TECHNICAL REPORTS SERIES NO. 448

Plant Life Management for Long Term Operation of Light Water Reactors

Principles and guidelines

IAEA
International Atomic Energy Agency

PLANT LIFE MANAGEMENT FOR LONG TERM OPERATION OF LIGHT WATER REACTORS

PRINCIPLES AND GUIDELINES

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PRINCIPLES AND GUIDELINES

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2006

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Sales and Promotion, Publishing Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
http://www.iaea.org/books

Printed by the IAEA in Austria
December 2006
STI/DOC/010/448

IAEA Library Cataloguing in Publication Data

Plant Life Management for Long Term Operation of Light Water Reactors. – Vienna : International Atomic Energy Agency, 2006.
p. ; 24 cm. — (Technical reports series, ISSN 0074–1914)
STI/DOC/010/448
ISBN 92–0–101506–2
Includes bibliographical references.

1. Nuclear reactors — Decomissioning. I. International Atomic Energy Agency. II. Series: Technical reports Series (International Atomic Energy Agency) ; 448.

IAEAL 6–00436

FOREWORD

The subject of this report was originally suggested by the IAEA Technical Working Group on Life Management of Nuclear Power Plants. It was then approved by the IAEA for work to begin in 2004. The participants in the group felt that it was time to address plant life management and ageing issues from the point of view of long term operation and licence renewal. It is believed that the nuclear power industry will only be able to survive if plant economics are favourable and safety is maintained. Therefore, the issue of ageing and obsolescence has to be addressed from an operational and safety standpoint, but also in the context of plant economics in terms of the cost of electricity production, including initial and recurring capital costs.

Use of new technologies, such as advanced in-service inspection and condition based maintenance, should be considered, not only to predict the consequences of ageing and guard against them, but also to monitor equipment performance throughout the lifetime of the plant and to help establish replacement schedules for critical systems, structures and components, and to better estimate the optimum end of the operating licence, which means the end of the nuclear power plant's lifetime.

The importance of nuclear power plant life management in facilitating the technical and economic goals of long term operation is presented in this report in terms of the requirement to ensure safe long term supplies of electricity in the most economically competitive way. Safe and reliable operation is discussed in terms of the overall economic benefits when plant life management is implemented. Preconditions for plant life management for long term operation are identified and approaches are reviewed. Plant life management should not be associated only with the extension of the operational lifetime of the nuclear power plant, but with an owner's attitude and a rational approach of the operating company towards running the business economically and safely.

This publication provides operating organizations and regulatory bodies with a comprehensive state of the science and technology overview of the main issues concerning safe long term operation, ageing management and the basic economic aspects of plant life management. It has been prepared by a group of experts from France, Hungary, Japan, the Republic of Korea, Spain, Switzerland and the United States of America. Also, reflecting the global interest in plant life management for long term operation and the need for collaboration in order to optimize resources, the European Commission's Joint Research Centre at Petten was actively involved in its preparation.

The work of all the contributors to the drafting and final review of this publication, listed at the end, is greatly appreciated. In particular the IAEA acknowledges the contributions of T. Katona (Hungary), G. Young (USA), F. Sevini (European Commission), L. Francia (Spain) and G. Bezdikian (France). Special thanks are due to P. Tipping (Switzerland), who also chaired the technical meetings. The IAEA officer responsible for this publication was Ki-Sig Kang of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

The primary task of nuclear power plants is to reliably deliver sufficient supplies of electric power in the safest and most profitable way. As in any other technology driven industry, improvements, monitoring, replacements and inspections are necessary operationally, as are economically driven actions to keep unplanned outages due to equipment failure to a minimum. Safety oriented activities are also essential to prevent or limit potential releases of radioactivity to the population and environment in cases of equipment failure.

A nuclear power plant's operating equipment, generically known as systems, structures and components, is subjected to a variety of chemical, mechanical and physical influences during operation. With time, stressors such as corrosion, load variations, flow conditions, temperature and neutron irradiation cause changes in materials. These time dependent changes are referred to as ageing. The effects of ageing become evident when there is a reduction in design margins that may approach established safety margins, and/or an increase in forced outages and repairs. It should be noted that ageing effects have usually been allowed for in a conservative manner in design specifications. However, particularly for large passive components whose replacement is impossible or not economically viable, ageing effects have the potential to be life limiting, especially if they occur at a faster rate and more severely than foreseen in the original design specifications and/or expectations.

The design lifetime of a nuclear power plant does not necessarily equate with the licence lifetime, the physical, technological or even the political end of life in terms of its ability to fulfill safety and electricity production requirements. Even allowing for significant ageing effects, it is quite feasible that many nuclear power plants will be able to operate longer than their original design lifetimes, provided appropriate and proven ageing management measures are implemented in a timely manner. This has generally been recognized by operating organizations and regulatory bodies alike, as seen in the number of licence renewal applications and approvals in the USA and elsewhere, and extended licensing procedures primarily based on periodic evaluation of safety (i.e. periodic safety reviews). Even nuclear power plants with unlimited licence terms will be able to operate only if safety requirements are fulfilled.

Operation of nuclear power plants beyond their original design lifetimes can make economic sense but, as a necessary precondition, regulatory bodies must be assured that the safety relevant systems, structures and components will continue to perform up to their technical specifications and satisfy all safety requirements. Such assurance may be gained by showing the regulatory body that state of science and technological methods and analyses have been used to identify, mitigate, manage or eradicate the ageing mechanism under consideration. A plant life management approach is a tool allowing an operating organization to follow ageing effects in systems, structures and components and to help in making decisions concerning when and how to repair, replace or modify them in an economically optimal way. Plant life management can be seen as a precursor to operation up to and even beyond the original design lifetime, referred to here as long term operation.

This publication describes plant life management from the technological, regulatory, economic and human standpoints. Furthermore, research requirements and international best practices that have been identified are highlighted (Appendix I). Principles and guidelines on how plant life management may be implemented and used to advantage are provided for operating organizations, with a view to ensuring safe long term operation of their nuclear power plants.

Article 6 of the IAEA Convention on Nuclear Safety (CNS) states the following concerning nuclear installations [1]:

> "Each Contracting Party shall take the appropriate steps to ensure that the safety of nuclear installations existing at the time the Convention enters into force for that Contracting Party is reviewed as soon as possible. When necessary in the context of this Convention, the Contracting Party shall ensure that all reasonably practicable improvements are made as a matter of urgency to upgrade the safety of the nuclear installation. If such upgrading cannot be achieved, plans should be implemented to shut down the nuclear installation as soon as practically possible. The timing of the shut-down may take into account the whole energy context and possible alternatives as well as the social, environmental and economic impact."

Those countries that have signed and ratified the Convention on Nuclear Safety are therefore required to upgrade safety by means of 'reasonably practical improvements' to their nuclear power plants. Plant life management addresses those actions necessary not only to ensure safety, but to provide nuclear power plant owners and operating organizations with a logical basis on which to form a policy or strategy concerning applications for long term operation.

1.1. DEFINITION OF TERMINOLOGY

The following standard IAEA terminology and definitions have been adopted throughout this publication:

— *Ageing:* the continuous, time dependent degradation of systems, structures and components due to normal service conditions, which include normal operation and transient conditions. Postulated accident and post-accident conditions are excluded. It is emphasized here that ageing is a broad term and may even be extended to include the extent and current level of personnel training (knowledge management aspects) and even the status of documentation (level of updating and relevance to the actual situation) used in the nuclear power plant.
— *Ageing management:* engineering, operational and maintenance actions to control, within acceptable limits, ageing degradation of systems, structures and components.
— *Ageing management programme:* any programme or activity that adequately manages the effects of ageing (e.g. maintenance programme, chemistry programme, inspection or surveillance activities).
— *Plant life management:* the integration of ageing management and economic planning to:
  - Maintain a high level of safety;
  - Optimize the operation, maintenance and service life of systems, structures and components;
  - Maintain an acceptable performance level;
  - Maximize return on investment over the service life of the nuclear power plant;
  - Provide operating organizations and owners with the optimum preconditions for achieving long term operation.

Plant life management is a methodology whereby all expenses are optimized to favour commercial profitability and competitiveness, while safe and reliable supplies of electric power are being produced.

Various other definitions apply to plant life management. For example, the Electric Power Research Institute (EPRI) in the USA has produced a glossary of common ageing terms. This glossary is being internationalized by the OECD Nuclear Energy Agency (OECO/NEA) and, if adopted, will form the basis for the terminology in this field.

In the case of western design nuclear power plants some of the analyses supporting plant safety assessment have been carried out based on a design lifetime of 40 years, for example on those components that cannot be replaced, such as the reactor pressure vessel and the containment. Consequently, these analyses cannot initially be used for plant safety assessment beyond 40 years of operation since a review of their acceptability for longer design lifetime hypotheses is required.

1.2. NECESSITY OF PLANT LIFE MANAGEMENT

The world's nuclear power plants are, on average, approximately 20 years old (Fig. 1) and most plants are believed to be able to operate for 60 years or more. The design lifetime of a nuclear power plant is typically 30 to 40 years. This may be extended by 10 to 20 years or more provided that the plant can demonstrate by analysis, trending, equipment and system upgrades, increased vigilance, testing, ageing management and other means, that licence renewal or permission to continue operation based on the original licence poses no threat to public health, safety or the environment.

The Calvert Cliffs nuclear power plant in the USA and Novovoronezh units 3 and 4 in the Russian Federation were among the first plants to receive approval to operate up to 20 years (5 years for Novovoronezh) beyond their original licences.

The relicensing process for the Calvert Cliffs nuclear power plant was successful and encouraged other plants in the USA such as Oconee, Arkansas Nuclear One and others to follow suit. As of the end of 2005, thirty-five nuclear power plant units had successfully and efficiently obtained licence renewal with

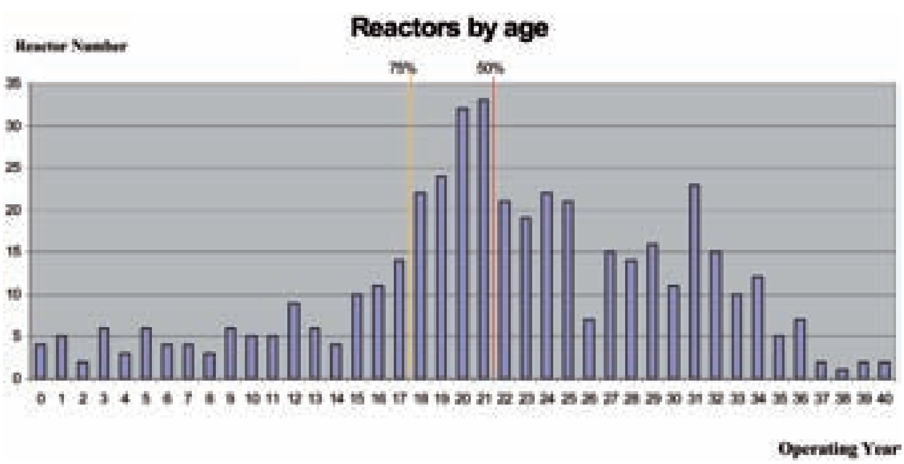


FIG. 1. Number of reactors in existence, by operating age (as of May 2006).

no major stipulations other than what is reasonably expected to ensure safe operation. In fact, almost all US plants have plans to apply for licence renewal and the relicensing procedures of the US Nuclear Regulatory Commission (NRC) are being further streamlined to implement lessons learned and make improvements to the regulatory process. This trend towards licence renewal efforts for long term operation contrasts with the situation about ten years ago, when nuclear power plants were more focused on dismantling and decommissioning.

The continued and increasing need for electric power and political pressures over environmental issues, as well as the slowdown in construction of new nuclear power plants, make convincing arguments for ensuring that existing nuclear power plants should not only continue to operate safely, but that they do so for longer periods than originally envisaged.

The Kyoto agreement came into force in February 2005 and has to date been ratified by 140 countries. The concentration of carbon dioxide, a so-called 'greenhouse gas', was at a level of 372 parts per million as of April 2005. This is higher than that calculated to have been present in the Earth's atmosphere during the past 42 000 years. The contribution of nuclear power to energy generation without the emission of greenhouse gases is significant.

Notwithstanding the environmental issues, long term operation of nuclear power plants is an economic issue, whereby operating organizations are striving to maximize the return on their investment by continued operation as long as safety requirements are complied with. Another factor is that fossil fuels are a finite resource. This also has a political aspect the certainty of supplies of fossil fuels may become difficult to guarantee in the future. It must, however, be acknowledged that the generation of electricity by nuclear power plants also gives rise to radioactive waste which, although not released as greenhouse gases, still may have an impact on the population and the environment. As operating organizations strive towards long term operation it is thus essential for them to plan for the storage and final disposal of the extra waste that will be generated. Sufficient spent fuel storage capacity must be planned for well in advance because of the time required for procurement and construction.

Disposal facilities will have to be found to safely store high level waste. Low and medium level radioactive waste will also need treatment and proper disposal as nuclear power plants operate longer. Finally, sufficient human and monetary resources, as well as state of technology methods, will have to be available for decommissioning. This requires long term planning on both the technical and managerial levels.

Nuclear power plants can fulfil their obligations to operate safely and be economically competitive by ensuring that their systems, structures and components are maintained in an optimum way through application of plant life management. It is, prima facie, cheaper to implement plant life management than to build a new nuclear power plant or another type of electricity generating plant.

1.3. GOALS OF PLANT LIFE MANAGEMENT

The goal of the nuclear power plant owners and/or operating organizations is to operate for as long as this is economically feasible and safety can be maintained. Plant life management is a tool for achieving this. Plant life management is a system of programmes and procedures for satisfying the requirements for safe operation while producing power competitively, for a time period which makes both technical and economic sense.

1.4. SCOPE OF THE PUBLICATION

This publication was developed based on the international experience of the nuclear power industry and input from experts on the ageing of systems, structures and components, long term operation, licence renewal, power uprates, regulatory aspects, periodic safety reviews, safety issues and economic improvements. It should be noted that plant life management may in a wider sense also entail human and organizational factors since sufficient and well trained personnel are essential for carrying out correct operating practices and also for maintaining exact documentation of operating experience. The importance of personnel/human factors/resources and knowledge management is thus also addressed.

1.5. OBJECTIVES OF THE PUBLICATION

Plant life management is not only a technical system, but requires an intention on the part of owners to keep the plant in operation as long as possible from a safety and business point of view. Asset management is thus a significant parameter and driving force behind plant life management.

The main objectives of this publication are to:

(a) Define plant life management;
(b) Explain the general approach to plant life management;

(c) Define the relationship between nuclear power plant maintenance and plant life management;
(d) Assemble a list of good practices and formulate guidelines for ageing management of critical systems, structures and components;
(e) Define the relationship between plant life management and long term operation.

Additionally, the issues of plant life management for long term operation are discussed in human, technological, economic and regulatory terms, as is the importance of the exchange of information regarding ‘lessons learned’.

1.6. STRUCTURE

Section 2 discusses current trends in plant life management for long term operation, as well as the preconditions for and approaches to it. Section 3 discusses the general approach of plant life management for long term operation. The approaches are not necessarily the same for different reactor types and different countries, but a growing need to create an internationally harmonized approach is perceived and many similarities in the approaches are evident. Section 4 examines the issues and themes involved in plant life management for long term operation. This includes key objectives of such programmes, regulatory considerations, asset management perspectives, power uprate, integration of methodologies into current programmes, organizational and technology infrastructure considerations, the importance of effective plant data management and finally, benefits and costs. Guidance on the implementation of the systematic ageing management process is provided as a means for increasing the technical and cost effectiveness of ageing management. Section 5 explains the relationship between maintenance and plant life management for achieving long term operating goals. The older a nuclear power plant gets the more likely it becomes that backfit or replacement of systems, structures and components (e.g. steam generator replacement) and special mitigation actions (e.g. reactor pressure vessel annealing) will need to be addressed to maintain safe and reliable plant operation. The relationship between maintenance and ageing management, condition based maintenance and the maintenance rule is introduced in Section 5. Section 6 introduces the current research activities on plant life management for long term operation, and also the European Commission programme. Section 7 provides conclusions and recommendations.

2. CURRENT TRENDS

2.1. PRECONDITIONS FOR PLANT LIFE MANAGEMENT

The use of plant life management as a method for managing the operating lifetime of nuclear power plants has preconditions. These are mainly technical in nature and related to previous practices and knowledge of the operating organization, such as:

(a) Good general condition of the plant and few if any unresolved issues;
(b) Existence of a well established practice for operation, maintenance, testing, surveillance, monitoring and inspection;
(c) Existence of all relevant nuclear power plant documents, data records, reports, and life histories of systems, structures and components;
(d) Sufficient knowledge of the design basis stressors accrued to date (number of load cycles, material properties, etc.).

Generally, the basic preconditions for the implementation of plant life management are good practices from startup on for keeping the plant in optimum condition, and the operating organization having sufficient information about past operating experience to make reliable forecasts and balanced decisions regarding all aspects of future operation. The nuclear power plant's current status with respect to the condition of its systems, structures and components is another vital parameter.

Key considerations for plant life management programmes include:

(1) Definition of realistic economic targets (i.e. target duration of long term operation);
(2) Identification of safety issues related to systems, structures and components, their ranking and timely scheduling of necessary measures;
(3) Identification of technical issues affecting the operational performance and costs;
(4) Forecasting of the market conditions and evolution of the economic environment;
(5) Forecasting of the political and regulatory environment;
(6) Availability of knowledge and personnel required to carry out the tasks.

Some of the above points will be difficult to address, but the most important starting point is the definition of the target operating lifetime of the nuclear power plant concerned. The programmes and measures for ensuring the required safety and performance levels, as well as the investments needed, depend on the targeted absolute end of operation. An ideal point in time has to be selected to ensure amortization of the investments for the plant life management actions foreseen (e.g. major replacements of systems, structures and components), and to obtain the expected profit while ensuring safe operation.

From the safety point of view the possible operating lifetime depends on the condition of non-replaceable long lived passive systems, structures and components. The required condition of systems, structures and components other than long lived passive ones may be ensured by proper maintenance, repair or replacement. This is mainly a matter of investment. The condition of large but still technologically replaceable systems, structures and components such as steam generators, reactor pressure vessel heads and core shrouds may still limit a plant's economic viability and hence its operating lifetime.

The optimum economic period of operation also depends on the plant's condition and that of long lived passive systems, structures and components. A large number of old and/or obsolete but replaceable systems, structures and components may affect the operational lifetime of the nuclear power plant if their reconstruction or replacement would make economic long term operation impossible or decrease competitiveness (loss of market share). The reasonable (target) operating lifetime should be defined taking into account the market conditions and forecast for business development. The period of operation will tend to vary with time as the business environment changes.

Plant life management may thus be seen as a management tool or method to:

(i) Achieve a balanced time target for safe operation during the lifetime of the nuclear power plant;
(ii) Deal with the ageing of systems, structures and components while maintaining optimal safety and economy.

2.1.1. Preconditions for the implementation of plant life management for long term operation

As increasing international experience shows, the operating lives of nuclear power plants are realistically and potentially longer than the original design lives. However, the implementation of plant life management for long term operation has quite specific preconditions (or conditions). The wish for long term operation is subject to various other factors, including political and regulatory approval. The system of regulatory control and approval depends on the political and legal system of the particular country involved. Basically, two regulatory concepts exist: licence renewal and periodic safety reviews. In countries where the licence is granted for a given operating lifetime a formal licence renewal process is used. In countries where the operating lifetime is not limited with the licence periodic safety reviews are usually a regulatory tool used to assess the utility or operating organization's arguments for continued or long term operation. The systems and regulatory approaches are discussed further in Section 7.

Important overall preconditions for plant life management for long term operation (independent from the regulatory concept) include:[1]

(a) Public acceptance of the nuclear power plant's intention to operate long term;
(b) Political acceptance;
(c) Acceptance of the international community, particularly neighbouring countries;
(d) Economic viability.

