major PLiM objectives, such as power uprates and lifetime extensions.

In other countries, utilities may have some contractual or regulatory obligations to supply customers with electricity. Given the fact, that the replacement of a nuclear capacity may take some years, even in the absence of the just mentioned regulatory obligations, the closure of existing plants without replacing them with a similar amount of new nuclear capacity would represent a lost opportunity regarding the market opportunity and the well functioning infrastructure and could enable competitors (including generators in neighbouring countries) to more easily enter the electricity market.

From the energy policy perspective, maintaining the nuclear share of electricity generation is often seen as a desirable objective for security of supply and energy diversity reasons. Yet a decision to invest in new nuclear capacity would almost invariably be a very difficult and controversial one. The main alternative to nuclear plant life extension would often be increased use of imported fossil fuels, with clear security of supply disadvantages. Furthermore, the political obstacles to constructing new large-scale generating capacity of any kind in some countries may make even this option difficult, with the most likely outcome being increased dependency on electricity imports.

2.3 Environmental considerations

Environmental considerations have for some years been a significant factor in energy policy decisions. For example, widespread concerns about acid rain and pollution have led to a shift away from coal-burning power plants to natural gas fired generation in recent years in many countries. This has also served to curb the growth in carbon dioxide emissions.

Although little new nuclear power capacity has been added in recent years, the existing plants have continued to provide a substantial proportion of total electricity output in several countries. As these plants start to approach the later stages of their original operating lives, the prospect of replacing them with fossil-fuelled capacity is raising concerns about the environmental impact (particularly the impact on carbon dioxide emissions).

From the overall energy policy perspective, increasing the power output of these existing plants and/or keeping them in operation for a longer period than originally planned can have important environmental benefits. A particular concern is the need to avoid the increases in emissions of atmospheric pollutants and carbon dioxide which would occur if present nuclear plants were shut-down and replaced with new fossil-fuelled capacity. In this respect, lifetime extension of existing NPPs minimises certain long term and irreversible impacts on the environment of meeting current energy demand.

The great majority of existing nuclear power plants are effectively included in the 1990 baseline against which changes in carbon dioxide emissions are calculated for most OECD member countries. Thus the closure of these plants and their replacement with carbon-emitting power sources would inevitably tend to increase emissions in comparison with this baseline. Where there is little prospect of new nuclear plants being built, at least in the next few years, extending the lives of existing plants will allow this rise in emissions to be largely avoided.

The direction of national policy on carbon dioxide emissions is a matter principally for governments rather than power plant owners and operators. However, governments may seek to achieve their policy goals on emissions by providing financial incentives for power plant operators to avoid increasing emissions; for example, emissions trading regimes. Such regimes could significantly alter the economics of electricity generation, to the advantage of carbon-free or low carbon sources such as NPPs benefitting from lifetime extension.

In any case, the environmental advantages of PLiM programmes for LTO can help to bolster public and political support for such programmes, and utilities in a number of countries cite environmental considerations as one of the motivations for PLiM programmes for LTO from the national perspective.

On a more local scale, the extended life and more efficient operation of existing nuclear facilities as a result of PLiM programmes may help to avoid the inevitable environmental impacts of the construction of new generating capacity. These may include the loss of agricultural land to provide sites for such capacity, as well as the disruption and resource-use implications of a large-scale construction project.

2.4 Social factors

As with any major industrial facility, long-established NPPs often have close relations with the local community. The plant is likely to be a major contributor to the local economy as a large employer, and well as through direct support for local community activities and programmes. In some cases, this can extend to wider benefits on a regional or national scale.

Thus, the closure of a NPP plant could have a significant detrimental effect on the local area. After a transient peak of activity in decommissioning, this may result in higher unemployment and an exodus from the area, with a corresponding reduction in overall economic activity. A PLiM programme leading to the extension of the plant’s operating life can help prevent such negative effects on the local region.

3. THE DECISION-MAKING PROCESS

3.1 Plant owners and industry

As noted above, for any NPP owner the prime motivation for considering a programme of PLiM for LTO is to achieve an improved economic return on the investment in the plant. In the case of a utility operating an NPP in a competitive electricity market, this must be assessed in the context of the outlook for the electricity market over the period in question. It must also take account of the government and regulatory position on LTO, set against the timescale for achieving a return on the investments required.

A business case needs to be made for any additional investments which might be needed to achieve such objectives as power uprating or lifetime extension. This includes comparing the risks and rewards of such investments with those of investments in other generating capacity. Where it is necessary to attract outside investors, the balance of risks and rewards needs to be comparable with investments in other sectors of the economy.

The precise process for this varies from utility to utility, but essentially it comprises a series of studies to examine the technical feasibility of PLiM activities, their expected costs, and their economic benefits to the company. The wider economic, environmental and security of supply benefits are also likely to be considered. In doing this, plant owners will consider a range of credible scenarios for future electricity prices and other factors. This helps to establish the overall robustness of the economic case for making the necessary investments.

Often such studies are carried out over an extended period of time, covering much of the plant's operating life. The decision-making process is thus more of a step-by-step approach rather than a single decision. At each stage, all programmes of repair, maintenance and upgrading of SSCs are considered for their implications for the overall PLiM objectives. In some cases, such reviews are the responsibility of an organisational unit within the operating utility specialised in plant life management.