Safety in nuclear power plant operation must be a priority at all times. If an accident occurs the nuclear power plant will, depending on its severity, cease operation for some time or even shut down permanently (if there is a danger of a non-recoverable loss). In addition, again depending on the severity of the accident, other operating nuclear power plants may have to be shut down (e.g. if generic weaknesses and/or design deficiencies were identified), or additional regulatory and economic penalties or restrictions may be applied.

The operating organization and owner's decision to carry out plant life management for long term operation will primarily be an economic one, but safety concerns have to be examined, satisfied, amply addressed and resolved, together with the regulatory authority. Political and other issues may, however, still impact the operating organizations' wishes to achieve long term operation.

2.2. APPROACHES TO PLANT LIFE MANAGEMENT

Two conceptual regulatory approaches to long term operation exist. One is based on periodic safety reviews [2], the other on licence renewal [3]. US practice and regulations follow the first concept while most of the European countries and Japan use periodic safety reviews to evaluate arguments for

[1] The existence, or future availability of sufficient radioactive waste storage capacity is an important issue for long term operation.

TABLE 1. EXAMPLES OF LICENCE TERMS IN IAEA MEMBER STATES

Limited term	Unlimited term with periodic safety review
Argentina (30 years)	Belgium (10 years)
Canada (3–5 years)	France (10 years)
Finland (10–20 years)	Germany (10 years)
Hungary (30 years)	India (9 years)
Republic of Korea (30–40 years)	Japan (10 years)
UK (10 years)	Spain (10 years)
USA (40 years)	Sweden (8–10 years)
	Switzerland (10 years)

continued or long term operation. Both approaches have been adapted in some Member States (see Table 1).

The technical requirements and the elements of the plant life management programme remain the same for all systems (i.e. preventive maintenance and ageing management programmes, time limited ageing analyses, maintenance of equipment qualification and response to the issues of obsolescence). From the regulatory point of view it is important to control the operating organization's ageing management practices and to check the validity of ageing forecasts for systems, structures and components important to safety. As a general rule, economic optimization is logically applied to plant life management programmes. The environmental impact of long term operation as a consequence of plant life management has to be assessed, although the detail of the study depends on the regulatory requirements.

2.2.1. Licence renewal applications for nuclear power plants operating in the USA

Licence renewal in the USA is based on the prerequisite that ageing management of active components and systems is adequately addressed by the maintenance requirements and other established regulatory processes [4]. This assumption is validated by the NRC regulatory oversight of the current licensing basis, which includes regulatory oversight to ensure implementation of continuous performance monitoring of active system functions in accordance with the maintenance rule, ongoing compliance with technical operating specifications and regular updating of the final safety analysis report. Licence renewal focuses primarily on the following three areas:

(1) Integrated plant assessment to evaluate the ageing management of passive, long lived systems, structures and components to ensure that they can support continued safe plant operation beyond the 40 year term of the original operating licence and remain within the safety requirements;
(2) Assessment of time limited ageing analyses (e.g. fatigue, neutron embrittlement, environmental qualification analysis) to address the additional 20 years of operation;
(3) Environmental impact assessment of the additional 20 years of operation.

The primary bases for determining that the ageing management of passive systems, structures and components is adequate are operating experience, research results and material sciences. Considerable documentation of operating experience is available in published reports such as NRC regulatory guides and generic ageing lessons learned (GALL) reports [5], and industry reports [6]. Nuclear power plants must have at least twenty years of operating experience to demonstrate the adequacy of existing ageing management programmes prior to submission of an application for licence renewal. Licence renewal provides nuclear power plants with the regulatory option to continue to operate beyond the 40 year term of their original licence, while the final decision to continue operation will depend on economic analyses. If the plant becomes uneconomic to operate it may be shut down and decommissioned at any time.

The current economic situation in the USA encourages licence renewal. The cost of electricity production from nuclear power plants is lower than that from any other competing source of electricity except hydro. Also, the cost of building replacement power plants of any type is significantly higher than the cost of licence renewal (i.e. tens of millions of US dollars for nuclear power plant licence renewal versus hundreds of millions or billions of US dollars for new plant construction). Environmental impact evaluations and/or public opposition to the creation of new sites may also cause considerable extra costs when construction of replacement plants and capacity is being considered as an option.

Some features of the environmental situation in the USA encourage licence renewal. Since nuclear power generation has little impact on the environment (especially the air), continuation of nuclear power plant operation helps ensure higher levels of air quality. Nuclear power is currently the single largest contributor to the voluntary US programme of reducing carbon emissions. The capacity gains made in the past decade have amounted to about half of the voluntary carbon reductions achieved so far by all US industries. Data for 2004 from the US Energy Information Administration indicate that nuclear power plants account for 73% of the emission free sources of electricity in the USA, with hydropower plants a distant second at 24% [7].

As a result of positive public opinion concerning the environmental advantages of nuclear power, the US nuclear industry is focusing public information campaigns on the ‘clean air’ and ‘emissions free generation’ messages, as shown in Fig. 2.

The US regulatory environment is currently favourable towards applications for licence renewal. Unlike the original plant licensing process, the licence renewal process is stable, predictable and efficient. By the end of 2005 more than 30% of operating US nuclear power plants had received renewed licences for 60 years of operation, and it is considered likely that more than 95% (possibly 100%) of the 104 licensed US plants will eventually obtain renewed licences.

The licence renewal process typically takes 4–5 years to complete. The operating organization takes about two years for the engineering and environmental assessment work needed to prepare an application, and the NRC takes about 22 months (within a range of 17–30 months based on experience so far) to review the application and prepare a safety evaluation report and environmental impact statement (Fig. 3). The overall cost of the licence renewal process is US $10–20 million (including operating organization costs and regulatory review fees) over this period.

The present net value of licence renewal, if all operating nuclear plants in the USA operate for 60 years, is estimated at approximately US $25 billion.

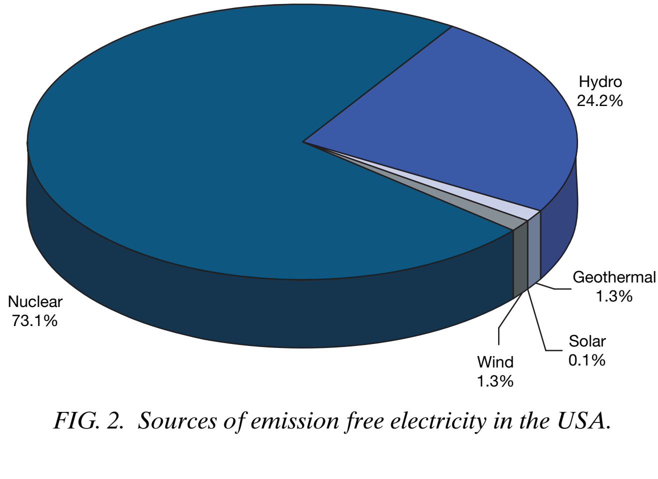


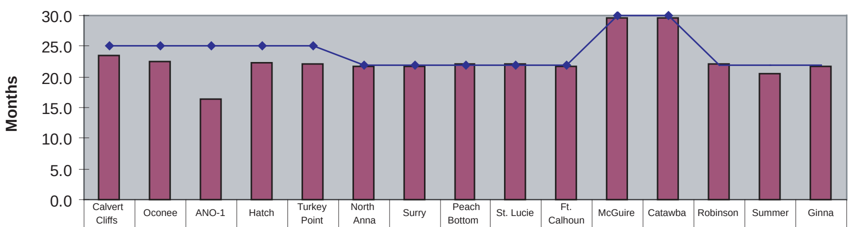
FIG. 2. Sources of emission free electricity in the USA.

This estimate is based on an average nuclear power production cost of 2.0 cents/kW·h and an average electricity selling price of 3.5 cents/kW·h, which is reasonable based on current economic conditions (Fig. 4).

Licence renewal addresses the nuclear safety aspects of continued plant operation, but does not address other important aspects of plant life management needed to ensure continued economic operation. Although licence renewal is a prerequisite for continued plant operation, plant life management is needed to address the additional issues associated with long term economic operation.

2.2.2. Periodic safety review applications in Japan and France

In many countries the safety performance of nuclear power plants is periodically followed up on using the periodic safety review methodology [2]. The regulatory review and acceptance of the periodic safety review gives the licensee permission to operate up to the end of the next periodic safety review



	Calvert Cliffs	Oconee	ANO-1	Hatch	Turkey Point	North Anna	Surry	Peach Bottom	St. Lucie	Ft. Calhoun	McGuire	Catawba	Robinson	Summer	Ginna
NRC Review (Actual)	23.4	22.5	16.3	22.2	22.1	21.7	21.7	22.1	22.0	21.7	29.6	29.6	22.1	20.6	21.7
NRC Review (Goal)	25	25	25	25	25	22	22	22	22	22	30	30	22	22	22

FIG. 3. Status of NRC licence renewal review schedules.

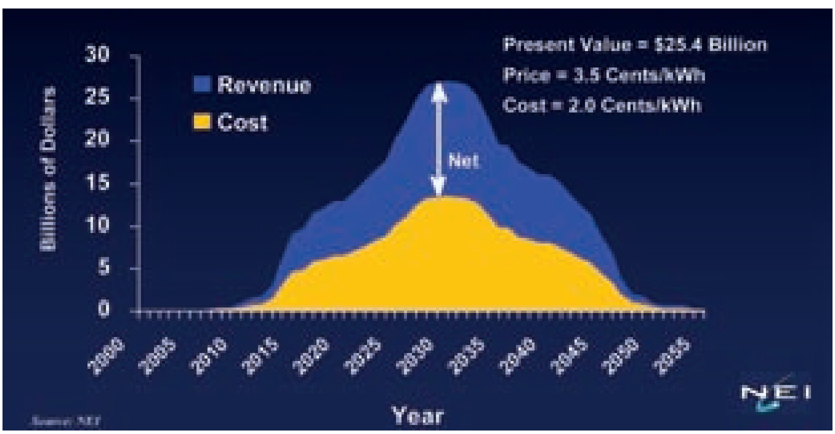


FIG. 4. Economic benefit of licence renewal (source: Nuclear Energy Institute).

cycle (usually 10 years). The regulatory system does not limit the number of periodic safety review cycles, even if the new cycle extends beyond the original design lifetime of the plant. The only condition is to demonstrate the safety of the plant's operation for the next periodic safety review cycle, while maintaining safety margins.

The periodic safety review is a tool that may be used by regulatory bodies to identify and resolve safety issues. In this framework, long term operation may be requested by applying the results of the periodic safety review and identifying and resolving the safety issues as a condition of operation for the new periodic safety review cycle. The periodic safety review is not an adequate tool to control changes and tendencies with an evolution period of less than ten years. It is also not suitable if the licensee needs a technological guarantee for long term operation longer than 10 years; in many cases economic considerations suggest extension of the original design lifetime by 20 years or more.

However, it must be noted here that the periodic safety review concept was developed as part of the normal regulatory or safety monitoring process, and not specifically to justify long term operation of a plant. The periodic safety review was originally used primarily to assess the safety status of plants designed to early standards. In these cases the periodic safety review gives an overall review of all aspects of plant operation that may be relevant to safety. This includes emergency arrangements, organization and administration, procedures, research findings and feedback of experience. All of them are mainly relevant to current operation and not directly related to the justification of long term operation.

According to current practice, the periodic safety review has to focus on the cumulative effects of plant ageing, assessment of plant status and modifications, operating experience, modifications to national safety standards, science and technology development and site hazard modifications. If the periodic safety review process is to be used to justify continued operation of the plant, special emphasis should be put on the assessment of the aged status and ageing management of those safety related systems, structures and components that limit the operating lifetime of the plant, i.e. those that cannot be replaced or readily reconstructed, such as the reactor pressure vessel and containment.

A periodic safety review carried out after the nuclear power plant's original design lifetime may require more detail, addressing the following:

(a) Evaluation of the plant's safety according to current standards;
(b) A new evaluation and/or qualification of items affected by time dependent phenomena;

(c) The ageing management programme, which has to be extended over the operating lifetime;
(d) A new safety assessment to show that the as-designed conservatism (not the safety margin) may be reduced, based on improved plant operating practices and better understanding of the degradation mechanisms. The overall safety margin must be kept consistent with current safety requirements.

In conclusion, a full scope periodic safety review applied with a view to long term operation is not different in principle from a review applied during the design lifetime at ten year intervals, but the emphasis has to be oriented to the ageing of systems, structures and components which limit the plant's total operating lifetime and always on the related safety issues. Table 2 shows the status of periodic safety reviews in IAEA Member States.

Japan

Thirty-five years have passed since the first commercial operation of a nuclear nuclear power plant in Japan. Fifty-four nuclear power plants are now in operation and among these, Tsuruga unit 1, Mihama units 1 and 2, Fukushima units 1 and 2, Shimane unit 1 and Takahama have been in operation for over 30 years.

The operating organization's safety management activities are governed by the safety preservation rules, approved by the Nuclear and Industrial Safety Agency (NISA). NISA conducts the Safety Preservation Inspection quarterly to check the operating organization's compliance with the safety preservation rules. Periodic inspection and safety management reviews are conducted by NISA and the Japan Nuclear Energy Society (JNS) within 13 months of the

TABLE 2. PERIODIC SAFETY REVIEW IMPLEMENTATION IN IAEA MEMBER STATES

Status	Member State
Periodic safety reviews completed	Belgium, Finland, France, Germany, Japan, Netherlands, South Africa, Spain, Sweden, Switzerland, UK
Periodic safety reviews being performed	Canada (Point Lepreau), China (Qinshan), Republic of Korea (KORI 1), Slovenia (Krško)
Periodic safety reviews being planned or considered	Brazil, Bulgaria, Czech Republic, India, Pakistan, Romania, Slovakia, Ukraine

previous periodic inspection (see Fig. 5). The periodic inspections are focused on the operating organization's maintenance activities. They are imposed on those systems, structures and components which have safety significance.

In Japan, light water reactor operating organizations perform periodic safety reviews on their nuclear power plants every 10 years. Periodic safety reviews started as a voluntary safety activity although the regulatory body examined the results. As of December 2003 they became a regulatory requirement. A standard periodic safety review consists of the following three key elements:

(1) Comprehensive evaluation of operating experience;
(2) Review of the activities of the past 10 years, e.g. data trends, inspection and maintenance records, improvements to systems, structures and components and management methods, feedback on events in Japanese and other nuclear power plants and lessons learned in the following areas:
    — Operation,
    — Maintenance,
    — Nuclear fuel management,
    — Radioactive waste management,
    — Emergency preparedness and planning;
(3) Check if the current safety activities have been appropriately improved, taking into account events in Japanese and other nuclear power plants.

Before 30 years of commercial operation are reached, operating organizations perform an in-depth and comprehensive periodic safety review, including a plant life management programme evaluation, and address the above elements. The plant life management programme evaluation may show where additional inspections and maintenance tasks are needed. Results of the plant life management programme are re-evaluated in the subsequent periodic safety reviews. Periodic safety reviews and plant life management programmes are not licensing processes. The regulatory body provides a one year (in effect, 13 month) operating licence after each refuelling outage, based on annual inspection results. However, periodic safety review and plant life management practices are important tools for assessing the prospects for long term operation of nuclear power plants.

To improve regulation of nuclear power plant activities involving ageing countermeasures, relevant laws were revised in 2002 and 2003 to codify the following activities of the operating organization, which it had previously carried out voluntarily:

(a) Operator's periodic inspection: The operating organization carries out the operator's periodic inspection within 13 months of the previous one. Its implementation is checked and overseen by JNES in the periodic safety management review. NISA evaluates the results of the review.

(b) Periodic safety management review and ageing countermeasures: The operating organization conducts the periodic safety review on each plant every 10 years following commissioning, and implements the ageing countermeasures seen to be necessary. The periodic safety review consists of the comprehensive evaluation of operating experience, the incorporation of the latest technical information and the ageing management review. Probabilistic safety assessment is requested on an optional basis as before. NISA checks the operating organization's implementation of the ageing countermeasures in the safety preservation inspection.

(c) Technical evaluation of plant ageing and 10 year maintenance programme: The operating organization evaluates plant ageing within 30 years of commissioning and every 10 years after that. Based on the technical evaluation, it develops a 10 year maintenance programme. NISA and JNES check the operating organization's implementation of that maintenance programme in the operator's periodic inspection and the periodic safety management review and ageing countermeasures.

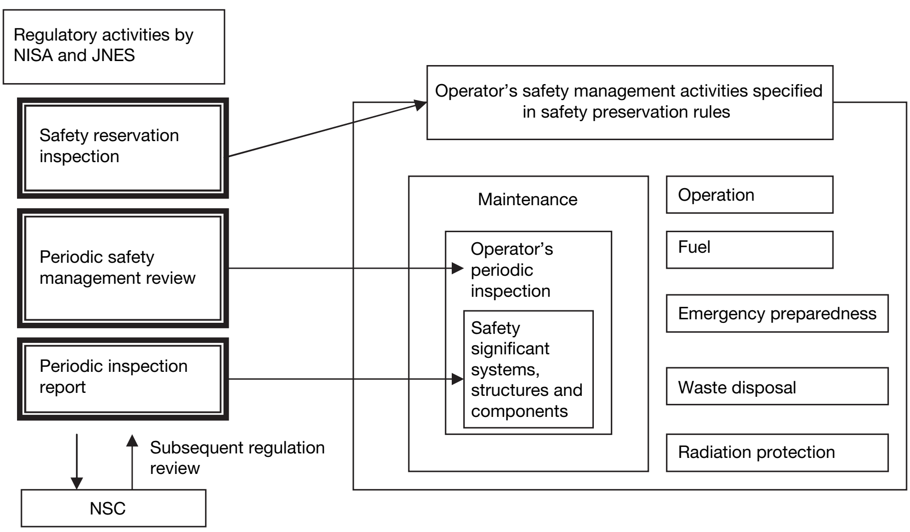


FIG. 5. Current regulatory inspection and review process for the operating period of nuclear power plants in Japan [8].

France

In France, like in many other countries, the operating lifetime of a nuclear power plant is affected by three main factors:

(1) Normal wear of its systems and components, which is particularly dependent on their age, operating conditions and maintenance practices applied to them;
(2) The safety level, which must consistently comply with the safety requirements applicable to nuclear power plants and which could change as a result of new regulations;
(3) Economic competitiveness, which must remain satisfactory compared with other energy production methods.

Regulations require that a periodic safety review be performed of each nuclear power plant after every 10 years of operation. There are no licence renewal procedures such as those used in the USA and there are no prescribed limits to the duration of the plants' operating lifetimes. Beginning with the commissioning of the plant, the French operating organization has to prepare a periodic safety review at the first 10 year outage. This periodic safety review is valid for the following 10 years, after which another is conducted.

The French operating organization uses periodic safety reviews for plant life management, with the following key elements and major directions:

(a) Good design and manufacture, including replacement parts and repairs;
(b) State of science and technology practices, with an updated construction code and standard or detailed specifications;
(c) Use of all available experience and knowledge;
(d) Taking into account maintenance and surveillance activities.

Four major principles are followed for the periodic safety review:

(1) Daily or periodic operation and maintenance inputs;
(2) Anticipation of exceptional maintenance (generic, costly, difficulties expected, etc.);
(3) A safety review of each plant every 10 years, including a systematic ageing management review, the results of which are used in the periodic safety review;
(4) The life management programme is reviewed at the corporate level.

The evaluation of operational effects from 40 to 60 years of operating experience requires complementary and specific ageing management programmes to be introduced in the periodic safety review and in the plant life management programme. All safety relevant components and structures are involved.

The procedure is based on a three step approach, in accordance with Ref. [9]:

— Step 1: selection of components: datasheet and grid;
— Step 2: degradation mechanisms: ageing analysis report;
— Step 3: comparison with existing practices: preventive basic maintenance programme and synthesis.

As part of this procedure it is necessary to check and verify:

— Compliance with the design changes/requirements, and the existence of a collection of feedback experience;
— The reliability of degradation mechanisms, recognition and surveillance programmes;
— Mitigation, repair and/or replacement;
— Comparison with international approaches.

The first item to be included in the nuclear power plant's periodic safety review report is a list of all systems, structures and components. A sublist is made of those components or structures which have a bearing on safety. Two lists are created in parallel, namely:

(1) A list of components vital for the nuclear power plant's continued operation;
(2) A list of components impacting safety and ageing.

All the components listed in the periodic safety review report which are involved in the life management programme and the ageing management programme are checked against a list of all known degradation mechanisms, i.e. cracking, thinning, pitting, loss of mechanical/electrical/chemical properties. Specific examples are fatigue, corrosion, thermal ageing, radiation embrittlement and thermal fatigue.

In a final step, an ageing analysis report for strategically important components of plant life management programmes is produced. This describes the ageing phenomena and the solutions, including: (1) no change to existing ageing management, (2) revision of the preventive basic maintenance programme, (3) other solutions such as mitigation, replacement or repair.

2.2.3. Combination of periodic safety review and licence renewal applications using Spain and Hungary as examples

Spain

As there is no legal or administrative limitation on the operating lifetime of nuclear power plants, and therefore no fixed operating period, the operating licences and permits of nuclear power plants in Spain are renewed periodically through ongoing assessments and periodic safety reviews. The periodic safety reviews provide a global evaluation of plant safety (including analysis of such factors as compliance with the standards in force, plant specific and industry operating experience and updating of the safety evaluation and improvement programmes). The periodic safety review is also the main tool used by the nuclear regulatory authorities to establish the additional requirements for any new operating licence period (typically 10 year periods).

In Spain, periodic safety review is used as a basis for renewal of the operating licences of all nuclear power plants. Safety Guide 1.10 of the Spanish nuclear regulatory authority (CSN) established the safety issues to be reviewed and resolved to obtain a new operating licence for the next period [10].

The regulatory process, which is based on ongoing assessment and periodic safety reviews, includes the necessary mechanisms and provides a reasonable guarantee that all factors potentially affecting plant safety or public health are incorporated into the plant licensing process.

Likewise, this regulatory framework is considered to be sufficiently rigorous to guarantee safe long term operation of nuclear power plants (beyond their original 40 year design lifetime), and constitutes the basis for the regulatory process and control system and for the granting of operating licences.

When 10 additional years of operation are being applied for, a new periodic safety review must be performed and submitted to CSN for approval three years before the end of the current operating period. If the new operating period covers long term operation of the nuclear power plant the main objective of the new periodic safety review will be to determine whether ageing of systems, structures and components is being effectively managed so that required safety functions are maintained, and whether an effective ageing management programme is in place for long term operation. Additionally, time limited ageing analyses must be evaluated to demonstrate that they will remain valid for the new operating period.

The scope of the periodic safety review has been reviewed by the CSN to incorporate other aspects related to long term operation of the plant. In order to accomplish this it has been concluded that the best and most detailed international basis for establishing the fundamental requirements for renewal of the operating licence beyond the original design lifetime is US regulation 10 CFR Part 54 [3]. Therefore, the licence renewal methodology constitutes the supplementary process that has been incorporated into the specific periodic safety review to be performed when a nuclear power plant is applying for licence renewal past its original design lifetime.

At present, Spanish nuclear power plants have lifetime management programmes that are periodically updated and inspected by the CSN. The updates to the plant life management programmes generally try to follow the US methodology as defined in Ref. [3].

Along with the assessments and studies required in current periodic safety reviews, additional specific requirements are included in the documentation when a long term operating licence is being applied for (see Fig. 6):

(a) A supplement to the safety analysis report with the studies and assessments that justify the operation of the plant during the extended operating period;
(b) A revision of the technical specifications, including the changes required to maintain safe operating conditions during the period foreseen;
(c) An integrated ageing assessment and management plan containing the ageing management report analyses (i.e. ageing mechanisms and effects

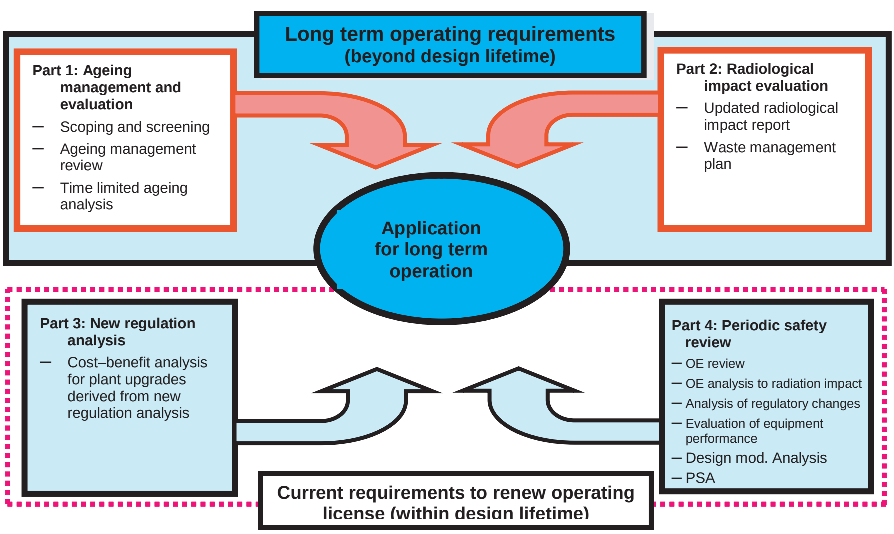


FIG. 6. Process for operating licence renewal beyond design lifetime in Spain.

and mitigating programmes), and time limited ageing analyses required for review of the assessments performed using defined lifetime hypotheses, providing a reasonable guarantee of the operability of the systems, structures and components contained within its scope [3];

(d) An update of the radiological analytical studies, covering the new operating period and taking into account the forecast emissions of effluents to the environment, changes in the environmental circumstances and those factors that, in view of their cumulative nature, may cause an increase in the radiological impact;

(e) A review of the radioactive waste management plan of the facility in order to demonstrate the availability of sufficient capacity to manage all the extra wastes generated during the extended operating period and long term operation.

A key point of the proposal is the reference to the US licence renewal rule [3]. The licence renewal rule focuses on the effects of ageing on the long lived passive structures and components and the time limited ageing analyses. In addition, the rule allows licensees to rely on the current licensing basis, the maintenance rule and the existing plant programmes when performing the process to demonstrate that the intended functions of the systems, structures and components will be followed during the period of extended operation applied for.

The tasks required to demonstrate that the ageing effects on systems, structures and components will be adequately managed during the renewed term of operation include:

(1) Identification of the systems, structures and components involved and their intended functions, which is commonly referred to as scoping;
(2) Identification of the systems, structures and components subject to an ageing management review, which is commonly referred to as screening;
(3) Demonstrating that the effects of ageing will be managed by evaluating the effectiveness of selected plant programmes, which is also part of the ageing management review;
(4) Identification and evaluation of the time limited ageing analyses;
(5) Preparation of the final safety analysis report supplement, identifying technical specification changes and describing the format and contents of the long term operating licence application.

The above considerations and tasks are illustrated in Fig. 7.

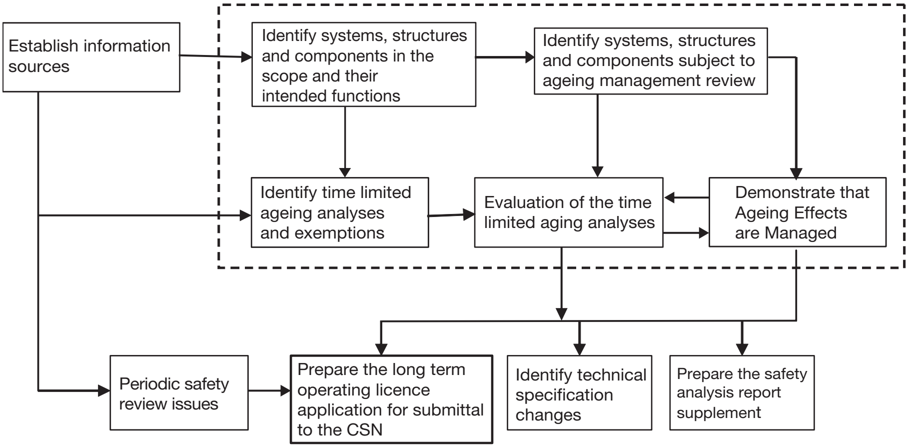


FIG. 7. Spanish plant life management for long term operation.

Hungary

Hungary has a practice similar to that of the CNS. Four WWER-440/213 type units are in operation at Paks in Hungary. The original design lifetime of the WWER-440/213 is 30 years. According to current Hungarian regulations the original operating licence is limited to the design lifetime of the plant. The licensee has to prepare and submit to the regulatory body a proposal for long term operation not later than 4 years before expiration of the currently valid operating licence and after 20 years of operation. During these 4 years the regulatory authority has the possibility to review the licensee's programme to ensure that the licensee's assessments of both safe lifetime and long term operation are realistic.

The content of the application for long term operation is similar to NRC practice. This means that long term operation focuses on the ageing of the long lived passive systems, structures and components, such as the licence renewal application, while the performance of active systems and components is controlled in accordance with the maintenance rule and regulatory requirements for maintaining the environmental qualification. Compliance with the conditions of the current licensing basis is controlled by means of annual updating of the final safety analysis report and the regulatory inspections and approval routine. The content of the final safety analysis report is defined in a Hungarian regulation which is similar to Ref. [11].

The annually updated final safety analysis report has to correspond to the actual plant configuration, and has to demonstrate compliance with the current licensing basis. Environmental impact studies have to be carried out assessing the effects of operation, including long term operation. An environmental licence relative to continued operation is a condition of the licence renewal application.

The periodic safety review is performed as a self-assessment by the licensee under the control of the regulatory body. The periodic safety review (performed every 10 years) is the tool for assessing the ageing processes and developments on a longer time scale, i.e. the overall ageing of the plant, the development of science and technology in relation to safety assessment techniques, evaluation and feedback of experience.

The content of the periodic safety review is similar to that defined in Ref. [2]. However, some of the information required by the IAEA for periodic safety review has to be documented according to Hungarian regulations in the annually updated final safety analysis report. The periodic safety review will validate the forecast made for the licence renewal application and the efficiency of the ageing management programme. The periodic safety review and the annual update of the final safety analysis report contain complementary information required for documenting and ensuring the safety status pertaining to the extended operation of the Paks nuclear power plant. This system is well structured and relatively easy to follow.

3. GENERAL APPROACH TO PLANT LIFE MANAGEMENT

While it is recognized that Member States have different numbers and types of nuclear power plants, with differing operating lifetimes, a general approach to plant life management is seen to be advantageous. The principles of plant life management remain the same, to maintain optimum operation and production at the lowest cost and highest safety level. A plant life management programme can be set up within the framework of the three phases described below. It should be noted that generic approaches can only give a broad overview and plant specific approaches are necessary. These must be based on generic inputs and state of science and technology information.

3.1. PHASE 1: FEASIBILITY STUDY OF PLANT LIFE MANAGEMENT

Given the desire to operate plants for as long as they are safe and remain economically competitive, the first step of a plant life management programme is a feasibility study with a view to maintaining or improving current operational goals. Plant life management is usually theoretically and technically feasible but its implementation, even for long term operational goals, is not always economically feasible. Nuclear power plant owners normally make a determination of the feasibility of long term operation based on the results of this phase 1 study. Its requirements are discussed in the following sections.

3.1.1. Review of the preconditions for plant life management and data collection

A good starting point in plant life management is to review its preconditions, as described in Section 2.1. Essential items are the existence of data records, reports and the life histories of systems, structures and components, for assessment of their condition and identification of ageing mechanisms, backed up by experience and existing knowledge from the nuclear power plant itself, owner's groups and published research sources. The operating conditions and the maintenance history will provide the basis to assess levels of degradation. Therefore, the owners and operating organizations should collect and maintain records of all monitoring and testing and also of operational transient data. Not only are records required but there is also a need to locate, where possible, representative archive materials for possible benchmarking tasks, future testing and verification efforts. Ideally, plant life management should be implemented at the beginning of the nuclear power plant's commercial startup and operation.

3.1.2. Evaluations of key life determining components of nuclear power plants

To verify the technological feasibility of long term operation it is necessary to perform life evaluations of long lived passive structures and components, e.g. those which are large and impossible to replace, such as the reactor pressure vessel and the containment, or those which are technically replaceable but only at great expense, such as steam generators and core shrouds. Their condition could have an economic impact (amortization) on long term operation. The components falling under categories 1 and 2 in Section 3.2.2.2, such as the reactor pressure vessel, steam generator, containment building, should obviously be covered in the life evaluations.

Life evaluations of key components included in phase 1 will be done using primarily existing licensing basis documents (final safety analysis report, technical specifications, etc.). Documents used in phase 1 of the plant life assessment are design data, manufacturing specifications, operating history, inspections, tests and generic life assessment procedures.

3.1.3. Review of regulatory requirements

Safety issues demand a continuous and interactive process between a plant's operating organization, which is responsible and accountable for the safe operation of the nuclear power plant, and the regulatory body, which provides operating authorization only when relevant safety issues have been resolved and safety levels are acceptable.

Therefore, a review of regulatory requirements is essential to the establishment of plant life management and for supporting arguments for long term operation. The regulatory environment varies greatly between countries. As stated earlier, some countries (e.g. Finland, Hungary, Mexico, the USA) have fixed term operating licences, while others do not (e.g. Belgium, France, and Switzerland). The regulatory requirements for long term operation differ, depending on the licence period, as do plant life management activities.

Safety issues and regulations interact with plant life management in two main ways:

(1) Directly through the operating authorization: if the number of incidents is too high or if safety related systems are not sufficiently reliable, regulatory bodies will require appropriate action. This may take a sufficiently long time to cause a serious financial burden on the operating organization.
(2) Indirectly through cost–benefit analysis: Regulatory bodies require that the plant operating organization and owner check whether or not the facility is complying with any rules that may be imposed. If not, the plant's operating organization and owner is asked what can be done to comply. If modifications are feasible, they may be required. Such actions can be very costly and may therefore have a detrimental effect on a plant's cost effectiveness and the economic viability of long term operation.

3.1.4. Preliminary economic analysis

If a nuclear power plant wants to aim for long term operation it is essential for it to review the economic feasibility. To operate the plant beyond its original design lifetime, economic benefits should be expected when compared with the projected investment costs (amortization and business case aspects). A logical approach to assessing the economic feasibility of the total operating lifetime would be to do so as part of a power system analysis. The costs of long term operation of a nuclear power plant are compared with the costs of equivalent replacement power. As replacement power alternatives, conventional power generation (fossil, hydro or gas), power imports and contracts with independent power producers all have to be considered. However, alternative energy generation options may entail additional issues (e.g. compliance with the Kyoto protocol, external costs, environmentalist opposition, public acceptance, etc.), as previously noted.

The preliminary economic analysis should include a review of the operating and maintenance costs during the extended operating period, the cost of hardware upgrades to the plant (including the refurbishment and replacement of components) and software, fuel cost, income during the extended operating period, amortization of investment, etc. Detailed economic analysis can only be achieved when all cost inputs (e.g. refurbishment, upgrading and replacement) associated with plant life management and long term operation are known, or best estimates are available. Costs entailed by radioactive waste generation, conditioning, storage and final disposal must also be integrated into the overall analysis.

3.2. PHASE 2: DETAILED PLANT LIFE EVALUATION AND ESTABLISHMENT OF A PLANT LIFE MANAGEMENT PROGRAMME

3.2.1. Steps for the establishment of plant life management

Past and ongoing maintenance and operating practices are key elements of an effective plant life management programme. Good previous maintenance, inspection and monitoring practices are prerequisites for using plant life management to achieve cost effective long term operation. Global experience has shown that the best maintained operating nuclear power plants have both the best nuclear safety records and the lowest production costs for electricity generation. This positive correlation between good maintenance practices and both high levels of safety and low cost of operation demonstrates the important relationship between plant maintenance and plant life management for long term operation.

Plant life management strategies for long term operation aim at obtaining high levels of equipment reliability at reasonable cost and maintaining or even increasing safety levels. An effective programme requires a good balance between preventive maintenance, predictive maintenance, corrective maintenance, successful monitoring and redesign of systems, structures and components, where applicable. Such goals have the potential to improve plant reliability, availability and safety, while also optimizing plant life cycle cost.

The Electric Power Research Institute (EPRI) in the USA has developed a number of software tools associated with plant life management programmes for its US and international customers to optimize life cycle costs. For example, EPRI has developed a life cycle management programme that begins with the classification and selection of systems, structures and components that warrant detailed technical and economic evaluation, employing criteria such as risk significance, safety significance, power production importance, cost of potential failure, obsolescence, and cost of maintenance. The screening identifies systems, structures and components that warrant further review and eliminates those that do not. Those that warrant further review are then subjected to technical and economic evaluations that include:

(a) Review of relevant plant specific operating and performance history;
(b) Review of relevant industry operating and performance history;
(c) Review of the existing maintenance plan;
(d) Assessment of ageing and obsolescence issues;
(e) Identification of possible alternatives such as:
 — Continuation of existing maintenance practices,
 — Design changes or modifications,
 — Discontinuation of existing maintenance practices (run to failure option),
 — Modification of existing maintenance practices to optimize reliability;
(f) Selection of alternatives that warrant further analysis;
(g) Assessment of the failure rate and the cost associated with each alternative;
(h) Determination of the present value of each alternative plan;
(i) Selection of the optimum alternative.

The screening criteria, software tools, assessment techniques, sample project results and numerous reports are available from EPRI. Sources such as EPRI provide information on the effective implementation of a plant life management programme based, in large part, on good maintenance practices.

3.2.2. Establishment of the plant life management programme

In order to operate a nuclear power plant safely and economically both during its design lifetime and beyond, it is important to assess the existing condition of the systems, structures and components in order to evaluate their remaining lifetime and to establish a corresponding ageing management programme.

Phase 2 of plant life management generally includes the following:

(a) Screening of critical systems, structures and components and their classification;
(b) Identification of ageing mechanisms;
(c) Detailed lifetime evaluation of the critical systems, structures and components;
(d) Establishment of an appropriate ageing management programme.

3.2.2.1. Set-up of screening criteria

Systems, structures and components are made of a variety of materials which age at different rates and are subjected to different types of degradation. To evaluate each of them in terms of subcomponents and their ageing mechanisms would be a big task. Therefore it is more efficient to categorize or 'screen' the critical ones in terms of their importance to safety and economic operation in order to prioritize the work and maximize the use of all available resources.

The first step in the screening of critical systems, structures and components is to select the appropriate screening criteria. There can be a large number of screening criteria but relevance to safety is the most important one. Screened structures and components are mostly passive long lived ones that are either safety related or non-safety related but could affect a safety function if they failed. Table 3 shows an example of BWR system scoping and screening.

The most widely used screening criteria are those described in US practices such as the:

— Licence renewal rule (10 CFR Part 54) [3];
— Maintenance rule (10 CFR Part 50.65) [4];
— NRC GALL report (NUREG-1801) [5];
— Industry guidelines (NEI 95-10) [6].

3.2.2.2. Screening critical systems, structures and components and subcomponents

The second step is to screen critical systems, structures and components on the basis of the chosen criteria and to classify the critical components into several categories. For example, the following categories would be an example of a good practice. It should be noted that the categorization of components given below may be plant specific.