In France, for example, a special programme is in place to consider all aspects of component ageing and lifetime. All components are analysed according to known and expected ageing mechanisms, taking into account existing maintenance procedures, and their importance for safety and reliable operation. They are then prioritised for further investigation, which includes identification of risk factors and comparison with international experience. A decision is then taken on whether it is necessary to make changes to the maintenance programme, to plan for the replacement of the component, or if the present level of maintenance is sufficient. A similar approach is taken in other countries. This process is facilitated in cases where, as in France, nuclear plants have been built to standardised designs with common components.

In many cases, actions such as improvements in maintenance procedures and upgrading of systems are attractive in their own right, in that they result in immediate benefits for the performance and/or safety levels in the plant. They may also be necessary to ensure that the plant continues to operate safely and efficiently for the remainder of its presently planned lifetime. For example, analyses carried out in Sweden have demonstrated that, with little or no additional cost, ongoing investment in O&M and modernisation which is required for the currently planned lifetime also serves to prepare the ground for lifetime extension. In some countries, such as the Czech Republic, Hungary and the Slovak Republic, safety upgrades which have been carried out on older plants mean that some SSCs have been replaced, upgraded or introduced, which strengthens the case for extended operation.

This allows utilities to effectively keep their options open for the future, without committing to a definite decision about lifetime extension. That is, utilities can plan for the possibility of lifetime extension, and ensure that maintenance procedures and required upgrades are compatible with such an objective, while postponing a firm decision until some of the uncertainties become clearer. This may be especially important in cases where a specific political decision would be required to allow plants to operate beyond a predetermined age, such as in Belgium or Germany. However, operators will still require sufficient lead-time in advance of the presently scheduled closure date to ensure that the investments needed for LTO can continue to be made.

In general, the direct, additional costs of PLiM activities, as distinct from those costs which would need to be borne in any case to ensure the continued efficient operation of the plant, may be relatively modest. In addition, factoring in the PLiM advantages of a project to upgrade an existing plant may provide additional economic justification for such investment. This can allow plants to be upgraded where the cost would not be justified by the benefits within the original design lifetime.

3.2 Governments

Even though the economic and technical feasibilities from the utility's perspective are likely to be the main factors in the decision-making process, taking major decisions on such matters as lifetime extensions and power uprates will almost always involve the government at some stage. The extent of government involvement will vary from country to country depending upon policy towards nuclear power.

Lifetime extension has particular implications for the overall national energy policy. Clearly, where nuclear power contributes a large share of total power generation, the prospect that much of the existing nuclear capacity might operate for an period beyond that originally envisaged has major implications for future security of supply and thus for decisions about investment in new generating capacity.

Governments are also likely to be aware of the implications for carbon dioxide emissions of the closure of existing NPPs and their replacement by fossil-fuelled capacity. At the same time, the evidence suggests that a decision not to oppose the lifetime extension of an existing NPP is often easier to take from a political perspective than a decision to construct new capacity (nuclear or otherwise).

Much the same applies, on a somewhat smaller scale, to uprating the power output of existing nuclear plants. In Sweden, while two nuclear plants have been prematurely closed as a result of political decisions, the government is nevertheless allowing plans for power uprating of the remaining plants to go ahead, effectively replacing the capacity lost in the closures. It has also not renewed previous legal provisions which would have required a nuclear phase out by 2010. This has allowed utilities to plan for lifetime extensions (which would not be subject to a government decision). However, a specific tax on nuclear power plant continues to be applied in Sweden, which serves as a disincentive for investment in upgrading existing plants.

In countries where a political decision has been taken to limit the lifetime of existing nuclear plants, such as Belgium and Germany, clearly this policy would have to be reviewed before any firm decisions could be taken about lifetime extension. In such cases, utilities can only take the necessary steps to keep open the option of lifetime extension, should the political process result in a change of policy in the future. It should be noted in this context that political decisions on phasing out NPPs are usually subject to review if alternative supplies which meet environmental and energy security of supply objectives are not available.

3.3 The regulatory framework and licensing

It is important that there is a clear and predictable regulatory process for introducing PLiM. Plant owners considering investments in plant upgrades will need to have reasonable assurance that their efforts to extend plant lifetimes will be successful. In general this is achieved by a process of consultation between the utility/operator (the licensee) and the regulatory body at each step of the process.

There are a number of different basic approaches to the licensing of nuclear plant lifetimes. In some countries operating licences have a fixed period of validity, while in others they have indefinite validity, subject to periodic review. In other cases, plants are operated under a series of short-term licences which are renewed regularly. The regulatory approach to life extension will differ in each case.

In the United States, for example, NPPs were originally granted operating licences for 40 years. A well-defined procedure has been established by the NRC to consider applications for these to be extended by up to 20 years. This procedure has already proved to be a success, with 41 plants having been granted extensions and 10 others having applied by May 2006, and with many more having indicated their intention to apply. Eventually it is expected that the majority of US NPPs will apply for licence renewal. The most widely used screening criteria for licence extension are those described in US regulations, such as:

- Licence Renewal Rule (10 CFR 54);[1]
- Maintenance Rule (10 CFR 50.65);[2]
- US NRC Generic Ageing Lessons Learned (GALL) report (NUREG-1801);[3]
- Industry Guidelines (NEI 95-10).[4]

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1. US NRC (1995), "Requirements for Renewal of Operating License for Nuclear Power Plants", 10 CFR Part 54, Washington, DC, USA.
2. US NRC (1996), "Requirements for monitoring the effectiveness of maintenance at nuclear power plants", 10 CFR 50.65, Washington, DC, USA.
3. US NRC (2001), "Generic Ageing Lessons Learned (GALL) report", NUREG–1801, Office of Nuclear Reactors Regulation, Washington, DC, USA.
4. NEI (2001), "Industry Guideline for Implementing the Requirements of 10 CFR PART 54 – The License Renewal Rule", NEI 95-10 (REV. 3) (March), USA.