(1) Category 1 components are those generally considered to be irreplaceable. Examples of such components include the reactor pressure vessel and the containment. With regard to irradiation embrittlement of reactor pressure vessels in older nuclear power plants it should be noted that more than 15 WWER reactor pressure vessels have been annealed to restore some degree of toughness.
(2) Category 2 components are those that are replaceable but whose replacement would be very costly in terms of capital expenditure and outage time requirements. For example, steam generators have been replaced in many plants due to unacceptable material performance (i.e. primary water stress corrosion cracking of nickel-base alloy 600, and cracking of reactor pressure vessel heads due to primary water stress corrosion cracking of Alloy 600 penetrations). Core shrouds with intergranular stress corrosion cracking and irradiation assisted stress corrosion cracking in boiling water reactors have also been replaced (e.g. in Japan), but tensile tie rods can and do provide an engineering solution. The use of tie rods is considered a final 'fix' in the USA, for example. Inspection and monitoring of such tie rods is an important task to ensure that they do not stop functioning due to ageing, for example through loss of constraining force over time.
(3) Category 3 components are those that are 'key' components in terms of plant safety and reliability and are susceptible to ageing, but which are replaceable on a routine basis (e.g. cables and instrumentation and control).
(4) Category 4 components are all other components not included in the other categories and not related to nuclear power plant operational time considerations.

Screened critical structures and components are normally composed of many subcomponents made of different materials. Subcomponents also have to be screened. For example, the subcomponents of a valve (packing, disk, stem, etc.) must be screened, as well as the valve itself.

3.2.2.3. Identification of ageing mechanisms

The systems, structures and components of nuclear power plants are made of a variety of materials, metallic and non-metallic, including concrete. Accordingly they are subject to different ageing mechanisms and rates of degradation. Since the aim of plant life management is ageing management from a technical and economic point of view, both known and expected or even plausible degradation mechanisms of the selected critical systems, structures

TABLE 3. EXAMPLES OF SYSTEM FOR SCOPING AND SCREENING OF BWRs

Reactor vessel, internals and reactor coolant system	
Reactor pressure vessel internals	Reactor pressure vessel Reactor internals Assemblies Control blades
Reactor coolant system	Reactor recirculation system, recirculation flow control and motor generator sets Reactor vessel head vent system Nuclear boiler instrumentation system Head spray system Reactor coolant pressure boundary components in other systems
Reactor coolant pressure boundary components in other system	High pressure coolant injection system Core spray system Reactor core isolation cooling system Residual heat removal system Low pressure coolant injection system Standby liquid control system Control rod drive hydraulic system Reactor water cleanup system Main steam system Feedwater system
Engineered safety features	
Steam and power conversion system	
Auxiliary system	
Structures	
Primary containment	
Reactor building (secondary containment)	
Main control room and auxiliary electrical equipment room	
Turbine buildings	
Diesel generator and high pressure core injection (HPCI) building	

TABLE 3. EXAMPLES OF SYSTEM FOR SCOPING AND SCREENING OF BWRs (cont.)

Electrical and I&C systems
Reactor protection system
Manual reactor control system
Alternate rod insertion
Intermediate range monitors
Source range monitors
Average power range monitors
Cable — safety related system in/outside the containment

and components and subcomponents should be allowed for. Degradation mechanisms for the metallic components in systems, structures and components in nuclear power plants include:

(a) Corrosion:
- Intergranular stress corrosion cracking, transgranular stress corrosion cracking, irradiation assisted stress corrosion cracking and primary water stress corrosion cracking (see below).
- Erosion/corrosion: corrosion or loss of material in usually plain carbon steel or low alloyed steel due to fast flowing and turbulent fluid such as feedwater or steam, or mixtures of these.
- General corrosion: thinning of metal by chemical attack (dissolution) uniformly over the entire exposed surface (e.g. uncladded reactor pressure vessels as in WWER-440/230 reactors). The attack of boric acid containing water coming from leaking reactor pressure vessel head penetrations is a specific example, referred to as 'wastage'. The Davis-Besse nuclear power plant in the USA was severely affected by this effect in March 2002 [12].
- Local corrosion: corrosion which may lead to rapid localized failure of a material. This includes crevice corrosion, pitting and microbiologically induced corrosion.
- Galvanic corrosion: corrosion due to electrochemical contact between dissimilar metals: The severity is influenced by corrosion potentials of the metals, relative areas of the metal surfaces and conductivity/aggressiveness/electrochemical properties of the corrosive liquid (electrolyte) involved.

— Primary water stress corrosion cracking: Alloy 600 is used to fabricate various parts in nuclear power plants, including reactor vessel top head penetrations for control rod drive mechanisms, control drive element mechanisms, in-core instruments and thermocouples, reactor vessel bottom head bottom mounted instruments, pressurizer heater sleeves, and various other instrumentation ports. Related weld materials Alloy 82 and Alloy 182 are used to join these Alloy 600 parts to the ferritic steel components and also as a bi-metallic weld joining ferritic base material to austenitic stainless steel base materials. Alloy 600 and its associated weld filler metals were originally used because of expectations of resistance to service induced cracking. However, parts fabricated from these materials have shown susceptibility to primary water stress corrosion cracking, also referred to as low potential stress corrosion cracking [13].

(b) Embrittlement:

— Irradiation embrittlement: embrittlement of steel by fast ($E > 1$ MeV) neutron irradiation and affecting several mechanical properties of the low alloy ferritic reactor pressure vessel steel (causes an increase of the ductile to brittle transition temperature and decrease in Charpy upper shelf impact energy combined with an increase in the tensile yield strength and hardness and decreases in the level of fracture toughness).

— Thermal embrittlement: microstructural changes and evolution of certain duplex austenitic-ferritic stainless steels at relatively high operating temperatures (>340°C) and/or long operating times. Often these microstructural changes result in change in mechanical properties (usually a decrease in toughness).

— Temper embrittlement: temperature causes embrittlement due to grain boundary phosphorus segregation in some reactor pressure vessel steels. This mechanism depends on the composition and reactor pressure vessel fabrication heat treatment, as well as on subsequent service conditions.

(c) Fatigue:

— Mechanical fatigue: the source of cyclic load is mechanical. This includes low and high cycle fatigue.

— Thermal fatigue: cyclic loading is caused by rapid temperature fluctuations causing dilatations (expansion and contraction) in the alloy involved.

— Corrosion fatigue: environmental effects, lower fatigue limits and resistance.

(d) Wear (loss of material):

— Adhesive wear: relative movement between two metal surfaces (friction mechanisms).

— Abrasive wear: wear due to hard abrasive particles removing material from surfaces.
— Erosion: loss of material due to flowing liquid removing protective layers (e.g. oxide).
— Fretting wear: small vibrating or sliding movements in corrosive environments.

(e) Fabrication defects:
— Casting and forming flaws (e.g. gas holes and cold overlaps).
— Welding related flaws (e.g. shrinkage holes and lack of fusion).
— Dilution and heat affected zone flaws (e.g. changes in microstructure through local heat input).
— Repair induced material conditions or flaws (e.g. wrong filler weld material and introduction of stresses).[2]

3.2.2.4. Detailed lifetime evaluation of critical systems, structures and components

While it is a precondition that safety must always be maintained there are two ways of determining the operating lifetime of a nuclear power plant, namely the technical and the economic limits. Technical plant lifetime is either the design or the engineering lifetime. The design lifetime of a nuclear power plant is commonly given as 30 or 40 years depending on the type, and this is quoted in the final safety analysis report. However, the design lifetime of the individual components may differ from the actual plant lifetime. The plant lifetime depends on the actual operating history, conditions and environments. It can be either longer or shorter than the design lifetime. The economic plant lifetime is reached when the nuclear power plant can no longer be run at a profit. (total costs of operation outweigh the revenue gained from energy sold).

Safety requirements or safety margins can influence the lifetimes of systems, structures and components. This means that the end of the lifetime is reached when ageing causes the safety margin to no longer satisfy requirements.

In the detailed technical lifetime evaluation of critical systems, structures and components, the following points need to be taken into account:

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[2] Inappropriate surface treatments, heat treatments or poor material selection may also be included here since, for example, internal stresses and cold-worked surfaces with residual tensile stresses may become more susceptible to stress corrosion cracking.

(1) The reasonably expected ageing mechanisms;
(2) Lifetime assessment methodology with provisions and guidelines;
(3) Computation codes and their validation.

Ageing mechanisms of screened subcomponents are reviewed to determine whether they will limit the lifetimes of structures and components based on the collected technical documents, operating history and environments. Component specific guidelines [14–30] provide design and material features; significant ageing mechanisms; inspection, monitoring and maintenance practices; and suggestions on how to establish ageing management programmes for key components.

When evaluating the detailed lifetimes of structures and components, the above guidelines use data from field test and system performance monitoring. The field data can confirm the actual ageing status and verify the current integrity of structures and components. Their remaining lifetimes are assessed in a qualitative way, based on experience as well as on qualitative engineering assessments and judgements using actual operating data acquired to date. The qualitative method resembles the ageing management review and report, and the quantitative method resembles the time limited ageing analyses of Refs [5, 29–31].

3.2.2.5. Attributes of an appropriate ageing management programme

The last step in phase 2 of plant life management is to establish an appropriate ageing management programme for systems, structures and components. To do so it is necessary to review the current ageing management programmes in use and the experiences of other nuclear power plants. The ageing management programme will show ways of mitigating the degradation and ageing of structures and components. All ageing management programmes have to be capable of maintaining current safety standards, even beyond the design lifetime. Specific ageing management programmes are introduced in Ref. [5].

Generic guidelines provide guidance on data collection, methodologies, establishment and implementation of systematic ageing management programmes, equipment qualification and how to assess the effectiveness of ageing management programmes. Existing programmes to manage the ageing of systems, structures and components, and which are recommended, should be coordinated within a comprehensive ageing management programme. They are presented in Refs [9, 24, 32–35].

The ageing management programme may be supported with the implementation of advanced maintenance concepts and tools, such as the ‘performance based’ and ‘risk informed based’ techniques. It should be kept in mind that the actual activities in the ageing management programme must be plant specific ones, but experience from other nuclear power plants may be applied as appropriate.

Implementation of several backfits should be considered, as required in Ref. [36]. Generic letters of the NRC also supply further information for setting up ageing management programmes. Following are backfit requirements for licence renewal according to Ref. [37] (see Table 4).

— Pressurized thermal shock;
— Anticipated transients without scram;
— Fire protection;
— Station blackout;
— Environmental equipment qualification.

3.3. PHASE 3: IMPLEMENTATION OF PLANT LIFE MANAGEMENT

The implementation of plant life management requires funding, personnel and time, as well as an awareness of safety issues and the assurance that efforts will be duly rewarded in terms of safety increases and economic gains. For the successful implementation of plant life management, the following general points must be considered:

— Existence of guidelines and procedures;
— Readily available expertise and knowledge of plant life management for long term operation;
— Schedule for implementation;
— Organization and management capabilities and capacities;
— Quality assurance activities.

3.3.1. Guidelines and procedures

Plant life management includes many complex activities, including design modification, engineering, inspection and application of research results, and therefore needs well defined guidelines and procedures. The use of generic information (i.e. possible applicability to plant specific aspects), and experience worldwide are essential for an efficient approach and to provide a good reference point.

TABLE 4. AGEING MANAGEMENT PROGRAMME ELEMENTS [5]

Element	Description
Scope of the activity	The scope of the programme and activity should include the specific structures and components subject to an ageing management report for licence renewal.
Preventive actions	Preventive actions should mitigate or prevent ageing degradation.
Parameters monitored or inspected	Parameters monitored or inspected should be linked to the degradation of the particular structure or the component's intended function(s).
Detection of ageing effects	Ageing effects should be detected before there is a loss of structure or component function. This includes aspects such as method or technique (i.e. visual, volumetric, surface inspection), frequency, sample size, data collection and timing of new and one time inspections to ensure timely detection of ageing effects.
Monitoring and trending	Monitoring and trending should provide predictability of the rate and extent of degradation and allow timely corrective or mitigating actions.
Acceptance criteria	Acceptance criteria, against which the need for corrective action will be evaluated, should ensure that the structure or component function(s) are maintained under all current licensing basis and design conditions during the period of extended operation.
Corrective actions	Corrective actions, including root cause determination and how to prevent recurrence, should be timely.
Confirmation processes	Confirmation processes should ensure that preventive actions are adequate and that appropriate corrective actions have been completed and are effective.
Administrative controls	Administrative controls should provide a formal review and approval process, and preservation of documentation.
Operating experience	Operating experience of the ageing management activity, including past corrective actions resulting in programme enhancements or additional programmes or activities, should provide objective evidence to ensure that the effects of ageing will be adequately managed so that the intended functions of the structure or component will continue to be maintained during the period of extended operation.

3.3.2. Implementation schedule

Ageing management programmes usually encompass the maintenance and repair of systems, structures and components, and their refurbishment or replacement. Therefore, use of a continuous ageing management programme is recommended during normal operation. However, significant tasks such as the replacement of steam generators require long outages. It is essential to set up an implementation schedule, which should be based on discussion with and approval by the regulatory body. Radiological protection issues require good advance planning to ensure that doses received by workers are as low as reasonably achievable (ALARA) and to facilitate quick and efficient inspection, repair or replacement work.

3.3.3. Organization and management

A nuclear power plant's organization and management are also very important. It is good practice to organize a team of specialists dedicated to the implementation of plant life management. Members of such a team will be familiar with the systems, structures and components, as well as the latest technical and scientific aspects of plant life management. Access to all documents pertaining to the operating histories of the systems, structures and components (time, environment, transients experienced, etc.) is necessary to be able to assess their status.

3.3.4. Quality assurance activities

The quality assurance programme activities associated with the corrective action process are essential elements of plant life management. Since operating experience continues to identify new or evolving ageing effects, the corrective action process is a key to documenting, evaluating and implementing any additional corrective actions such as new ageing management programmes, or adjustments to existing ones, based on ongoing operating experience.

The overall quality assurance programme is an essential element of nuclear power plant operation. Implementation of an ageing management programme or plant life management not only includes repair and maintenance, but also the replacement or refurbishment of key components, and even includes organizational changes. Therefore, it is important to keep the implementation of ageing management programmes or plant life management programmes as quality assurance processes. This includes the following:

(a) Quality assurance programme and regular quality assurance audits;
(b) Compliance with regulatory requirements.

4. ISSUES CONCERNING PLANT LIFE MANAGEMENT

4.1. TECHNOLOGICAL ISSUES

The purpose of this section is to present the principal methods used by different countries to identify the ageing of nuclear power plant systems, structures and components. The considerations described give an overview of the practices of some operating organizations.

4.1.1. Methods for monitoring systems, structures and components

Pre-service and in-service inspection

In order to maintain a high level of safety for the mechanical components of the nuclear steam supply system, a detailed programme has been established by operating organizations for application on-site; it includes in-service inspection and on-line monitoring.

On-line monitoring and diagnosis systems

On-line monitoring covers all the operations by which the operating organizations continuously ensure that components continue to conform with requirements and technical specifications (i.e. monitoring of pressure boundary leaktightness, recording of transients, monitoring of loose parts, monitoring of valve functionality, etc.).

Requirements and feedback from experience have often resulted in decisions to design and implement an integrated diagnostic and on-line monitoring system. The objectives of the on-line monitoring system are the following:

(a) To improve and automate the detection of anomalies by using new computerized variables such as peak values, Fourier spectra, vibration residues, critical speed values;
(b) To have a tool for predictive and condition based maintenance;
(c) To extend the software to include diagnosis;
(d) To have a versatile and flexible common host structure to monitor the main components, namely the turbine generator shaft line, the inlet valves, the primary coolant pumps, the internals and the generator, and to detect loose parts;
(e) To automatically manage the data generated.

The on-line monitoring system will make it possible in the long run to follow and trend the behaviour of the equipment and to build up and maintain knowledge.

Monitoring of nuclear steam supply system fatigue

Transient data collection is a regulatory requirement for LWRs. The requirement is twofold and its aim is to:

(1) Check that the number of transients detected during the operating lifetime of the plant does not exceed the number of transients defined in the design, assuming that a conservative margin is always maintained during the logging procedure;
(2) Undertake data collection for each primary system component during the plant's operating lifetime.

For each operating transient detected, the proper bounding design transient category should be identified. The pressure and temperature history are compared with the different design transients. This allows both transient detection and data collection. These comparisons are carried out on special recording sheets with curves plotted by dedicated recorders connected to standard operating sensors.

After more than 10 years of experience with the above data collection procedure, the main difficulties encountered to date are:

(i) The use of elementary standard operating instrumentation.
(ii) The use of pressure and temperature deviation criteria with no knowledge of the stress range.
(iii) The use of comparisons between operating transients and highly conservative design transients. The design transients do not cover all operating transients, and certain unclassified operating transients must be taken into consideration.

It sometimes happens that the procedure cannot be used because the number of transients is too high and the list of associated design transients is not sufficiently detailed (e.g. surge line and charging line). The literal application of the procedure would be far too conservative and the number of permissible transients would be exceeded after only a few years of operation. The databank resulting from the monitoring procedure is still highly valuable as regards the analysis of current plant operation. Such feedback information has already resulted in certain modifications to the initial design of plants (e.g. improvement of pressurizer level and pressure control systems).

4.1.2. Degradation detection and damage evaluation of some selected components

Monitoring systems must be in place to reliably follow degradations which can occur and are caused by physical phenomena such as irradiation embrittlement (reactor pressure vessel surveillance programme), corrosion (water chemistry control), fatigue usage (registration of transients), wear, flow accelerated corrosion and environmentally assisted cracking, wall thinning of housings and piping (on-line detectors), vibrations and loose parts (acoustic noise detection and strain gauge methods) and thermal stratification (thermocouples and dilatometers).

Reactor pressure vessels and closure heads

The dominant and expected type of damage in the reactor pressure vessel is ageing (embrittlement) under neutron irradiation of the reactor vessel steel, especially in the core (beltline) area, since this experiences the most severe irradiation. Neutron irradiation damage can be detected, for example, through an increase of RT_{NDT} (reference temperature of nil ductility transition, indicating a loss of toughness). Hardness and tensile yield strength also increase. Neutron damage can be modelled by means of predictive formulas used to evaluate the RT_{NDT} shift as a function of the neutron fluence received by the reactor vessel, as well as the content of elements (i.e. alloy and impurity chemical composition) likely to cause enhanced embrittlement sensitivity in the reactor pressure vessel steel and welds (e.g. copper, nickel and phosphorus under certain concentrations and conditions).

Predicted values from models can be compared with actual results obtained from test specimens (‘irradiation surveillance capsules’) placed inside the reactor pressure vessel. Each of these test specimen capsules should include temperature monitors (melting of special alloys at precise temperatures) and neutron dosimetry sensors (sensitive to fission or capable of being activated). The reactor pressure vessel specimens (typically Charpy V-notch with and without precracks, and tensile rods) which are intended to be used for mechanical tests (mainly fracture toughness) at one, two, three or four quarters of the design lifetime, may be supplemented with reference material specimens for comparison.

The programme entails irradiating, inside the reactor vessel, specimens of the reactor pressure vessel steel (base metal, heat affected zone, welds) in a stainless steel capsule. By staggering the withdrawal, testing and interpretation of the capsules and samples it is possible to determine the real behaviour of the steel in advance throughout the design lifetime of the reactor pressure vessel and to check the validity of predictions. The capsules are subjected to a higher flux than the reactor pressure vessel wall, in order to create a lead effect in neutron fluence with time. Usual lead factors are as much as 3, but some programmes have used 10 or more. Flux rate effects are still being studied. For surveillance of the irradiation damage after 40 years two reserve capsules are usually installed after withdrawal of two capsules, which are situated at a maximum neutron flux in-vessel position.

Tested specimens may be reconstituted (i.e. new specimens are created by welding stubs onto undistorted fragments of tested specimens) and then reloaded into the reactor pressure vessel to facilitate more tests in the future. This practice, which is well qualified, greatly extends the scope of the reactor pressure vessel surveillance programme, allowing advances in fracture mechanics technology to be taken advantage of and, in the case of reactor pressure vessel annealing, to assess the response after irradiation annealing and re-irradiation. This latter possibility is of particular relevance to WWER reactors that have undergone annealing and re-irradiation (e.g. the Loviisa nuclear power plant in Finland).

The reactor pressure vessel is inspected every 10 years and undergoes a regulatory hydro test. As a further measure, so-called ‘reduced leakage’ or ‘low leakage’ core fuel loading schemes may be implemented, which allow the neutron flux (hence fluence accumulation with time) in the critical zone of the reactor pressure vessel to be reduced by 20–40%. Low leakage cores use dummy elements or high burnup fuel elements in the peripheral positions, which are normally associated with high neutron flux levels.

Reactor pressure vessel closure head ageing under primary water stress corrosion cracking conditions

The first indication of cracking in Alloy 600 penetrations of a reactor pressure vessel closure head was identified in France at Bugey unit 3 in 1991, during the 10 year primary system hydrostatic test. The leakage was from an axial flaw which had developed on the inside surface of the nozzle near the elevation of the J groove weld. Several other partial depth axial cracks were identified at a similar elevation in this nozzle. Failure analysis confirmed that the cracking was due to primary water stress corrosion. In the USA the NRC and the industry initiated activities to assess the safety significance of vessel head penetration nozzle cracking. An action plan was implemented by NRC staff in 1991 to address primary water stress corrosion cracking of Alloy 600 vessel head penetrations at all US PWRs.

Various areas may be affected by ageing degradation under primary water stress corrosion cracking, such as the vessel head and the bottom mounted instrumentation penetrations. The expected damage in these areas is degradation by stress corrosion cracking under PWR primary water conditions (see Fig. 8). More precisely:

(a) The Alloy 600 adapters of the control rod drive mechanisms or thermocouple columns for the vessel head adapters;
(b) The Alloy 600 bottom mounted instruments;
(c) Heater penetrations of pressurizers.

Cracking may be detected by using eddy current testing and examination. When cracks are detected, visual, dye penetration and ultrasonic tests are used to characterize their depth as well as the thickness of the residual ligaments.

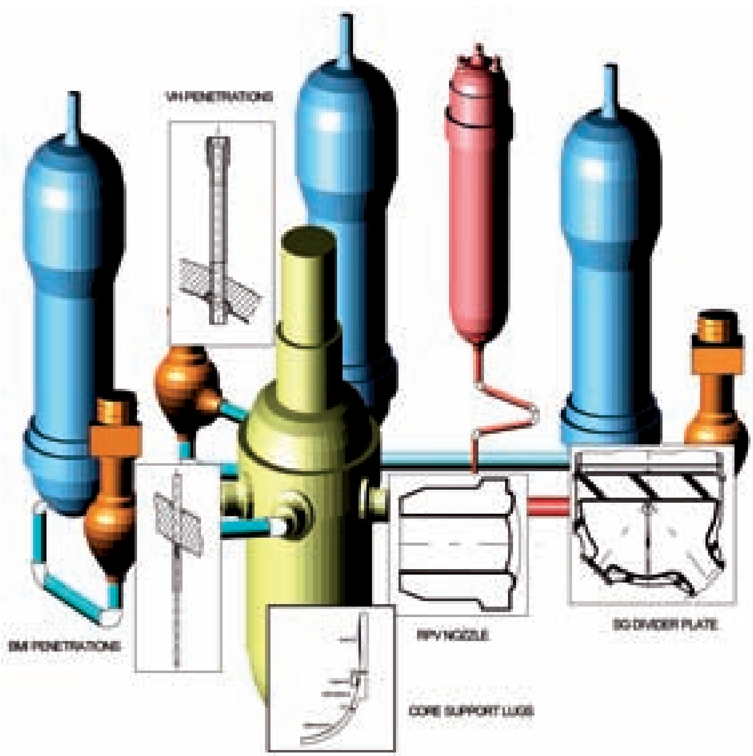

FIG. 8. Risk of stress corrosion cracking in other Inconel areas in the primary system.

When a crack is deep enough to incur a risk of in-service leakage during the following operating cycle, economic considerations may result in a decision to replace the reactor pressure vessel head. A similar inspection programme will be implemented for bottom mounted instruments.

Primary system pipes

Certain main primary system pipes made of cast duplex (austenitic-ferritic) stainless steel were found to be susceptible to thermal ageing under primary circuit temperature conditions (hot leg 325°C, cold leg 285°C) when the alloy's delta-ferrite content exceeded approximately 25%. Such ageing, caused by microstructural evolution and change with time at temperature, results in segregation and the precipitation of a brittle delta-ferrite phase, entailing a loss of material toughness. Susceptibility to this type of ageing is assessed in a laboratory using cast ingots with a chemical composition representative of the products used in operation.

In order to confirm the laboratory assessments and to establish formulas for predicting ageing as a function of temperature, on-site specimens are taken from certain components deemed to be among those most susceptible. A criterion has been developed, taking into account the chemical composition with respect to chromium, silicon and molybdenum content. The criterion, called the 'chromium equivalent', is determined as follows:

Percentage chromium equivalent = % Cr + % Si + % Mo (wt%)

The critical value indicates sensitivity for this type of thermal ageing where the percentage chromium equivalent is higher than 23.5%.

Analyses of this kind show fatigue and embrittlement endangered components or areas and lead to the decision as to whether global or local monitoring is necessary.

Concerning actual measurements, a distinction must be made between monitoring of the 'slow' (quasi-static) load changes and monitoring of 'dynamic' processes. Slowly changing mechanical loads can be separated into a group of 'global' and a group of 'local' loading. Loading spectra should be characterized as well as possible.

In general, all permitted loads as specified in the design base are assigned to 'global' loading. Operational measuring equipment is used to monitor these specified loads. The operational instrumentation is not adequate for monitoring local loads. Additional local measuring points have to be installed on the component. These local processes are mainly of a thermal nature and therefore temperature sensors dominate in quasi-static local monitoring.

Alloy 600 primary water stress corrosion cracking occurs at locations on the inside surfaces of recirculating steam generator tubing that has a high residual tensile stress (introduced during fabrication and installation of the tubes). These locations are primarily the roll transition regions in the tube sheets, the U bend regions of the tubing in the inner rows (i.e. the tubes with a small bend radius) and any dent locations in tube support plate areas. Tube denting is a deformation (resulting in residual stresses) resulting from the buildup of corrosion products. Primary water stress corrosion cracking generally occurs on the hot leg side of recirculating steam generators. However, cold leg primary water stress corrosion cracking has also been observed.

Outside diameter stress corrosion cracking is a degradation mechanism which includes both intergranular stress corrosion cracking and intergranular attack on the outside surfaces of Alloy 600 steam generator tubing. Most of this type of degradation has taken place in the tube to tubesheet and tube to tube support plate crevices, although sludge pileup and free span outside diameter stress corrosion cracking have been observed at some plants. Intergranular stress corrosion cracking requires the same conditions as primary water stress corrosion cracking (i.e. tensile stress, material susceptibility to crack in the medium it is in). Intergranular stress corrosion cracks occur along the grain boundaries, oriented perpendicular to the maximum principal stress direction. Intergranular attack is characterized by local corrosive loss of material on the grain boundaries; it does not require a high degree of tensile stress but it is believed that stress accelerates the initiation and growth of this mechanism.

The severity of outside diameter stress corrosion cracking strongly depends on the concentration of active chemical impurities in ‘hideout’ regions in the steam generator. Impurity levels in secondary side systems are highly variable and are probably influenced by at least the following: crevice geometry, water treatment history, plant attention to secondary side chemistry, types of remedial measures and the history of their application. Most outside diameter stress corrosion cracking is primarily oriented in the axial direction. However, significant circumferential outside diameter stress corrosion cracking is sometimes found near dents.

Fretting, wear and thinning of steam generator tubes are broadly characterized as mechanically induced or mechanically aided degradation mechanisms. Degradation from slight oscillatory motion between continuously rubbing surfaces is generally termed fretting. Steam generator tube vibration of relatively large amplitude, resulting in intermittent sliding contact between the tube and the support, is termed wear or sliding wear. Thinning generally results from concurrent effects of vibration and corrosion. However, thinning occurs at some locations where flow induced vibrations are not expected, so it is not certain that tube motion is required for this mechanism. Fretting and wear make tubes susceptible to fatigue crack initiation at stress levels well below the fatigue limit, resulting in through-cracks or even tube rupture.

The major stressing agent in fretting and wear is flow induced vibration. Initiation, stability and growth characteristics of damage by these mechanisms may be functions of a large number of variables, including the gap size between the tube and the support, secondary flow rates and geometries, oxide layer characteristics and the influence of chemical impurity buildup in the tube-to-tube support gap.

Denting is the mechanical deformation or constriction of the tube at a carbon steel support plate intersection caused by the buildup of deposits and the growth of a voluminous support plate corrosion product in the annulus between the tube and the support plate. Dents do not themselves result in tube wall penetration or reduction in piping wall integrity. However, denting at some plants in the past has been sufficiently severe to cause structural damage to the tube supports. Denting is a concern because even small dents can induce tensile stresses above the yield strength in the tube wall. As a result, these tubes may be subject to primary water stress corrosion cracking or intergranular stress corrosion cracking on the dents during subsequent operation. In addition, severe denting in tubes with small radius U bends has accelerated stress corrosion cracking in the U bends due to distortion of the tube legs. Furthermore, tubes with dents at the top tube support plate in the U bend region of the steam generators are more susceptible to high cycle fatigue failure.

In-service inspection of steam generators and strategy for replacement

Steam generators belong to the set of main components on which specific maintenance is carried out. The objectives of steam generator tubing maintenance are the following:

(1) To keep the probability of a tube rupture to an acceptably low level;
(2) To limit the number of forced outages due to primary to secondary circuit leakage.

Therefore, many surveillance techniques are required in the corresponding guidelines. They are of three types:

(i) Leakage monitoring, involving:
- Radioactivity level determination of condensates and bleeds (continuous monitoring);

— ^{16}N content in the steam;
— Hydro and helium testing during the regular 10 yearly outages.

(ii) Non-destructive examinations, including notably:
— Eddy current testing (standard bobbin coil and rotating probes);
— Advanced signal processing;
— Ultrasonic testing (under development);
— Tele-visual inspections.

(iii) Destructive examinations of extracted tubes:
— All analyses, including leak and burst tests;
— Correlation with non-destructive examination results.

The type of surveillance programme for steam generators will depend largely on the characteristics of the steam generator tube bundles, namely:

(a) Tube bundles having undergone a stress relieving heat treatment;
(b) Tube bundles without stress relieving heat treatment;
(c) Inconel 690 thermally treated tubes (alternative, more resistant thermally treated material now used for replacement steam generator manufacture).

The lifetime of steam generators primarily depends on the condition of their tube bundles. When the number of plugged tubes exceeds a certain value, called the plugging rate value, it is no longer possible on the basis of present knowledge to operate at full power. Typically, 'overplugging' tubes beyond the allowed limit for full power operation is an alternative solution until replacement of the steam generator, and is preferred to other maintenance options (sleeving, etc.) for economic reasons.

A strategy for steam generator replacement consists of replacing the steam generators before the number of plugged tubes reaches the allowed plugging rate limit (end of steam generator lifetime). To be able to forecast the technical end of a steam generator's lifetime, eddy current test results are used with the help of a computer code based on probabilistic fracture mechanics, while taking feedback from actual experience into account.

At the beginning of the 1980s, wastage corrosion of the secondary side of the steam generator tubes became known worldwide as a steam generator life reducing and limiting mechanism. After this problem became known, operating organizations started to change their water chemistry regimes from phosphate treatment to all-volatile treatment with an increased pH (>9).

Containment

The expected causes of ageing of the prestressed reinforced concrete containments are likely to be loss of prestressing in the case of underestimation of delayed strains (creep and shrinkage) on certain areas, and more classical ageing mechanisms such as cracking, corrosion and carbonate formation in other regions.

Containments can be monitored by a comprehensive set of special strain gauges installed in the concrete wall, as well as by other redundant measuring methods including equipment installed on a permanent basis around the nuclear island. The different monitoring methods are used to detect local deformation, possible losses of prestressing values and overall displacements occurring in the containment.

A monitoring system typically applies different measurement methods, such as the following:

(1) Local deformation in the containment is detected by strain gauges installed in the base mat, the gusset plate, the barrel and in the dome.
(2) Plumb lines are used for overall displacements of the structure and variations in containment diameter, the Invar wires for variations in the height of the cylindrical wall and optical levelling for reactor building settling and slope.
(3) Variations in tension are monitored on a few vertical prestressing cables grouted with grease and fitted with dynamometers. The first plant unit on every site includes four cables fitted with instruments.
(4) Thermal variations in the structure are monitored using thermocouples installed in the same areas as the extensometers.

In most cases the plant operating organization carries out a quarterly metering operation on all detectors, with the exception of special periods such as prestressing installation or containment pressure testing. However, a number of units have adopted a monthly metering cycle. All measuring devices are subjected to scrutiny, either by manual operation or by using automatic data acquisition devices capable of transmitting all measurements to a central database by means of a computer. The experts then conduct certain analyses largely aimed at isolating irreversible structural deformations such as shrinkage, creep, relaxation of prestressing cables and reversible distortions of thermal or pressure related origin.

Continuous monitoring is implemented at the start of the nuclear power plant's operation and will end when final shutdown takes place. It gives an accurate picture, throughout the lifetime of the structure, firstly of the phenomena which affect the tension of prestressing cables, and therefore the residual compression prevailing in the structure and, secondly, of the overall and relative settlement of the reactor building.

When analysed, the above elements can be used to assess the capacity of the third engineered barrier (containment) to prevent the release of radioactivity during an accident and to satisfy the mechanical design criteria.

Periodically, during the ten yearly outage period, the containment is tested under pressure to verify if there is potential for a leak. Specific monitoring during the test is performed to evaluate the leaktightness of the containment and to verify it in relation to the design criteria.

Turbines

In-service vibration monitoring of shaft lines is of the utmost importance for the service life of turbines in that it may be first to reveal the occurrence of faults, such as the loss of a blade. This would result in imbalance or the initiation of through-cracking on a shaft due to oscillating rotating motion fatigue. Note that in-service vibration monitoring cannot detect the incipient propagation of cracks in the longitudinal plane of the rotor, such as those caused by stress corrosion phenomena. These can only be detected by in-service inspection using non-destructive ultrasonic examination methods.

Furthermore, accidental rotor–stator contact due to the existence of relatively small radial clearances may not only scratch the relevant components but also may induce local overheating, causing permanent deformation of the rotating parts of the rotor assembly, which can easily be detected by the associated vibratory disturbance.

Vibration behaviour monitoring of shaft lines, which is usually done by shaft displacement detectors installed on the bearings, is carried out on a permanent basis. All nuclear power plants are equipped with basic instrumentation which emits alarms and, more rarely, trips the turbine. Some are equipped with more sophisticated diagnosis systems.

It is also essential to monitor the in-service vibrational behaviour of inlet valves, whose failure could have serious consequences for turbine safety and therefore the turbine's lifetime. In particular, when a turbine trip occurs the failure to close of one or more inlet valve(s) can increase the risk of shaft line overspeeding.

Inlet valve monitoring is done with axial and radial accelerometers. These are mounted on the spindle assemblies of the control valves and the measurements are logged continuously. This device has already detected damage to internal parts in certain control valves.

Most safety and control channel components are subjected to periodic in-service inspections to check that they are in good operating condition. The shorter the interval between tests, the lower the probability of component failure. Such inspections are usually done weekly, or at the least monthly for components related to turbine safety such as:

— The safety and control channels;
— High pressure or low pressure inlet valves;
— Overspeed detectors;
— Pressure detectors at the outlet of high pressure components and housings;
— Emergency lubricating pumps.

In-service preventive maintenance consists of routine inspections of the mechanical state of large component parts throughout the turbine's lifetime and during normal annual, five-yearly or ten-yearly outages. The usual rate is:

— Every 6–7 years for high pressure components and housings;
— Every 5–6 years for low pressure components and housings;
— Every 4 years for inlet valves.

Other inspections can be carried out at the same time and/or during refuelling shutdowns. These may include:

— Non-destructive testing of rotors and blades (e.g. stress corrosion cracking, fatigue);
— Support block inspection before and during shutdown to decide on a possible re-alignment;
— Cleaning or replacement of regulating oil filters;
— Real testing of the mechanical overspeed at restart, where appropriate.

During the course of these revisions, parts deemed faulty are repaired or replaced. Such measures also contribute to increasing the lifetime of turbines.

Generators

Generator lifetime depends on the following main components:

(a) Rotor rings, which are to be checked for absence of corrosion to avoid the risk of cracking;
(b) Stator insulation, which has not been the cause of any dielectric faults but which requires further knowledge and monitoring of its condition using new diagnostic methods;
(c) Rotor winding, of which further knowledge is required, particularly under power cycling stresses;
(d) Shafts, for which knowledge of fatigue resistance to torsion stresses is required.

The above mentioned rotor rings are those made from 3% chromium steel, which exhibits an increased risk of cracking in the presence of moisture. Some of these rotor rings were replaced by others made from an 18% chromium steel, while periodic ultrasonic monitoring was carried out on others, either with the rotor in place or with the rotor removed. In addition, precautions must be taken when opening generators to avoid moisture deposits beneath the bindings. This is achieved through the use of heating elements.

A system of periodic off-line monitoring of stator insulations by partial discharge has been set up to allow improved monitoring of the insulating wall of the stator windings. Calculations of fatigue resistance of shafts to varying power network demands and constraints indicate that, in general, lifetime fatigue usage of shafts is low, with only very rare network operating conditions requiring consideration.

The following problems have arisen in operation:

(1) Lack of leaktightness in water boxes, with a risk of water ingress into the insulating wall, causing a deterioration in dielectric properties;
(2) Plugging of the hollow conductors of stator bars, causing reduced water flow, corresponding increased temperature in the bars and accelerated ageing of the insulating wall;
(3) Unsatisfactory vibrational behaviour of the stator end windings.

These three problems are significant in that the only possible solution involves a significant and extensive maintenance programme. The problems in question arise not from the natural ageing of the machine's components, but from the consequences of the choice of technological design and assembly. Monitoring has been enhanced to optimize the scheduling dates for the significant maintenance tasks.

Feedback from experience now indicates that the reasonably expected lifetime of a stator winding is approximately 180 000 hours. Replacement of the winding must therefore be planned half way through the original 40 year design lifetime, the aim of condition based maintenance being to operate the generator up to this stage at the lowest possible direct and indirect cost, and then to the end of its normal lifetime.

So far information has been gathered from surveillance sensors, i.e. vibration, temperature, flow rate, etc. Such information is used to define maintenance operations and prevent the equipment from failing unexpectedly, entailing extra costs. The insulator is the most sensitive component, being subject to:

(i) External attack (various loose parts and missiles);
(ii) Vibration and related friction;
(iii) Temperature (which accelerates the ageing process);
(iv) Chemical attack (oil, miscellaneous products).

Electrical cables

Both theoretical and experimental studies have been conducted on cable ageing mechanisms, on parameters which can be used as ageing indicators, and on the foreseeable service life of cables. The experimental part of the studies included two parts:

— An experiment on laboratory aged samples, where the environmental conditions were fully controlled in terms of temperature and irradiation;
— An experiment on samples taken from a nuclear site, where they had aged naturally.

The latter type of testing on specimens is of twofold interest:

— It shows the 'state' of the cables after a number of known operating years;
— It can ensure, as a benchmark reference, that the accelerated ageing tests are truly representative of the phenomena that occur under normal/representative operating conditions.

There are two cable types, with different sheathing and insulating materials:

— Standard cables with PVC;
— Cables with ethylene propylene rubber insulation and chlorosulphonated polyethylene or 'Hyplon' sheathing. These cables, certified

'K1',[3] supply power to the equipment required to operate before, during and after a design based accident.

Initial estimates of cable life (e.g. approximately 50 years) must make allowance for operating uncertainties in cable behaviour, e.g.:

— Thermal ageing of PVC cables;
— Behaviour of K1 certified cables during a design basis accident.

Cable qualification tests are based on accelerated ageing methods which allow an assessment of the behaviour of a material over time, as well as a comparison between cables. However, they do not enable cable life to be determined with sufficient accuracy.