In some other countries, NPPs do not have pre-determined lifetimes. They may have an assumed economic life, which is necessary for determining their value in the accounts of the utility or operating company, or a nominal design lifetime. From a licensing point of view, the plant may be licensed (or may have its licence renewed periodically) to continue operating so long as it meets all necessary safety requirements. These requirements may, however, change over time, requiring safety-related SSCs to be upgraded during the life of the plant.[5]

In such a situation, life extension is a decision taken by a utility in light of technical and economic assessments of the plant, rather than as a one-time formal licensing procedure. This is the case in Sweden and the United Kingdom, for example. Essentially, the end of a plant's life will come when it is no longer practicable from a technical or economic viewpoint to continue to maintain it in compliance with the regulatory requirements.

However, in all cases regulators are involved in PSRs of plants, typically conducted every 10 years, and they are closely consulted by plant operators in determining the steps necessary to ensure that plants continue to meet safety requirements as they age. In some countries, including Hungary, Korea and Spain, this also constitutes a formal review of the licence. Some regulatory authorities (e.g. in the Czech Republic and Spain) are preparing specific guidelines on the requirements for LTO of NPPs. In the case of Spain, these requirements will be based on experience gained with the Santa Maria de Garoña plant.

The different approaches to licensing which exist in different countries may limit the scope for standardisation in the approvals and licensing processes which apply to lifetime extensions. However, it is expected that the considerable co-operation and exchange of information which exists between regulatory bodies is likely to result in some harmonisation of standards for similar designs. There would seem little justification for greatly different standards to be applied to two plants of the same design and manufacture simply because they are located in different countries.

In cases where plants are to undergo significant refurbishment and/or modifications, such as steam generator replacement, or where the power output is to be increased, there is a different set of regulatory requirements. In some cases a special licence is required, while in others the existing operating licence

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[5] IAEA (2003), "Periodic Safety Review of Nuclear Power Plants", Safety Guide No. NS-G-2.10, Vienna.

has to be amended. Such licensing activities are generally handled under established procedures, which are not specific to PLiM-related modifications.

In addition to nuclear-specific regulatory and licensing requirements, there are also other regulatory conditions which must be met, notably environmental requirements. These may also become more stringent over time, potentially increasing the costs of compliance.

3.4 Public acceptance aspects

Where significant changes are to be made to aspects of a plant's operations, especially those involving changes in the operating licence, there is usually a requirement to conduct formal public consultations in some form. These are carried out according to the appropriate legal framework for public consultations foreseen in the licensing procedures.

In most cases PLiM programmes in themselves are not subject to any requirement for formal public consultations. However, existing NPPs invariably have programmes of public communication with the population living in the area of the plant. PLiM programmes and decisions are covered by this process.

In general, NPPs are viewed positively by the majority of the population in the surrounding area. They are often major local employers, and contribute significantly to the local economy. The plant may also play a wider role in the local community, for example, by sponsoring activities and organisations.

Experience in several countries has shown that, in the majority of cases, the public in the local area around the plant is supportive of lifetime extension, which will ensure that the benefits to the local community will continue. It is clearly extremely important in this respect that the plant has been seen to operate safely at all times.

Nevertheless, major decisions about the future of the plant, including increases in power output and lifetime extension, may raise public concerns, especially about whether the ageing plant will remain safe. There is clearly a need for accurate information to be available to the public about PLiM activities, to permit informed discussion about whether the ageing process is being properly managed. Such debate should take place within an appropriate legal framework.

In terms of the wider public in the country as a whole, and in some cases in neighbouring countries, evidence suggests that there is significantly less concern about an existing plant continuing in operation, than there is about the prospect of a new NPP being built. Provided a plant is demonstrably operating safely and efficiently, public opposition to its continued operation can be expected to be limited.

4. RESOURCE MANAGEMENT ISSUES

4.1 Nuclear fuel and waste management

As with any investment in nuclear generating capacity, consideration of lifetime extensions involves an analysis of the requirements for nuclear fuel, and its likely availability over the extended operating period. The economics of the project will partly depend on the expected nuclear fuel costs over the remaining operating life.

This is less problematic with a lifetime extension than a new reactor project, as the period to be considered will be 10 to 20 years rather than 40 to 60 years. However, nuclear fuel costs and availability will remain a significant factor.

While most processes in the nuclear fuel cycle are generic and the costs will be similar for all nuclear plants, this may not be the case for fuel fabrication. This may be a particular concern where there is only a single supplier for fuel fabrication, and/or the fuel design required by the plant is unique or unusual. In this case, it may be necessary to consider whether the fuel fabrication facilities can also operate for the extended period being considered, and what additional investments will be required.

Overall, however, it is a general aim of PLiM programmes to improve the fuel performance of reactors, to reduce the specific consumption of uranium and fuel cycle services. This provides important economic benefits for plant operators, and helps to support the case for extended lifetimes.

Operating existing NPPs for an extended period inevitably means that additional quantities of radioactive waste and spent fuel will be created, compared to closing the plant at the end of its original design life. However, from the national perspective this can be compared to the waste and other environmental impacts of alternative generating capacity (nuclear or non-nuclear) which would otherwise need to be built.

An important factor in the upgrading of a plant as part of a PLiM programme will often be to reduce the specific production (per kWh) of waste and spent fuel. This can be achieved by such measures as improved systems for handling spent fuel and more efficient fuel design and usage.

Furthermore, the process of decommissioning a plant at the end of its operating life will inevitably produce significant quantities of low and intermediate level waste. Extended operation will defer the production of decommissioning wastes, and will extend the period available to set aside funds to cover the cost of decommissioning. The years of additional electricity production will also reduce the costs of waste management and decommissioning per unit of electricity generated.

In the United Kingdom, for example, before a nuclear plant lifetime extension can be approved the operator must demonstrate to the Nuclear Decommissioning Authority (NDA) that there will be a cost benefit for waste management and decommissioning as a result of the additional years of operation. This is separate from the operator's own need to demonstrate the economic case for life extension.

Plans to extend the operating life of a plant need to fully consider the implications for waste management and spent fuel storage. It may be that existing facilities need to be enlarged or new facilities constructed. The costs of this would need to be factored into the economic justification for life extension.

4.2 Industrial infrastructure

Where NPP owners/operators introduce PLiM programmes with a view to long-term operation of their plants, they need to do this in close collaboration with the reactor vendors and other nuclear engineering companies. Often these will be the same companies who are involved in the regular repair and maintenance operations which take place throughout a plant's life.

Thus there will normally be no need to develop any completely new engineering capacities, although there will be clearly the need to develop and extend existing maintenance procedures to accommodate PLiM programmes. This process is already well under way in many cases.

One side effect of the lack of orders for new nuclear plants in recent years has been that reactor vendors, nuclear engineering companies and specialist nuclear suppliers have retrenched, which may have reduced the range and depth of the expertise available. There has been significant consolidation in the industry since the period when nuclear power was expanding rapidly. It is vitally important for long term operation of nuclear plants that the required industrial infrastructure and know-how continues to be available.

However, much of the business of the remaining companies now focuses on repair and maintenance operations at existing nuclear plants, with the most important specialist capabilities being made available globally. These companies are thus well-placed to participate in PLiM programmes. Indeed, the lack of new NPP orders may even have resulted in greater emphasis to be placed on matters relevant to PLiM programmes in recent years than would otherwise have been the case.

PLiM programmes are by their nature medium to long term projects, covering a series of activities spread over one or more decades. This allows sufficient time for adequate industrial capacities to be developed where they do not already exist. The obsolescence of existing SSCs, and the continuing need for replacement parts, are issues which need to be considered.

To carry out many of the necessary studies and evaluations SSCs for life extension and power uprates, it is also necessary to be able to call on adequate nuclear research and development capabilities. Nuclear research centres in several countries have been participating in PLiM programmes, and it is essential that these capabilities be maintained as these programmes are implemented.

4.3 Human resources and knowledge management

The issue of human expertise and knowledge is one of the major challenges in carrying out PLiM programmes. NPPs have an operating life of at least several decades, and these may be extended to 60 years in some cases. This is clearly beyond the working lifetime of any individual engineer who works on the design, construction and operation of the plant. Many of the engineers who worked on the design and construction phases of existing plants have retired or will do so in the near future.

Similar considerations apply to those involved in the research and development activities required to support the plant, and to those responsible for its regulatory oversight. In this sense, nuclear power plants can be considered as multi-generational projects, in that they will be the responsibility of several generations of specialists over their lifetime. The plant itself is likely to outlive many of those who work on it.

In such a situation, the issue of knowledge management and preservation is of critical importance. Of course, NPPs always have extensive documentation which is constantly updated. This process of updating and revising documentation, and improving information management and retrieval systems, becomes of even greater importance when an extended operating life is contemplated.

However, even the best documentation is no substitute for experienced personnel who are familiar with the plant. There is an ongoing need to recruit and train skilled engineers and support staff, and for them to gain experience by working with experienced employees for a sufficient period of time to allow for transfer of knowledge and understanding of the plant.

The rapid expansion of nuclear power in the 1970s drew in many young engineers, a large cohort of which is now approaching retirement. If a large number of existing NPPs are to extend their operating lifetimes, there will be a need for a new generation of engineers to replace them. The adequacy of human resources is an issue which utilities and governments will need to take into account when considering long-term nuclear operations.

For example, in Finland it was a requirement that the adequacy of human resources be demonstrated before approval was given for the construction of the new EPR unit at Olkiluoto. One of the key tools for this is the national research programme for operational and structural safety of NPPs, known as SAFIR. The main objective of SAFIR is to train new nuclear experts to meet the requirements for additional human resources of the Olkiluoto 3 project, and to replace the large number of experts who will retire within the next 5-10 years. Courses held during 2003-2006 on nuclear safety technology, with the co-operation of all nuclear-related organisations in the country, have already trained about 150 young experts and newcomers to the nuclear industry, and further courses are likely to be held in future years. Training materials for internal training programmes have also been developed.