The objective is to set up a periodic monitoring plan for PVC cables to provide ongoing cable diagnostics and track changes in cable condition. The method offering the most certainty remains in-plant monitoring of the natural cable ageing process.

Non-destructive testing methods are recommended as they allow long term monitoring and keep costs down. A non-destructive testing approach also allows monitoring of a single cable over time, thus limiting the number of parameters likely to vary between two readings. The planned non-destructive tests are as follows:

— Measurement of insulation properties;
— Measurement of bulk modulus of elasticity using an indenter technique (elongation and hardness);
— Visual inspection (cracking and colour change).

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[3] Proof must be provided by testing or analysis that equipment is capable of fulfilling its functions under ambient conditions and demands that are to be placed upon it. All safety classified equipment must be qualified. Class 1E electrical equipment is divided into 3 qualification categories:

- Category K1: equipment installed inside the containment, having to perform its function in accident conditions;
- Category K2: equipment installed inside the containment, having to perform its function in normal conditions;
- Category K3: equipment installed outside the containment.

The ambient conditions include normal conditions, accident conditions and earthquake loading, depending on the equipment and its qualification category.

Life assessment studies show that insulation properties are a simple to measure and effective indicator for PVC cables. It is an electrical criterion which varies in efficiency with different cable families, but which shows chemical deterioration such as the migration of constituents between the insulating sheath and coverings or fillers. The test only covers insulating sheaths and requires the cable to be disconnected at both ends so that the measurement only involves the cable in question.

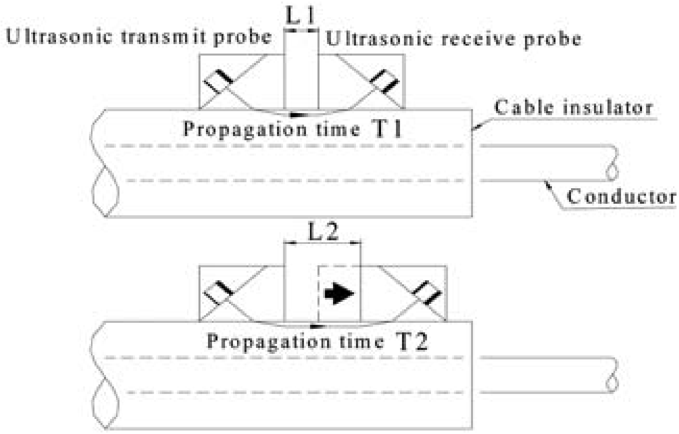
The indenter is a device used to obtain a quantified version of the qualitative measurement carried out by pressing a fingernail into the external covering of a cable to test its elasticity or hardness. The device consists of a clamp and a control and processing system. The clamp immobilizes the conductor or cable to be tested. The device measures the displacement of the probe and the force applied to the cable.

Visual inspection concerns the external appearance of the cable and conductors, which may only be visible at the cable ends. Its aim is to detect cracks, tears or changes in colour. Cracks are more likely at the end as a result of handling of the connected device during maintenance. In addition, cable ends may be subjected to higher temperatures than the rest of the cable if the terminal or its vicinity gives off heat. Visual monitoring offers simplicity and marginal cost but is limited by its qualitative, or even subjective, nature.

As shown in Fig. 9, degradation diagnosis methods for cable condition monitoring are available. Two methods are recommended that use either ultrasonic waves or the surface hardness. The ultrasonic wave method correlates the velocity of ultrasonic waves in the surface layer of the cable insulation or jacket to values of elongation at break, which is a good indicator of degradation. Equipment for performing this diagnosis is composed of a set of two ultrasonic probes that move to a predetermined position and measure the ultrasonic velocity automatically in a sequential manner. The cable degradation diagnosis method with these diagnostic devices has been applied to cables in some PWR plants in Japan [35].

Additionally, a new technique with the application of optical diagnosis for detecting degradation is being developed. In this technique, light sources of two wavelengths are used and the change in reflective absorbance between the two wavelengths is measured. The difference of this reflection absorbance is used to predict the lifetime of the insulation. When the insulation darkens, as a result of ageing degradation, the reflective absorbance increases, which indicates an increase in cross-linking density due to degradation (Fig. 10).

In order to control a loss of coolant accident (LOCA), which may occur at any time, the electrical and I&C equipment must be able to withstand a 160°C steam atmosphere coupled with high irradiation (gamma irradiation),



$$V_u = \frac{L_2 - L_1}{T_2 - T_1}$$

FIG. 9. Principle of ultrasonic wave propagation velocity measurement.

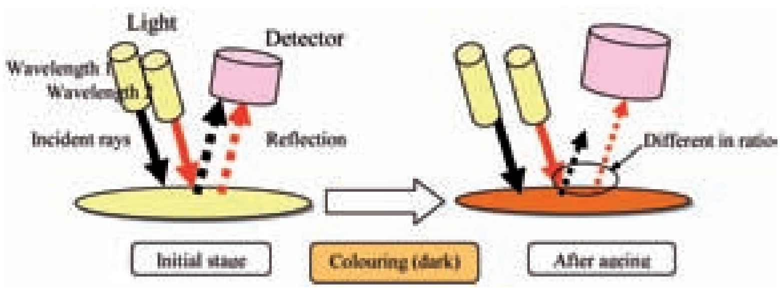


FIG. 10. Application of optical diagnosis for detecting degradation.

aggressive radioactive chemical species and boric acid solution exposure. For every group of relevant components, specifications for non-destructive tests during plant outages are being developed.

Instrumentation and control

Studies have resulted in the following conclusions regarding I&C equipment:

— Small equipment items (sensors, actuators, recorders, etc.) are to be replaced on an individual basis. Strategies must be defined, when needed, to overcome the obsolescence of component parts.

— Process control equipment must be maintained at least until the second ten-yearly outage. To meet this requirement, long term maintenance agreements must be drawn up with the main suppliers concerned.

Several scenarios can be defined within the scope of prospective studies. The scenarios can range from minimum replacement tasks to complete refurbishment.

The chosen strategy had to give priority to meeting the following objectives:

— Replacement of an equipment item whenever a financial or technical assessment (ageing, obsolescence) has shown that its lifetime could not be extended to the third ten-yearly outage;
— Retaining the original nuclear safety principles as defined in the nuclear safety report;
— Improving productivity; however, functional modifications must be rigorously justified and limited in number in order to minimize risk, in terms of cost, schedule and impact on normal plant operation.

Studies have revealed all the main operational constraints to be taken into account for refurbishment operations. They include:

— Maximum admissible unit unavailability;
— The rate at which work should be completed on all units;
— Requalification of process control equipment on all systems involved;
— Costs;
— Updating of documentation (system manuals, equipment operation and maintenance manuals, etc.);
— Operating and maintenance constraints: training, maintenance and periodic test procedures;
— Control room ergonomics;
— Human resources likely to be assigned to these operations;
— The need, in some cases, for an interface between new and existing equipment (instruments, actuators, other process control equipment).

Therefore, at the present time, to seek to refurbish all process control equipment in a single operation can be considered unrealistic. For the reasons outlined above, Electricité de France has shifted towards a strategy of partially or progressively refurbishing the process control equipment of its three loop plants. Each of the measures undertaken has to ensure, with a high level of probability, the efficient performance of process control equipment for a full

20 years. As part of this approach, any equipment about which there is a strong uncertainty that it could be maintained through to the third ten-yearly outage will be refurbished during the second ten-yearly outage.

To take into account the potential obsolescence of many strategic I&C components a functionally equivalent list of alternative I&C components is established and a qualification procedure for alternative equipment is in place.

To determine the feasibility of maintaining equipment in service until the third ten-yearly outage and to draw up a technical and economic assessment of actions to be carried out to achieve this goal, the ageing of the process control equipment was observed and assessed. The purpose was to integrate both equipment and functional issues (availability, nuclear safety, etc.), and only involved equipment outside the containment. Only the most important systems were studied during this phase.

For each group of equipment identified the observation phase covered the following aspects:

— Equipment behaviour report;
— Visual on-site examination of equipment (through sampling);
— Inquiry into maintenance difficulties encountered by plants;
— Determination of the state of spare parts and rejected component inventories;
— Examination of problems encountered by suppliers;
— Study of the sensitivity of components to obsolescence;
— Anticipatory study aimed at solving identified ageing problems;
— Inventory of the main functional modifications to be made to equipment;
— Identification of equipment margins before making modifications;
— Study of the sustaining of equipment qualification under accident conditions (particularly earthquake) in the event of modifications to modules;
— Technical report;
— Economic report.

Other actions within the scope of the observation phase included:

— Studies on the operating environment of process control rooms and equipment, i.e. ventilation, power supply, cables, etc.;
— Studies on equipment ageing aimed at determining whether or not it was possible to anticipate an increase in the number of failures before the end of the operating lifetime of the plant.

It is recommended that preliminary refurbishment studies be carried out with a view to drawing up a technical and economic assessment of the refurbishment conditions required for process control subassemblies and to making it possible to define the following:

— Specifications for refurbishment operations;
— Specifications for subassembly refurbishment;
— A market offer evaluation programme.

These studies make allowance for the following constraints:

— Duration of unit refuelling outages;
— The obligation to implement the same functional and technological solutions on all units on the same site (equivalency);
— The necessity of avoiding too many different types of equipment on the same site;
— Evaluation of the risks related to installation and requalification studies;
— A design lifetime of equipment which enables it to reach the end of a plant's operating lifetime;
— Refurbishment must contribute to a reduction in the number of times a nuclear power plant goes into forced outage and thus also cut maintenance costs.

The basic studies should include:

— Descriptions of existing equipment;
— Identification of the level of nuclear safety to be achieved for the process control equipment;
— Definition of the design architecture;
— Equipment refurbishment studies;
— Studies of the impact of refurbishment on the control room;
— International technology trend study;
— Summary report and optimization solutions;
— Definition of refurbishment specifications.

The functional capability of electrical and I&C equipment is verified in the course of periodic in-service testing performed during plant operation and scheduled outages. The capability of the equipment to withstand accident conditions also has to be verified. The operating organizations have worked out basic principles for testing such accident resistance.

In most cases, long term functional capability of plant I&C systems can be ensured by just replacing them with new equipment. The present trend in nuclear power plants is to replace old I&C equipment — both that for control of normal operation, as well as safety I&C — with digital systems. The new digital I&C technology requires a considerable amount of software, which must first be subjected to a verification and validation procedure.

Secondary system pipes

Flow accelerated corrosion, often called erosion corrosion, is a specific ageing process influencing piping components manufactured from plain carbon or low alloy steels. The result of two processes, first creation and then dissolution and removal of the protective surface oxide layer, is wall thickness loss, which may eventually cause pipe rupture.

The main parameters influencing flow accelerated corrosion are temperature, flow rate, oxygen content and environmental pH, chemical composition of the steel, component geometry and thermodynamic state of the environment (water, mixture steam water, live steam). The secondary circuit's parameters of nuclear power plants are in many cases close to the critical limits for influencing the individual parameters. Temperatures between 130 and 260°C, pH below 9.5, low alloy carbon steels (i.e. <0.5% chromium) and flow rates >1 m/s form favourable conditions for flow accelerated erosion corrosion.

Efforts to minimize damage to the secondary piping by flow accelerated corrosion in nuclear power plants combine two approaches:

(a) A combination of the operational and geometrical parameters, which excludes or significantly reduces flow accelerated corrosion. This may be, for example, replacement of the materials for heat exchange surfaces or condensers and following change of the coolant's chemical regime, or replacement of the whole piping line with material more resistant to flow accelerated corrosion.
(b) The system measures, for example, the systematic and on-line monitoring of wall thickness, reliable damage prediction and implementation of all known operational experiences for the evaluation of selected piping lines. The aim is to eliminate, in advance, the possibility that the defect (thinning either locally or over a large area) may cause damage to the integrity of the piping system.

Both methods are often combined since it is difficult to make significant changes to the main operating parameters. Severe wall thinning and even failure due to flow accelerated corrosion have occurred in both conventional fossil fuel and nuclear power plants, e.g. the accident at the Surry 2 nuclear power plant in the USA in 1986 and that at the Mihama 3 nuclear power plant in Japan in 2004, both of which resulted in fatalities. Referring to the latter accident, part of the main feedwater pipe in a turbine system was ruptured during rated power operation at the Mihama 3 nuclear power plant, a PWR. A large amount of high temperature water was flushed out of the ruptured pipe in the turbine building. This accident claimed five lives and injured another six workers on duty in the vicinity of the broken piping.

4.1.3. Obsolescence of equipment

With long operating periods (e.g. 40 years and, with long term operation, perhaps 60 years or more), some nuclear power plant components will become obsolescent. This is the result of normal evolution of technology and construction materials. Obsolescence is particularly relevant for I&C.

From the plant life management point of view, key points must be considered, namely:

(a) To identify strategic components likely to be affected by obsolescence (e.g. computing equipment or I&C), and to establish a comparison and equivalence level;
(b) To qualify the new components and to evaluate the capability of replacing and/or repairing and improving the previous equipment.

Many nuclear power plants are currently operating using programmable electronic systems and equipment. Future nuclear power plants and retrofit projects will also use these types of devices, which are the state of science and technology solution for I&C. The life cycle of such equipment has to be considered, taking into account the specific characteristics of electronic information technology and not limited to the ageing of components (hardware). Some features of this are described below:

(1) The component base for programmable I&C system products is less stable than that used for the older series of I&C (hardware using discrete components or simple integrated circuits). Rapid evolution in the technology leads to a shortened life cycle for the commercial availability of processors, memories and peripheral devices.
(2) The state of the science and technology of I&C design moves rapidly compared to the overall lifetime of a nuclear power plant, particularly in the information technology area (software tools, operating systems, engineering tools, human–machine interface software).

(3) Specific problems can arise due to the disappearance and mergers of I&C equipment and component manufacturers.
(4) Human resource difficulties for the long term maintenance of software technologies are also important considerations. Information technology career management is based on permanent updating of technologies, while nuclear power plant operation requires a 'freezing' of technologies for compliance with safety regulations and operating cost reduction. Retaining expertise and arranging for the transmission of expertise to counter the retirement of the original designers of the older I&C and information technology will become increasingly difficult in the future [23].

Analog and digital electronics used to convert the sensor signals, provide signal conditioning and digitize the data should be included in the management of I&C ageing. This equipment has not in the past been the subject of ageing concerns because it is normally located in instrument cabinets in the easily accessible and environmentally benign areas of the plant and consequently ages very slowly. However, obsolescence of this equipment is important, especially in the case of long term operation. Obsolescence is more of a problem with this equipment than ageing because electronic components and digital systems are frequently upgraded by manufacturers and older equipment is no longer available. Consequently, in the focus of ageing management for such systems it is necessary to ensure that the required functions are met independently of the I&C technology applied.

4.2. REGULATORY ISSUES

4.2.1. Regulatory aspects of plant life management and regulatory control of long term operation

From a regulatory perspective, the basic elements considered for plant life management are:

(a) Preventive maintenance;
(b) Ageing management, including maintenance of equipment qualification conditions;
(c) Surveillance and inspections;
(d) Obsolescence issues.

Studies and assessments which are required to demonstrate safe operation of the plant throughout the period of long term operation should be added to the assessments and studies required in the current periodic safety review. These are listed below:

(1) An integrated ageing management plan which contains both the ageing management report analyses and the time limited ageing analyses to provide for safe operation of the systems, structures and components [3];
(2) A supplement to the safety analysis report, including the studies and assessments that justify operation of the plant during the extended period of operation;
(3) A revision of the technical specifications, including the changes required to maintain safe operating conditions during the period foreseen;
(4) An update of the radiological analytical studies covering the new operating period, taking into account the expected changes in the radiological environment;
(5) A review of the nuclear power plant's radioactive waste management plan to demonstrate the availability of sufficient ability to manage the wastes generated during the extended operating period, including the storage of spent fuel elements.

4.2.2. Communication between operating organizations and regulatory bodies

Regulatory bodies have their own systems and organizations in place which facilitate the exchange of information, e.g. the Western European Nuclear Regulator's Association (WENRA), or the World Association of Nuclear Operators (WANO), the Westinghouse Owners Group (WOG) and the Boiling Water Reactor Owners Group (BWROG) for utilities and operating organizations. Notwithstanding these, direct communication between operating organizations and regulatory bodies is essential to promote the common goal of safe operation at all times.

Communication may be achieved in several ways, for example monthly reports of the nuclear power plants on all operational aspects, meetings, operational talks, nuclear power plant walkdowns after outages, inspection reports and notices regarding reportable events. Accurate, open and traceable information will serve both formal and practical requirements in addressing plant life management and even the goal of long term operation.

Regulatory bodies will be concerned with safeguarding the public and the environment from any consequences arising from the use of nuclear energy. Operating organizations and owners will be concerned with supplying electric power and, where appropriate, district or industrial heating at the most competitive price while maintaining the highest achievable level of safety. A plant life management programme based on state of the science and technology approaches, which has been accepted by the regulatory body on the basis that by its use safety levels are either maintained or increased, will also work in favour of the goal of long term operation. Therefore, if nuclear power plants provide the regulatory bodies with all information in a timely manner the best conditions for requests for long term operation will be created.

4.2.3. Public acceptance

Public acceptance of nuclear power plant operation varies considerably from country to country, and even within regions and localities of each country. Nuclear power plants provide not only energy, but also employment. In general, public acceptance of nuclear power was low in the 1980s and 1990s, due in part to the nuclear power plant accidents at Three Mile Island and Chernobyl. However, recent surveys in the USA have indicated a significant improvement in public opinion towards nuclear power and licence renewal.

According to Bisconti Research, Inc. [38], the percentage of the US public favouring the use of nuclear energy has risen from 49% in 1983 to a peak of 70% in 2005. The percentage of the US public that is opposed to the use of nuclear energy has dropped from 46% in 1983 to a low of 24% in 2005. In addition, public survey results in May 2005 show that 85% of the public support the idea of nuclear power plant licence renewal (see Fig. 11).

Contributing factors to this improving public image include:

(a) Good nuclear power plant performance (safety, cost of electricity and capacity factor);
(b) Recent energy and electricity supply concerns (recurring ‘rolling blackout’ problems and the ongoing Middle East conflicts);
(c) More outspoken support for nuclear power by leaders in government and industry;
(d) The news media finding the nuclear industry renaissance intriguing (more positive news coverage of nuclear power).

A positive public image of nuclear power in general and favouring licence renewal specifically creates a favourable economic climate that encourages plant life management and long term operation.

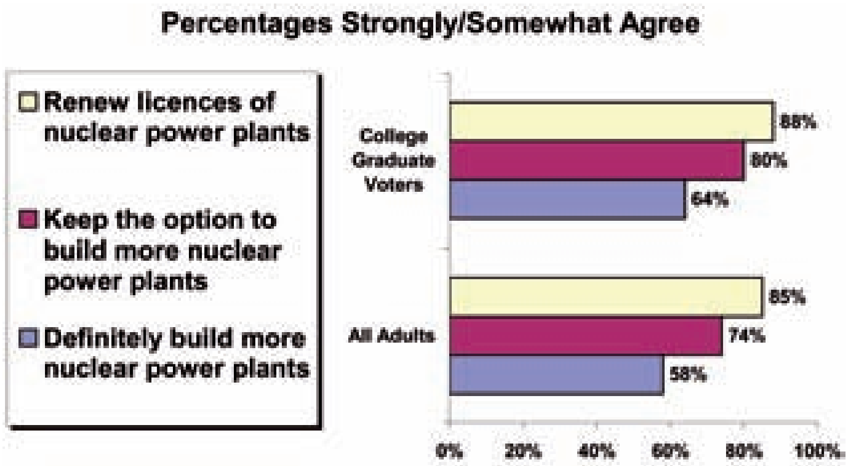


FIG. 11. Public opinion in the USA on nuclear power.