As with the construction of new NPPs, lifetime extensions represent an opportunity to attract highly qualified new personnel to work in the nuclear power sector. While it may be difficult to recruit sufficient talent when many NPPs are expected to close in a few years, the real prospect that these plants still have many more years of operation ahead will make the nuclear industry a more attractive option for younger scientists and engineers. However, this will only be possible if policymakers ensure that sufficient facilities and student places are available in universities and other educational establishments to provide the necessary pool of people with nuclear-related skills and training. For example, Belgium has launched a programme known as BNEN that provides an inter-university educational programme to obtain a masters degree in nuclear engineering taught at the national research centre. This effort gave rise to a similar effort within the European Union, called ENEN.

5. THE INTERNATIONAL CONTEXT

5.1 Exchange of experience

As in other aspects of NPP operation, international exchange of experience on PLiM is of great value, especially where NPPs in different countries are built to similar designs. Operators can exchange information about technical issues which have been encountered, and solutions which have been implemented. Furthermore, international co-operation on research programmes on ageing management and other relevant issues are often the most efficient and effective way to overcome the technical challenges of PLiM.

This is an area where international organisations such as the OECD Nuclear Energy Agency, the International Atomic Energy Agency (IAEA), the European Commission (EU), World Association of Nuclear Operators (WANO) and others play a vital role. Utilities, research organisations and governments who are considering or carrying out PLiM activities participate in numerous international programmes coordinated by such bodies. There is also intensive bilateral co-operation between countries, especially amongst European countries.

There is also a broader benefit to be derived from international experience. By demonstrating the economic and security of supply benefits and how they can be achieved, PLiM programmes in one country can serve to encourage the adoption of similar programmes in other countries. As the steps necessary for plant life extension, for example, are successfully completed by one operator, this paves the way for others to follow. This may also be true in the political context as well as with the technical challenges.

With the regulatory aspects of PLiM, there is also a need for exchange of experience internationally. The regulations and standards developed in one country can provide a useful model for other countries at an early stage in their PLiM programmes, particularly where similar designs are in use. For example, several countries operating US-designed plants pay close attention to the regulations set by the US NRC and the respective supplier’s user group.

Co-operation and full exchange of information with agencies in neighbouring countries is also needed to provide confidence that PLiM activities are in conformity with international standards on safety. This may include consultations with neighbouring countries which do not themselves have operating nuclear plants, particularly where plants are operating in border regions.

Safety concerns about potential LTO of NPPs have been expressed by Austria. Therefore the Austrian government has engaged in consultations with the Czech Republic, France, Germany, Hungary, Slovenia, the Slovak Republic and Switzerland, and has instigated a series of independent evaluations of the risk implications for its territory, environment and population of LTO of NPPs in neighbouring countries. While accepting the ultimate responsibility of the individual licensing authorities, given its geographical situation Austria is obliged to observe the safety status of a variety of NPP designs of various vintages in combination with the individual legal and regulatory frameworks established in the respective countries.

Austria would like to avoid incurring increases in cross-border risks, and therefore has to observe possible changes in these risks. In assessing cross-border risks in the broadest sense, and changes in these risks over time, ageing is of special interest, particularly during LTO of NPPs. Risks will inevitably change during operation of any technological installation. This is partly due to physical changes in the plant itself, but also due to the rapidly evolving political, economic and technological environment. Safety culture constitutes the fundamental basis of safety. Therefore its condition ought to be judged in all its aspects, independently of the immediate economic gain. When observing the state of safety, obviously information needs to be obtained from operators, manufacturers and international organisations such as the OECD/NEA, to keep abreast of developments in all important areas. In this context, the transfer of information facilitated by the NEA is very important for further developing knowledge and keeping it up to date.

5.2 Harmonisation of standards

For NPPs built to common or similar designs, or even where similar SSCs have been used, the technical issues related to PLiM will usually be the same or similar. This will inevitably lead to a great deal of commonality in the solutions which are adopted. It is likely that plant owners will opt for a proven solution which has been developed already rather than spend time and money looking for other options. The relatively small number of international nuclear design, construction and engineering companies are likely to offer similar technical solutions to plants operated in different countries.

Different countries have developed somewhat different approaches to the licensing and regulation of NPP operations, and this will result in differing requirements and approaches to PLiM issues, including power uprates and lifetime extension. Nevertheless, there are many common technical issues which can best be addressed in the context of international standards.

The development of such standards is continuing. The IAEA has produced safety and technical guidelines for specific components and is continuously producing technical standards which specifically apply to PLiM programmes. In Europe, efforts are underway to introduce more harmonisation in safety guidelines between countries, and this may impact the approach to PLiM. Austria in particular strongly advocates a legally binding harmonisation of safety requirements at the European level for all types of civil nuclear installations and activities, to ensure the highest level of nuclear safety for the citizens and the environment of Europe.

However, harmonisation of standards does not mean that differences of approach between countries need to be eliminated. Each country can adopt national requirements to suit its particular circumstances (for example, the number and type of NPPs in operation), while meeting internationally agreed standards.

The Western European Nuclear Regulators Association (WENRA) was created in 1999 with three main objectives: to develop a common approach to nuclear safety; to provide an independent capability to examine nuclear safety in the EU applicant countries; and to be a network for chief nuclear regulators in the EU for the exchange of experience and to discuss significant safety issues. More recently, WENRA has been working on harmonisation of safety standards in Europe. To facilitate this, regulators in Bulgaria, Romania and Switzerland were invited to join the organisation, bringing membership to 17 countries.