4.2.4. Environmental radiological impacts of plant life management for long term operation

It needs to be assessed whether operation of a nuclear power plant beyond its original design lifetime might have an unacceptable impact on the population and the environment, to identify additional requirements that might be necessary and to guarantee the protection of workers, the general public and the environment. The following needs to be considered from a radiological point of view:

(a) The radiological impact of a nuclear power plant's operation is largely independent of its operating lifetime. The rigid implementation of, and compliance with, accepted and well proven radiological protection practices is considered sufficient to meet the requirements of the radiological protection laws and standards at this time. The periodic safety reviews, operating experience programmes and regulatory oversight activities are currently considered adequate for reviewing operational aspects contributing to radiological impact. These include:
— The bases of the environmental radiological surveillance plans, taking into account the possible accumulation of radionuclides;
— Review of the environmental radiological impact to take into account possible changes in the environment and new trends in radiological protection and evolution in associated legislation and requirements.

(b) Because of their cumulative nature some factors have a direct radiological impact and should be given special attention as regards justification of long term operation. Therefore:
- The radiological studies and reports should be reviewed, taking into account the forecast of emission of effluents to the environment and the evolution of other aspects such as population growth and living habits, the evolution of agriculture, the existence of recent hydrogeological studies, changes in the dose assessment standards or the updating of meteorological data with a view to covering the proposed new operating period.
- The management and storage plans for the plant's irradiated fuel and radioactive wastes should be reviewed in order to demonstrate that sufficient radwaste management capacity is available for long term operation. Also, sufficient nuclear power plant personnel must be available to ensure that long term operation is possible with no unacceptable impact on radiological safety.
- The radioactive waste management plan should include the management of major components replaced as a result of plant modifications. This may become critical as time passes and the components age, since it may be necessary to extend the existing storage capacity to allow for replaced contaminated or activated materials (e.g. fuel elements, waste, steam generators, reactor pressure vessel heads and piping).

4.2.5. Codes and standards

A regulatory body's consideration of plant life management programmes is by nature restricted solely to the issues of public and environmental safety. It is the operating organization of a nuclear power plant that has the legal responsibility to ensure safe operation, and also to bear the total cost of operation and the associated plant life management activities. Long term operation is decided on by the operating organizations; a regulatory body will only be interested in safety issues.

Based on established ageing management programmes it is apparent that such programmes will create conditions under which plant life management naturally becomes integrated. Keeping systems, structures and components at a high level of fitness for service favours high availability and trouble free operation. The latter is closely associated with a high level of safety as well as economic benefits.

The current licensing basis is usually maintained within the framework of the periodic safety review as a regulatory instrument for addressing requests for the renewal of operating licences. For long term operation, the current licensing basis is usually maintained. The expression ‘maintenance of the current licensing basis’ does not mean that these bases are fixed, but rather that they may evolve during the next operating period through the same process as was followed since operational startup. Generally, no modifications will be required to the current licensing basis unless its requirements cannot be met during the next operating period.

Likewise, after the periodic safety review or licence renewal process, nuclear power plants will be operated on the current licensing basis, which is updated through the recurring process of ‘analysis of new standards’, as established in the operating licence. In addition, the applicability of new standards will be assessed, taking into account that they are:

(a) Not included in the current licensing basis;
(b) Affected by the new long term operating conditions;
(c) Identified as being important for safety on the basis of systematic and justified methods (i.e. cost–benefit analysis in term of safety enhancement).

For example, in the case of Japan the following four technical codes and standards for nuclear power plant ageing countermeasures were developed by technical experts from academic societies as third parties:

(1) The rules on fitness for service for nuclear power plants, developed by the JSME in 2002 and endorsed by NISA;
(2) The periodic safety review standard, in progress by the Atomic Energy Society of Japan (AESJ);
(3) The plant life management standard, in progress by AESJ;
(4) The pipe thinning management standard, in progress by JSME.

The NISA cooperates with AESJ and JSME in the development of these rules and standards and will endorse them for actual application only after detailed examination.

4.3. ECONOMIC ISSUES

4.3.1. Economic planning

Three main economic requirements that need to be continually reviewed with a view to improving them are:

(1) Maximizing annual power generation;
(2) Minimizing operating costs;
(3) Assessing the additional cost of ensuring continued safe and profitable operation.

Therefore, plant life management includes systems, structures and components important for safety and production. In order to sustain low generating costs in the long term the plant has to be maintained in an optimal technical condition.

For the business evaluation of plant life management the total cost contributors have to be assessed and compared to income during plant operation. The three major inputs are income, expenditures and financing.

General macro-economic tendencies, as well as market development and expectations, have to be considered in the income forecast. The plant's expected load factor has to be assessed. As a good plant status can be ensured through plant life management, high availability of the plant can be assumed to be constant. Power uprate, which itself has a short payback time, provides a good opportunity to improve the price (the fixed costs will be distributed over a greater production volume).

Major forced outages due to, for example, the loss of the (secondary side) single generator through destruction of the stator windings can have an impact on economic plans. Not only the replacement or repair of the generator, but also the loss of power sales for several months while fixed costs remain relatively high, will have an impact on forecasts. The nominal cost of such an outage may reach US$ 1 million per day. Some time may be gained if other activities such as refuelling and inspections are done earlier, during the wait for new parts or equipment. The above mentioned scenario occurred in Switzerland at the Leibstadt nuclear power plant (BWR) in April 2005.

Generating costs consist of capital charges, fuel and non-fuel operating and maintenance costs. Capital charges are the dominant portion of cost in the initial years of plant operation. During the long term operation phase the initial construction capital costs will already have been amortized. This impacts favourably on the market position of the nuclear power plant.

The operating and maintenance costs might rise with time, both due to price increases and increasing requirements for preventive and predictive maintenance, repair and replacement of components. However, they may decline due to improvements in management, technology and changes in the economic environment.

The generating costs will also include insurance and liabilities, including plant decommissioning and management of operating and decommissioning wastes, and costs for radioactive waste conditioning, storage and disposal.

These costs might be positively influenced by an extended operating lifetime since the total amount of radioactive waste to be stored is not proportional to the extended operating period and the energy produced.

One of the most important cost components is provision for major exceptional maintenance (e.g. replacement or repair of major components). These expenditures have to be defined on the basis of plant status assessment. The maintenance and ageing management programmes have to be reviewed, the expected lifetimes of the systems, structures and components defined, the need for major repairs or replacements identified, and the projected costs have to be allowed for. The earliest start and latest finish of the replacements are important for financial and business planning. In some cases, the probability of replacements has to be assessed and used as weighted elements for cost assessment.

In some cases major refurbishment or improvement measures will require an extended outage, the costs of which also have to be assessed. Additional costs for major replacements have to be taken into account, such as construction of new storage facilities for replaced large, contaminated components. The costs of minor annual replacements also have to be defined and allowed for. These might influence the business viability of long term operation. In some cases, excessive numbers of low cost replacements may also threaten the economic viability of long term operation and may lead to premature retirement of relatively old or small nuclear power plants, in particular when other operational or regulatory problems arise.

Examples of early retirements of nuclear power plants include Rancho Seco, San Onofre-1, Trojan, Yankee Rowe and Connecticut Yankee (all in the USA). Some nuclear power plants have been (or will be) shut down either for technical reasons (e.g. reactor pressure vessel integrity concerns at the Greifswald nuclear power plant in Germany) or political policies or circumstances (e.g. current German and Swedish nuclear power phase-out policies and the Zwentendorf nuclear power plant in Austria, which was built but never operated).

Figure 12 is a flow chart of the definition of costs of plant life management for long term operation. Economic evaluation methods for plant life management are:

— The marginal cost of continued operation;
— The net present value of the improvement;
— The internal rate of return on the improvement costs.

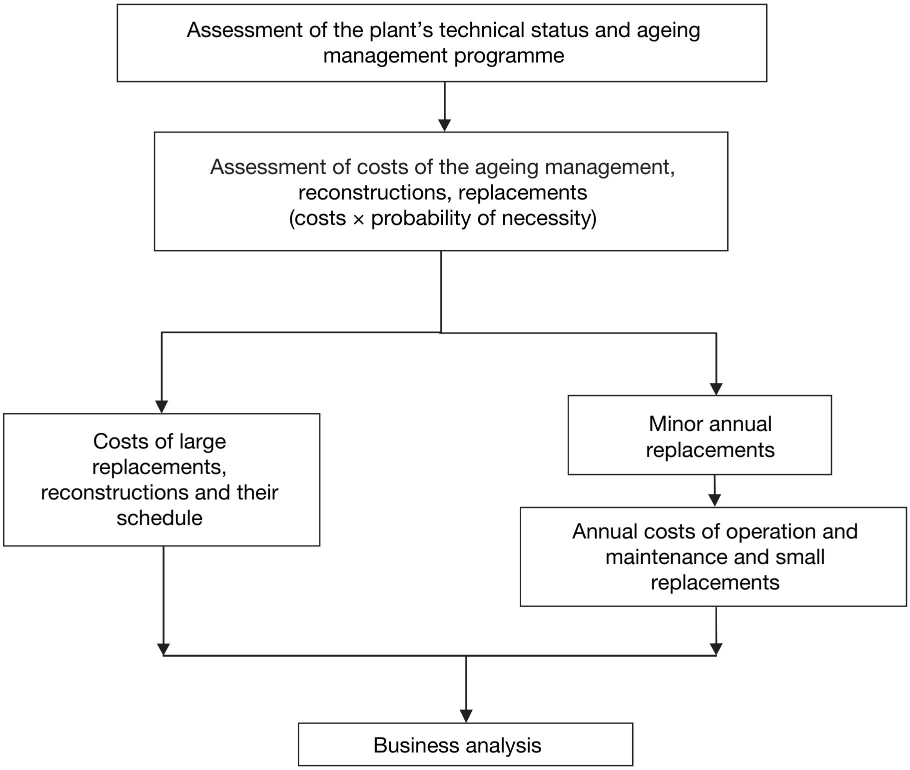


FIG. 11. Overview of cost drivers for the business analysis of long term operation.

Timing effects of the expenditures and incomes will be analysed by means of a cash flow analysis. Since the costs are unevenly distributed over time, their time dependent value is considered by discounting.

The marginal costs of continued operation after improvement will then be compared to the marginal costs of other options to determine the economically preferable solution. The net present value of the improvement project is the present value of its cash flow, which is calculated from its revenues and costs.

The internal rate of return is defined as the discount rate at which the net present value becomes zero. It can be calculated iteratively by varying the assumed discount rate until the net present value becomes zero. Essentially the same approach might be applied to the business assessment of particular ageing management programmes and major replacements. In this case the following steps are necessary:

(i) Assessment of the costs of the alternatives to ageing management (replacement, repair, run to failure);
(ii) Probability or rate of failure;
(iii) Consequences of failure (cascading);
(iv) Economic impact of failure;
(v) Impact of failure on the overall lifetime of the nuclear power plant;
(vi) Sensitivity study (to vary the scenarios, probabilities, earliest start, latest finish, production consequences).

It is a good strategy to begin (ideally at startup) to invest in condition monitoring, preventive maintenance and refurbishment programmes as soon as possible, to maintain the plant in an optimum condition for the long term, in order to preserve the valuable option of licence renewal (where applicable) and long term operation.

From the point of view of the electricity market, regulated plants have different economic drivers than deregulated ones. In principle, regulated plants can pass additional costs on to the consumers. Deregulated plants are under competitive market pressures regarding the price of electricity. This difference makes economic analysis of extended plant operation fundamentally different for these two situations.

The largest unknown in determining the future value of a plant is the market price of electricity. This variable outweighs all other cost drivers but is also one of the least well defined parameters.

Asset management from the financial viewpoint includes several levels:

— Component level;
— System level;
— Plant level;
— Nuclear fleet level;
— Corporate business level.

Information is needed at each level to make the final decision on whether it makes economic sense to continue plant operation and, if so, for how long. Adequate cost accounting systems that address this range of financial data are often lacking; however, financial decisions must still be made at all these levels with the best available data. Recognition and understanding of these financial issues should encourage development of improved cost accounting approaches (e.g. activity based costing) to ensure that data are available to better evaluate plant life management options (e.g. repair, replace, upgrade).

4.3.2. Cost–benefit analysis

The nuclear power industry carries out an ongoing assessment of nuclear power plant operation and maintenance as the plants continue to age and new operational, analytical or research information is acquired. Particular emphasis is given to major refurbishment activities such as core shroud replacement (BWRs), reactor pressure vessel head or steam generator replacement (PWRs) that may impact nuclear safety and/or have considerable economic importance.

Measures to minimize ageing which involve backfitting or replacement of systems or components may be very expensive and require a cost–benefit analysis before a decision is made. It must be noted that when plants get older this type of cost–benefit analysis will require some assumptions about the planned remaining operating lifetime of the plant.

These issues are generally so complex as to warrant a formal decision making process. A cost–benefit analysis may also be used to evaluate and make decisions with respect to the various alternatives that may be available. The cost–benefit analysis process consists of a systematic sequence of steps carried out in accordance with a framework that provides clear, consistent and well documented input to the decision making process with the aim of achieving the maximum safety benefit, given the resource limitations that must be taken into account.

Although repair or replacement of most systems, structures and components is technically possible, their ageing can indirectly impact on plant costs because ageing related behaviour can lead to unplanned extended outages, reduced availability and increased production costs. Such factors may raise regulatory questions about the actual plant safety level, the operating organization's ability to manage ageing issues and the possibility that the industry may have insufficient capacity to support numerous replacements or backfitting of qualified and quality assured components in a short procurement time. Ageing thus may become a threat to continued plant operation.

When new or different design components are used they must fulfil functional equivalence (or better) requirements compared with the original components. This may entail qualification and regulatory approval processes that can increase overall costs, especially if exceptional delays occur.

Further, ageing can have a direct impact on a plant's cost effectiveness when degradation approaches limits (maximum allowable value according to technical specifications or regulatory limitations) and repair or replacement of systems, structures and components is necessary. This entails additional expenditures such as the purchase of parts, personnel costs or extension of outages. Ageing can also have an indirect impact, namely that although operating organizations do their best to manage ageing it is not possible to totally eliminate the risk of component failure due to ageing. This can lead to an age related event or incident or a forced outage that will increase production, and operating and maintenance costs (resources to cope with the event, consequences of the incident, loss of power, etc.). Efforts to minimize ageing also have a cost, but minimizing contributors that cause premature ageing represents avoided costs.

For some components, accepting 'normal' ageing and just waiting for repair and replacement time can be the most cost effective solution. This is sometimes known as the 'run to failure' strategy and is often used for small, easy to repair and replace non-safety related components. But in cases involving more expensive equipment, ageing may be slowed down by proactive measures which need only limited resources, for example by optimization or adjustment of operating and maintenance procedures. This is the 'management of ageing' strategy. Experience has shown that a combination of ageing strategies is most beneficial, but a plant life management programme, with its systematic assessment of ageing behaviour, is usually needed to select the appropriate combination.

4.4. PERSONNEL ISSUES ASSOCIATED WITH PLANT LIFE MANAGEMENT FOR LONG TERM OPERATION

4.4.1. Qualification and availability of nuclear power plant personnel

The availability of sufficient personnel is a vitally important issue for plant life management for long term operation. The following needs to be considered:

(a) Systematic and validated staff selection methods (e.g. testing for aptitude, knowledge and skills), maintaining a high level of personnel training;
(b) Organization issues such as shift work and overtime restrictions, and dose penalty limits associated with plant life management tasks.

Operation of nuclear power plants at high levels of safety and economic competitiveness not only requires sound maintenance, inspection and ageing management programme/plant life management approaches, but also, a priori, sufficiently trained personnel to carry out the work. Even if nuclear power plants are technologically at a high level they still need to be operated in a manner that conforms to safety standards, technical specifications and good practices including, for example, avoidance of transients.

However, due to the global slowdown in new nuclear power plant construction over the past 20 years there has been little incentive for young engineers to embark on careers in the nuclear power sector. Universities and other centres of learning have thus stopped, or drastically reduced, the number of nuclear technology courses as a response to falling demand. The problems with staffing of nuclear power plants, particularly for long term operation, were reported on in depth at an IAEA symposium on nuclear power plant life management [39].

For example, in 2003 the Nuclear Energy Institute [40], as shown in Fig. 13, also made a study of the ageing nuclear workforce in the USA and found that approximately 50% of the workers are between the ages of 43 and 52, which is significantly outside the normal age distribution of the general US working population. About 28% of US nuclear workers (or approximately 16 000) are currently eligible for retirement and that number will continue to grow as the workforce continues to age. The normal attrition rate of workers leaving the nuclear workforce (excluding retirement) is about 10% per year.

Utilities and nuclear power plant owners contemplating long term operation must take such trends into consideration. Even if systems, structures and components are optimized and backfitting has been done, personnel must be available to run the nuclear power plant during this period and then ultimately for decommissioning and disposal.

The mid to long term challenge for the nuclear industry is to attract young, well trained entrants to fill the vacancies created by the large number of retirements and attrition. Employees today are highly mobile. For example, US workers in their 20s, 30s, and 40s do not mind moving for career advancement

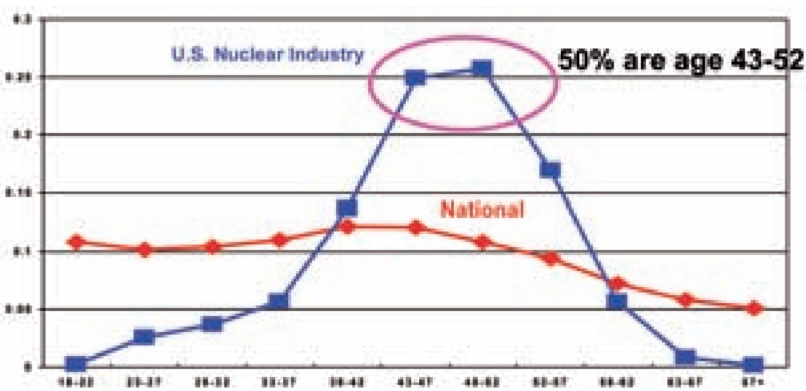


FIG. 12. Age distribution of the nuclear workforce compared to the national trend in the USA in 2003.

or better work opportunities. Due to technology enablers such as email and the Internet, US workers expect flexibility in where the work gets done.

The challenge for experienced and knowledgeable nuclear workers is to teach and train their younger colleagues before they retire and take their knowledge with them. Considerable succession planning is therefore required over the next few years to ensure a successful and ongoing transition to younger nuclear workers.

4.4.2. Personnel exposure associated with plant life management for long term operation

As systems, structures and components age, the level of activation and the need for reconstruction, replacement and inspection may increase. For long term operation, ease of accessibility to them for monitoring, inspection or replacement purposes is an important factor since it favours better overall work quality in the tasks performed, particularly when personnel may be exposed to radiation.

ALARA principles require the optimization of shielding, reduction of time spent on a task, and therefore good work planning in advance. Wherever possible, dry runs using mock-ups should be done to optimize all actions and work processes and so facilitate ALARA goals.

4.4.3. Roles and responsibilities of operating organizations and regulatory bodies

There have been several instances where existing knowledge regarding the potential for a materials failure was not used adequately to check whether the same problems could occur elsewhere. Existing requirements for tracking events and feedback of experiences in other nuclear power plants become even more important for nuclear power plants aiming for long term operation.

In some cases, operating experience may have shown that a system, structure or component was not so affected by a given ageing mechanism as had been assumed in the design specifications. This may justify reduced inspection frequencies or more superficial inspections, allowing resources to be focused on more critical systems, structures and components that could be showing degradation at rates in excess of those assumed at the design level.

Risk informed methods facilitate this approach. It is necessary to justify the implementation of improvements such as water chemistry adjustment, neutron shielding (low leakage core configuration), and the substitution of better designed components featuring optimized materials (e.g. better alloys) and production methods (e.g. surface and heat treatments). Actions such as these must be validated (state of science and technology) to obtain regulatory approval.