Early in 2006 WENRA released three reports setting out “reference levels” to be used for harmonisation of safety standards in the areas of reactor safety, waste management safety, and decommissioning safety. By the end of 2006 national regulators were due to have developed action plans for implementation of these reference levels by 2010 in their regulations. The reference levels are being reviewed by the nuclear industry and consultations with WENRA are expected to take place.

The European Union has established, in its FP6 programme, a network of excellence called NULIFE. This programme also aims at harmonisation of standards and working procedures in the nuclear industry.

6. FINDINGS AND CONCLUSIONS

6.1 Findings

The continued operation of existing NPPs beyond their original design lifetime, known as long-term operation (LTO), has become an important option for countries with established nuclear programmes. In most OECD countries LTO has already been accepted as a strategic objective, to ensure adequate supplies of electricity over the coming decades, while in others it is being actively considered.

During the operating lifetime of several decades, it will often be possible to enhance plant safety levels by upgrading SSCs. Some such upgrades may be required by regulators, while others will be made by plant operators as part of regular maintenance or in pursuit of improved operating performance. Thus, while a NPP may have been in operation for 30 or 40 years, many of its SSCs will be much younger. LTO helps to justify the investment in such upgrades, which means that it can also help to raise safety levels.

Plant SSCs can be classified as either critical or non-critical. Critical items are those whose failure would cause concerns for the safety and reliability of the plant, and which therefore need to be repaired or replaced before they fail. Preventive maintenance programmes are designed to achieve this.

Although the great majority of critical SSCs in an NPP can be replaced when necessary, there are a few major components (notably the reactor pressure vessel in most plants) which can be considered non-replaceable, either for technical or economic reasons. For such components it is necessary to implement ageing management programmes.

This process of optimising the upgrading and ageing management of the plant is vital in preparing for LTO. It includes ongoing research and development efforts to understand and mitigate the effects of ageing mechanisms, particularly in non-replaceable components, and involves plant operators working closely with reactor vendors and other nuclear engineering companies.

One important aim of PLiM for LTO is to improve a plant's operating performance. This includes upgrades to improve reliability, and hence achieve increased capacity factors. In many cases a plant's power output can also be increased, through uprating the reactor and/or the turbine systems, while continuing to comply with all licensing and regulatory requirements.

PLiM programmes have already resulted in significantly improved operational performance at many NPPs in OECD countries, which has often greatly increased the value of these nuclear generating assets. Further increases in operating performance have been achieved by optimising fuel management (e.g. higher enrichment levels and increased burnups), while reducing specific (per kWh) production of radioactive waste and spent fuel.

The decision-making process for LTO is mostly a step-by-step process, but it often includes some significant licensing and investment milestones.

To achieve LTO it is important that there is a clear and predictable regulatory framework. Timely investments need to be made in upgrading the plant and replacing SSCs, and these will be influenced by the prospects for LTO. Only if the requirements which will need to be met are clear many years in advance will this process be optimised. There is thus a need for the process of consultation between regulators and plant operators to begin well in advance. Once decided, the necessary licensing and approval processes need to be carried out in a timely manner.

The energy policy framework and political background are also important factors. If national energy policy regards LTO of NPPs as valuable and facilitates it, then clearly this will encourage plant owners to plan accordingly and make the necessary investments well in advance. A decision to allow LTO to go ahead may often be easier to take from a political perspective than the alternative decision to construct replacement generating capacity. However, in some cases NPP owners have continued to plan for possible LTO even where political support for it is unclear.

It is vital to build public confidence in the LTO of NPPs. While the public in the immediate area around an existing nuclear plant is usually supportive, nevertheless in most cases, LTO might raise concerns about safety. The public needs to be properly informed about plans for LTO and the basis for ensuring that safety will not be compromised. Furthermore, it is necessary to discuss the advantages and concerns about LTO.

The availability of the necessary nuclear fuel cycle and waste management facilities will need to be assured for LTO. The costs of providing such support facilities will, of course, need to be considered in the overall assessment of the costs and benefits. However, an important benefit of LTO will be a reduction in specific (per kWh) costs for waste management and decommissioning.

With LTO, NPPs may well operate for a total lifetime of 50 to 60 years. For this reason, management and preservation of knowledge are of critical importance. NPPs can be considered multi-generational projects, which will be the responsibility of several generations of engineers and other specialists over their lifetime. Steps should be taken by plant owners and by governments to support education programmes and provide suitable career opportunities for young scientists and engineers to guarantee a sufficiently large skilled workforce for the nuclear industry.

International co-operation and co-ordination are important in building confidence in LTO. There is a need to ensure that internationally recognised norms apply to all NPPs, to address the concerns of governments and the public in neighbouring countries. At the regulatory level, there is considerable scope for exchange of experience and information about plants with similar reactor designs, and this is likely to result in a considerable degree of harmonisation of requirements for LTO. International organisations have an important role to play here.

At the industrial level, co-operation between plant operators, reactor vendors and technical support organisations from around the world in planning and in R&D will help ensure that the best practice is followed in implementing PLiM programmes for LTO at NPPs in all countries. This is especially true where plants have been built to similar designs in several countries. Such co-operation can also help ensure that the expected benefits of LTO can be realised as widely as possible.

6.2 Conclusions

While the LTO of each plant must be considered individually in the light of its particular condition and economic circumstances, the general conclusion from studies carried out in several OECD/NEA member countries is that, for most reactor types, there are no significant technical challenges known which would limit plant lifetime to less than 50 to 60 years.

LTO has several potential advantages for the owners of NPPs, as well as for the wider society, although the nuclear option is viewed differently in different countries.

- The principal advantages are economic, in that extending the life of a major generating asset avoids the need for immediate investment in new generating capacity. The capital costs of LTO will be much smaller than investment in any type of replacement capacity, although there might be a need for some additional investment in plant upgrading. With nuclear fuel costs being generally lower and more stable than fossil fuel costs, this means that LTO can be expected to provide electricity at a lower cost than any other available option, which has a clear benefit to the national economy.

- In addition, LTO of existing NPPs contributes to security and stability of energy supply and to maintaining the diversity of energy sources.
- Furthermore, it can do this without the significant environmental impacts that would be created by alternative power generation options (notably CO_2 emissions). Most countries with operating NPPs consider nuclear energy contributes to the sustainability of their overall energy supply system, in that it minimises the long-term and irreversible impacts on the environment of meeting current energy demand.

LTO can potentially provide a bridge between the present generation of NPPs and future generations of power plants – either nuclear or non-nuclear. With 85% of OECD nuclear capacity already over 15 years old, if nuclear capacity is not to decline significantly then LTO of existing NPPs will be necessary to cover the period until Generation III, Generation III+ (and later Generation IV) plants can replace in large scale the current second generation reactor fleet in operation.

PLiM programmes for LTO of NPPs also require the support of adequate R&D capabilities, particularly for material degradation and unknown phenomena. As well as human resources such as scientists and engineers, this means that the facilities of the various nuclear research centres and laboratories in several countries which are playing a vital role in such areas as ageing management will need to be maintained. Some basic research activities which are essential for the success of LTO might benefit from governmental support in countries wishing to maintain or expand their reliance on nuclear energy.

Safety is of paramount importance in the operation of a NPP. Of course, existing NPPs were designed and constructed according to the licensing requirements and regulatory standards of the time, using technologies and knowledge then available. These requirements were sufficiently stringent to ensure that a considerable amount of conservatism was built in to the safety and design margins. Operating/industrial experience, improved analytical techniques and training of personnel mean that this conservatism can be allowed for in considering the safety of LTO, though proper regard must still be given to the possibility of unknown ageing mechanisms.

Appendix A

LIST OF EXPERT GROUP MEMBERS

Austria

Dr. Helmut Hirsch
Austrian Nuclear Advisory Board
Tilsiter Straße 41
D-30657 Hannover
Tel: +49-511-606 30 28
EM: cervus@onlinehome.de

DIng. Geert Weimann
Buchberg Straße
A-1014 Wien
Tel: +43-676 500 8080
EM: geert.weimann@europe.com

Belgium

Eric van Walle
SCK•CEN
Boeretang 200
B-2400 Mol
Tel: +32 14 33 30 00
EM: evwalle@sckcen.be

Paul Havard
S.A. ELECTRABEL
Boulevard du Régent, 8
B-1000 Bruxelles
Tel: +32 2 382 2559
EM: Paul.Havard@electrabel.com

Czech Republic

Ladislav Dubský
CEZ – Dukovany NPP
CZ-675 50 Dukovany
Tel: +420 56110 4819/2217
EM: Ladislav.Dubsky01@cez.cz

Finland

Liisa Heikinheimo
VTT
P.O.Box 1000
FI-02044 VTT
Tel: +358 0227225354
Fax: +358 07227002
EM: liisa.heikinheimo@vtt.fi

France

Patrick Raymond
Direction de l’Énergie nucléaire
(DEN/DSNI)
CEA – Centre d’étude de Saclay, Bât. 121
F-91191 Gif-sur-Yvette Cedex
Tel: +33 (0)1 69 08 56 96
EM: patrick.raymond@cea.fr

Hungary

Tamás J. Katona
Nuclear Power Plant Paks Ltd.
P.O. Box 71
H-7031 Paks
Tel: +36 20 973 8026
EM: katonat@npp.hu

Mihály Lehota
Hungarian Atomic Energy Authority
P.O. Box 676
H-1539 Budapest
Tel: +36-1-436-4807
EM: lehota@haea.gov.hu

Slovak Republic

Ludovit Kupca
NPP Bohunice
SK-91931 Jaslovske Bohunice
Tel: +421 805 555 2410
Fax: +421 805 559 1527
EM: Kupca.ludovit@ebo.seas.sk

Spain

Miguel Morales Lobo
TECNATOM S.A.
Integrity of Components
Avenida Montes de Oca, 1
ES-28709 San Sebastian de los Reyes, Madrid
Tel: +34 91 659 8722
EM: mmorales@tecnatom.es

Javier Alonso Chicote
TECNATOM S.A.
Avenida Montes de Oca, 1
ES-28709 San Sebastian de los Reyes, Madrid
Tel: +34 91 659 8600
Fax: +34 91 659 86 77
EM: jalonso@tecnatom.es

Sweden

Karl-Fredrik Ingemarsson
Vattenfall AB Generation
Jämtlandsgatan 99
S-162 87 Stockholm
Tel: +46 8 739 5465
EM: Karl-Fredrik.Ingemarsson@vattenfall.com

United Kingdom

Chris Eley
British Energy
Barnett Way, Barnwood
UK-Gloucester GL4 3RS
Tel: +44 1452 652585
EM: chris.eley@british-energy.com

David Norfolk
British Energy
Barnett Way, Barnwood
UK-Gloucester GL4 3RS
Tel: +44 (0) 1452 654113
Fax: +44 (0) 1452 652900
EM: david.norfolk@british-energy.com

United States

Elizabeth G. Lisann
US Delegation to the OECD in Paris
12 avenue Raphaël,
F-75116 Paris
Tel: 33(0)1 45 24 74 24
EM: lisanneg@usoecd.org

INTERNATIONAL ORGANISATIONS

International Atomic Energy Agency

Ki-Sig Kang
Nuclear Power Engineering Section
Division of Nuclear Power, IAEA
P.O. Box 100
A-1011 Vienna
Tel: +43 1 2600 22796
EM: Ki-Sig.KANG@iaea.org

European Commission

Claude Rieg
EC – JRC – IE
Postbus 2
NL-1755 ZG Petten
Tel: +31 224 56 5153/5184 (Sec.)
EM: claude-ives.rieg@jrc.nl

OECD Nuclear Energy Agency

Nuclear Development Division
Le Seine Saint-Germain
12 boulevard des Iles
F-92130 Issy les Moulineaux

Stan Gordelier
Head of Division
Tel: +33 (0)1 45 24 10 60
EM: stan.gordelier@oecd.org

Evelyne Bertel	Tel:	+33 (0)1 45 24 10 65
Deputy Head	EM:	evelyne.bertel@oecd.org
Pál Kovács	Tel:	+33 (0)1 45 24 10 68
Administrator	EM:	pal.kovacs@oecd.org
Martin Taylor	Tel:	+33 (0)1 45 24 10 67
Consultant	EM:	martin.taylor@oecd.org

Appendix B

QUESTIONNAIRE

1. **Describe the overall current nuclear energy policy of your country** (e.g., phase out, stagnation, development) **and provide information on the social context surrounding nuclear energy** (e.g., general support, strong anti-nuclear movements, local opposition to nuclear facilities, public and political acceptance of PLIM activities):

2. **Give list of the nuclear power plants in operation or in construction and the status of PLIM activities for each plant.**

Name of the plant	Type, capacity	Commissioning date	Planned closure date	Plant life management activities*	Expected closure date after PLIM

* Please list the plant life management/extension activities already completed, ongoing and/or planned. If necessary attach a textual description and schedule of the activities completed, ongoing and/or planned.

3. Outcomes/results obtained or expected from PLIM activities

(e.g., life extension, safety enhancement, capacity up rating, improved fuel management capabilities, cost reduction)

4. Decision-making process for PLIM activities

4.1 Describe the motivation and decision making process of the plant owner/operator (e.g., cost/benefit analysis, assessment of alternatives, manpower/staff management).

4.2 Describe the regulatory framework (legal and safety requirements, Parliament approval, political or governmental involvement) and decision-making process for obtaining the authorisation necessary for undertaking PLIM activities (e.g., reports to be prepared, authorities involved, time schedule).

4.3 If applicable, describe the involvement of local, regional and global public in the decision-making process.

5. Technical challenges

Describe the technical issues and concerns that had/will have to be addressed in the process of implementing PLIM activities, including knowledge acquisition or preservation and manpower training.

6. Economic and financing issues

Describe the financing scheme adopted for covering PLIM expenses, if available; please provide information on the cost of PLIM activities (e.g., number of man/months for various categories of workers, equipment needed, studies, etc.). Describe the resources management (utility resources, predictability of investment, etc.).

7. International context

Describe the impact, if any, of the international context on PLIM activities in your country (e.g., role of international conventions, international reports and recommendations issued by organisations such as the IAEA, role of international references, international trends, tendencies, perspectives, and differences between decision-making environments in different countries).

Appendix C

LIST OF ACRONYMS

AGR	Advanced gas-cooled reactor
AM	Ageing management
AMP	Ageing management programme
BNEN	Belgian Nuclear Higher Education Network
CANDU	Canadian Deuterium Uranium Reactor
EBP	Extra Budgetary Programme
EC	European Commission
ENEN	European Nuclear Education Network Association
EPR	European Power Reactor
EU	European Union
IAEA	International Atomic Energy Agency
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
LTO	Long-term operation
LWR	Light water reactor
NDA	Nuclear Decommissioning Authority
NDC	Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle
NPP	Nuclear power plant
NRC	Nuclear Regulatory Commission
O&M	Operation and maintenance
OECD/NEA	Organisation for Economic Co-operation and Development/Nuclear Energy Agency
PLiM	Plant life management
PSR	Periodic safety review
SAFIR	Finnish public research programme on nuclear power plant safety
SALTO	Safety aspects of long-term operation
SCM	Steering Committee Meeting
SKI	Swedish Nuclear Power Inspectorate
SSC	Systems, structures and components
VVER	Water-cooled and water moderated energetic reactor
WANO	World Association of Nuclear Operators
WENRA	Western European Nuclear Regulators Association

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This book, prepared by NEA member country experts, contains data and analyses relevant to nuclear power plant life management and the plants' extended, longer-term operation (LTO). It addresses technical, economic and environmental aspects and provides insights into the benefits and challenges of plant life management and LTO.

It will be of interest to policy makers and senior managers in the nuclear power sector and governmental bodies involved in nuclear power programme design and management. The data and information on current trends in nuclear power plant life management will be useful to researchers and analysts working in the field of nuclear energy system assessment.

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