Clearly, a priori, any known weaknesses will be accounted for and corresponding strategies will be in place to handle failures. The caveat lies in the fact that potential weaknesses or precursors for accidents may not be readily identified, and corresponding contingency plans will then not be available. The following examples emphasize the importance of implementing actions based on available knowledge and lessons learned.

4.4.3.1. Flow accelerated corrosion and erosion corrosion

An accident with fatalities occurred at the Surry nuclear power plant in the USA in 1986 due to low alloy carbon steel pipe wall thinning. Nevertheless, a similar accident occurred at the Japanese Mihama unit 3 nuclear power plant in August 2004. In the latter case a condensate pipe suddenly burst, scalding workers who were in the turbine hall, four of whom died instantly. The pipe, which had been in service for some 27 years, was scheduled for its first inspection in November 2004, so the accident occurred just three months prior to the first inspection. When new, the pipe walls measured 10 mm thick, but were found to be 1.4 mm thick when the accident occurred. This is an 86% loss in thickness and the pressure–temperature conditions correspondingly became too demanding for the remaining pipe material. Weaknesses in inspection schedules may thus lead to accidents. Awareness of ageing mechanisms that have already caused problems at other nuclear power plants, anticipating potential weak spots and a corresponding inspection, monitoring or replacement programme are essential for safe operation.

Problems associated with flow accelerated corrosion and erosion corrosion in this class of steel have been known of for many years. Carbon steel piping in feedwater, recirculation, extraction and heater drains is liable to be affected by flow accelerated corrosion and erosion corrosion (thinning of the alloy through loss of protective magnetite oxide layers due to flow of water or wet steam). It appears that the lessons learned from the Surry accident had been forgotten. It is noted here that various proprietary tools and computer software packages are available to predict the wall thinning rate, average rate of thinning since startup, total loss in thickness to date and remaining lifetime. Such on-line tools have now been installed in many nuclear power plants.

4.4.3.2. Reactor pressure vessel head degradation

Another case is the external corrosion of reactor pressure vessel heads from boric acid attack (wastage) due to leakage of control rod drive mechanism nozzles caused by primary water stress corrosion cracking of Alloy 600. The problem of wastage was discovered in 1971 in a Swiss PWR, Beznau 1, after it had been shut down for service. The amount of wastage was not severe enough to call the integrity of the reactor pressure vessel head into question, as was demonstrated with comprehensive fracture mechanical and engineering analyses. The reactor pressure vessel head is still in service and is subject to annual control and continual monitoring. No further deterioration has been detected to date.

In 2002, 31 years after discovery of the Swiss situation, significant wastage was discovered in the Davis-Besse PWR in the USA. In the latter case the reactor pressure vessel's relatively thin (about 7 mm) stainless steel cladding was exposed locally, thus making it a pressure boundary. If this cladding had been breached a LOCA would likely have occurred, although the emergency cooling and other measures would have been adequate to limit the consequences. A lengthy and costly outage of the Davis-Besse nuclear power plant resulted.

The problems caused by wastage are being addressed through improved inspections and shorter inspection intervals, monitoring and, in many cases total replacement of the reactor pressure vessel closure head, using materials for the penetrations that are expected to be more resistant to primary water stress corrosion cracking. The presence of insulating material is a hindrance to reactor pressure vessel head inspection, and this feature has thus created conditions in which a developing problem has been hidden from view.

4.4.3.3. Alloy 600 issues

The unsuitability of Alloy 600 in some applications in PWRs, due to primary water stress corrosion cracking, has been known for many years (e.g. steam generator tubing degradation), so it was to be expected that where it is present (e.g. control rod drive mechanism penetrations) cracking may also become a problem. Subtle factors such as product form and surface treatment (surface tensile stress) and heat treatment applied make the alloy variable in its resistance to primary water stress corrosion cracking. In this case, the leaking control rod drive mechanism penetrations were responsible for a far more serious secondary degradation of another component.

4.4.3.4. General comments on the above examples

Accidents do not occur by coincidence, but rather due to unforeseen and unfavourable situations and factors, and combinations thereof, that create conditions severe enough to overwhelm or bypass safety features or directly breach the integrity of critical systems, structures and components. The precursors (errors) of accidents may be present in buying, commissioning, design and specifications, management (human), production, operation, inspection and repair actions. Avoidable and unavoidable errors are all connected with human actions.

Much research and operational experience has been accrued since the first commercial nuclear power plants were connected to the supply grid. These first nuclear power plants were, in essence, pioneer installations, built and operated to the best possible specifications and designs available at the time. Materials that had performed well in other industries (e.g. chemical) were natural candidates for nuclear power plant applications. Nevertheless, unexpected degradations have occurred under operating conditions. The interaction of system, structure and component materials with the working environments and the actions (experience gained) of operating organizations are time dependent aspects.

Various databanks have been set up and updated over the years as information on root causes of accidents, events or impacted safety has become available. Information has been exchanged between vendors, operating organizations, regulatory bodies and research facilities. This is a necessary and good practice, but nevertheless new occurrences of old problems have taken place. Excluding the case where a previously unknown degradation mechanism develops, it can be seen that the failure of humans to use existing knowledge correctly or to implement appropriate and timely strategies (inspections, monitoring, replacements, etc.) can be an important factor where events or accidents are involved.

Design codes address 'as new' plant conditions and are not intended to cover assessment of nuclear power plants that are in service. To address this, design codes feature conservative assumptions, based on engineering judgement and/or scientific knowledge and service experience. Periodic assessment, inspection and monitoring of aged systems, structures and components is therefore needed to provide assurance that they are still capable of performing their intended design functions. Comprehensive ageing management and surveillance and inspection programmes are essential tools for the achievement of reliable and safe operation.

Various networks exist for sharing experience and lessons learned (e.g. nuclear power plant owners groups, regulatory information exchange groups and the IAEA–OECO/NEA advanced incident reporting system and EU networks). Nevertheless, such information sources must be fully analysed and knowledge regularly applied to raise questions on the possibility of the same events occurring at other plants. If information is available it must be used correctly and efficiently. Accident and event databanks are only useful if their contents, especially the analyses of root causes, are intelligently applied to assess operating nuclear power plants.

Legal limitations are in place concerning radiological doses that nuclear power plant personnel may accumulate during a given period of time. Legally allowed dose limits are laid down very conservatively such that they are not expected to cause health effects. For example, for nuclear power plant personnel or other professionally exposed persons, a typical individual annual dose limit is 20 mSv. Considering that plant life management for long term operation may involve special circumstances that may lead to increased personnel exposure to radiation, it is essential that all such tasks be planned in advance with a view to limiting the dose received.

The ALARA principle must be rigorously applied according to regulations in force. Shielding, distance to source and time spent on the activity must be optimized to create conditions amenable to ALARA principles. Practice on mock-ups will facilitate an efficient and technically sound work programme. Therefore, radiological protection measures, where applicable, become an integral part of plant life management programmes.

Regulatory authorities follow the above procedures closely to ensure that the radiological protection goals are met during plant life management for long term operation.

4.5. PLANT LIFE MANAGEMENT AND POWER UPRATING

The process of increasing the licensed power level of a commercial nuclear power plant is called a ‘power uprate’. The impact of power uprate on plant life management is an important issue. Typical uprates have ranged from approximately 1 to 20%, depending on the margin allowed in the original plant design and the extent of plant modifications needed to support the increased power output.

Power uprates are categorized based on the magnitude of the power increase and the methods used to achieve the increase. Measurement uncertainties result in power level increases that are less than 2% and are achieved by implementing enhanced techniques for calculating reactor power. Stretch power uprates typically result in power level increases of up to 7% and do not generally involve major plant modifications. Extended power uprates result in power level increases that are greater than stretch power uprates and usually require significant modifications to major plant equipment. The NRC has approved extended power uprates for increases as high as 20%. This review standard is applicable to extended power uprates [41]. Figure 14 shows the typical stretch power uprate licensing procedure.

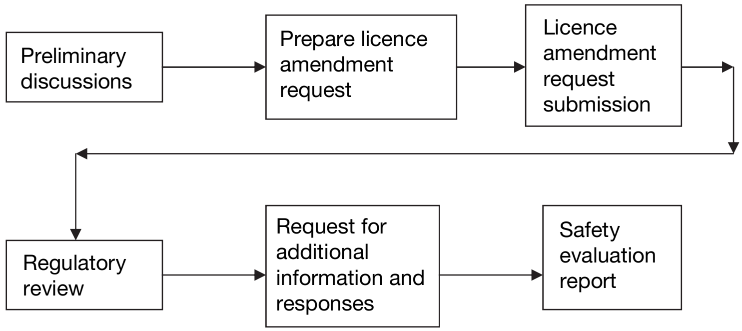


FIG. 13. Typical stretch power uprate licensing procedure.

The expected benefit of extended nuclear plant operation can be significantly increased by power uprate projects due to the anticipated higher revenue generated during the extended period of operation. However, without proper plant life management the impact of power uprate on plant reliability and availability may reduce or eliminate some of the expected added value.

Plant ageing issues may be aggravated by power uprate due to higher temperatures, higher steam and water flow rates, etc. The result may be a need for more inspections, potentially reduced service life of certain critical components that are needed to ensure the plant's extended operational life, or premature plant shutdown due to unexpected ageing effects. A specific example concerns cracking found in BWR steam dryers due to increased vibration and throughput.

With careful consideration of the impact of power uprate on subsequent plant operation and ageing management issues, plant life management and power uprates can work together to enhance the financial advantage of extended plant operation. The Institute of Nuclear Power Operations (INPO) suggested the success factors for power uprate as shown in Table 5.

More than 40 events have occurred in the USA over the past seven years as a result of inadequate analysis, design or implementation of plant power uprates. Many of the events involved equipment damage, unanticipated responses to plant conditions or challenges for operating staff. The number and types of events indicate that more significant consequences could result from future events if power uprates are not conducted in a thorough and carefully controlled manner.

Significant aspects of these events include the following:

(a) An extended, unplanned shutdown was required to retrieve several loose parts as a result of a flow induced high cycle fatigue failure of a steam dryer cover plate in a BWR;

(b) Operational transients and equipment damage occurred as the results of weaknesses in identifying, communicating and training of plant staff on expected changes to secondary plant operating characteristics;
(c) Unanticipated operating challenges and degraded equipment performance resulted from reductions in operating and design margins;
(d) Some units have operated beyond their licensed power levels for extended periods because of errors in reactor thermal power calculations following uprates that changed secondary plant operating characteristics.

TABLE 5. POWER UPRATE SUCCESS FACTORS AS SUGGESTED BY INPO

Success factor number	Success factor	Description
1	Involvement by site and corporate management	Senior management clearly communicates throughout the organization the goals, priorities and expectations for the power uprate activity, emphasizing its importance to nuclear safety, plant economic viability and personnel quality of life
2	Effective project management	The nuclear power plant uses the fundamentals of project management with tools for scope control, phased work approach, schedule and budget, to plan and implement the power uprate
3	Assessment of actual plant conditions	The as-built design margins and performance capabilities of the plant are well documented, understood and used in the power uprate planning
4	Focus on operating experience	Plant efforts are focused on using operating experience and industry expertise to review power uprate planning and progress at key project milestones
5	Post-uprate testing and monitoring plan	Efforts are taken to predict how plant performance can change as a result of power uprate and defining which key parameters are trended; when actual performance deviates from predictions, the plant aggressively seeks to understand the differences
6	Maintain in-house ownership	The project team maintains a balance of interaction between non-plant personnel and plant staff while keeping the emphasis on site ownership
7	Anticipate design shortfalls	The project predicts and plans for the contingency of reconstituting some aspects of the original plant design

4.6. ADDITIONAL ASPECTS OF PLANT LIFE MANAGEMENT

Plant life management and ageing management must deal with regulatory and non-physical issues, as well as technical ones.

Two important issues are:

(1) Safety level reassessment;
(2) Conformity to standards.

Six key non-physical issues must be dealt with to prepare for the future and to create strategies for plant life management:

(1) Organization;
(2) Documentation;
(3) Competences, taking into account ‘old generation’ personnel;
(4) For some components, the obsolescence of some strategic equipment such as I&C;
(5) Evolution of industrial structures;
(6) Information system.

Table 6 gives an overview of the above topics.

TABLE 6. PLANT LIFE MANAGEMENT PROGRAMME MATRIX AND PARAMETERS

Technical aspect	Regulatory aspect	Non-physical aspect
Component ageing	Safety level	Organization
Operating modes and requirements	Conformity to the standards	Documentation
Degradation mode of materials and components	Radiological impacts of plant life management activities and long term operation	Maintaining the level of personnel and technical competences, knowledge management and human factors
		Solution for equipment obsolescence and procurement
		Industrial structure evolution
		System information

4.6.1. Organization

The organization of utilities and their relationship with the industry are important for plant life management for long term operation. In some cases the operation and generation services and R&D divisions are integrated in operating organizations (e.g. in France). In other cases, operating organizations have engineering services but do not have R&D departments. In such cases operating organizations subcontract some engineering studies to specialist companies (e.g. in Japan), or cooperate with a specific R&D division of another operating organization (e.g. in the USA).

All operating organizations applying either licence renewal rules or the periodic safety review approach need engineering studies and R&D results to back them up. To study the impact of all modifications, and to research alternative solutions, operation, maintenance, engineering and R&D departments have to capitalize on all the available experience and feedback concerning installation and operating procedures. Utility organizations supply information to each other regarding operating experience, lessons learned and generic issues. This information has to be correctly applied on a plant specific basis (see Section 4.3).

4.6.2. Documentation

Design basis documentation is essential for long term operation. If this is inaccurate or incomplete, design documents should be reconstituted. A key requirement for a nuclear power plant implementing plant life management and aiming for long term operation is the availability of the original and basic design information and documents on materials and equipment. The documentation must be kept updated. Utilities frequently ask nuclear power plant constructors, sometimes several years after commissioning, for original documentation or original specifications, since these are needed for databases and to determine benchmark and reference points to allow assessment of the level of ageing that has taken place (actual status of systems, structures and components) and of how much residual life is to be expected.

All necessary documentation should be available and validated to confirm the current plant configuration. Some operating organizations have a configuration management service dedicated to managing documentation. This may be considered a good practice, particularly when combined with the overall knowledge management strategy.

4.6.3. Maintaining the personnel level and technical competence

As nuclear power plants strive towards operation beyond their original design lifetimes it is vital to ensure that lessons learned are handed over to new generations of personnel. Configuration management assuring comprehensive documentation is thus vital as a part of overall management systems. Such management systems will contribute towards maintaining or even increasing safety in operation.

The aim of knowledge management is to identify where knowledge is, acquire it, verify its correctness, preserve it, disseminate it to the personnel and apply it to advantage for ensuring that the nuclear power plant is operated and maintained in the best way to create profit and maintain safety. Classical or explicit knowledge is often well documented in publications and manuals but implicit knowledge, which is experience based, is often difficult to preserve. Experience based knowledge is that which could be lost when personnel leave the nuclear power plant. More often than not it is precisely this sort of knowledge that is the most valuable, having been accrued by an individual or team over the course of many years.

Techniques and systems to counteract the loss of knowledge are needed, particularly when nuclear power plants aim for long term operation. For this reason, knowledge management must be a priority item at the management level and resources must be invested to ensure that enough personnel are involved. It is likely that knowledge management programmes will be plant specific, but the main features and goals of knowledge management remain generic for all nuclear power plants.

Training and retraining based on knowledge management is necessary to ensure that nuclear power plant personnel remain sufficiently qualified to carry out their tasks. Programmes for initial training and for later upgrades in training, including the use of simulators, should be in place. These should also include:

(a) Training in safety culture, particularly for management staff;
(b) Adopting a questioning attitude;
(c) Developing and maintaining a 'pride of ownership' of the nuclear power plant;
(d) Nurturing an appropriate attitude, and therefore safety culture.

The problem is compounded by the fact that the pioneer generation of nuclear engineers, who started their careers in the late 1950s and 1960s, is now approaching retirement age, and much of their expertise could be lost by 2015. This period of time corresponds to that in which many nuclear power plants will be entering their new licensing period, which may be regarded as going beyond the original design life for long term operation, or will continue to operate supported by the results of periodic safety reviews.

In particular, these highly experienced personnel not only possess detailed knowledge concerning the particular systems, structures and components they were responsible for, but also have a good general appreciation of the characteristic behaviour of the nuclear power plant as a whole. A central factor in a nuclear power plant's life management strategy and for possible long term operation must, therefore, be to ensure that sufficient replacement personnel are available and that the transfer of knowledge is guaranteed by means of adequate on the spot training and comprehensive documentation. A comprehensive debriefing should be carried out when any nuclear power plant personnel leave, irrespective of the length of their service. The process should have both formal and informal aspects, but the results must be fully documented and given to remaining and new personnel.

A good practice for transferring technical excellence is to involve young nuclear power plant employees in major replacement projects within plant life management, under the leadership of experienced personnel. Young employees will thus be motivated to acquire essential knowledge through participation.

In some countries, the practice used for training and knowledge transfer is temporary job duplication. During the last working year of the senior engineer or technician the new person works with the senior to capitalize on, and to learn, their knowledge. This is one means of training (i.e. hands-on experience). It is a good practice but can pose financial burdens on the nuclear power plant. However, the cost–benefit analysis of such actions mostly shows profit, at least in terms of continued reliable operation.

In parallel, the nuclear industry has to recruit young engineers and technicians. In fact, the recruitment issue impacts not only operating organizations but also:

(1) The nuclear industry as a whole — manufacturers, contractors and engineering companies;
(2) Regulatory organizations.

Careers in nuclear power generation have to be made attractive for young technicians and scientists. This will be a multifaceted task, involving financial incentives and the prospect of long term employment for those contemplating careers in nuclear technology.

4.6.4. Evolution of the industrial structure

Manufacturers and contractors who participated in the original nuclear power plant construction are sometimes no longer in business 20–30 years later. Company mergers are common and the nuclear industry is no exception. It is therefore essential for nuclear power plant operating organizations to ensure that they will have future access to replacement or equivalent parts verified by quality assurance. Furthermore, some components play key roles in the operating lifetime of the entire nuclear power plant, including the long term operation segment, and the construction of new equipment with new requirements takes several years (e.g. steam generators and reactor pressure vessel heads).

This gives rise to procurement problems requiring long term planning. An engineering (but not necessarily an economic) solution is to identify all such strategic components and to have them ready on-site as spare parts whenever they are needed. Obviously, care in storage to avoid ageing effects is required. Non-service storage degradation can occur through, for example, moisture ingress, temperature influence, chemical attack through breakdown of plastics (e.g. chlorine from PVC) and dust accumulation.

4.6.5. Information systems

Information systems are important within the operating organization's organization (as well as the main manufacturers) to trace, record and update the evolution of:

(a) Operating procedures;
(b) Equipment requirements and modifications;
(c) Actual state and status of equipment in the plant (e.g. introduction of modifications);
(d) Diffusion of information.

A specific network needed for the first activity is to collect the feedback experience from the sites and to update the database of the safety level and status of all equipment.

5. RELATIONSHIP BETWEEN PLANT MAINTENANCE AND PLANT LIFE MANAGEMENT

5.1. RELATIONSHIP BETWEEN BACKFIT AND REPLACEMENT OF SYSTEMS, STRUCTURES AND COMPONENTS AND SAFE OPERATION

As a nuclear power plant ages, it becomes more likely that the issue of backfit and replacement of systems, structures and components will need to be addressed to ensure continued safe and reliable operation. Although the safety aspects of this issue are currently being addressed as part of the regulatory oversight process, the use of plant life management can help ensure that the backfit process is conducted as efficiently as possible.

For example, equipment obsolescence issues can result in replacement parts for critical safety or power production components becoming unavailable. The result of this can impact both safety and reliability, and production goals. This can be dealt with by using the plant life management processes to anticipate, plan and efficiently implement upgrades, design changes or other options to address obsolescence issues in the most cost efficient manner.

5.2. RELATIONSHIP BETWEEN THE MAINTENANCE PROGRAMME AND AGEING MANAGEMENT

A key aspect of plant life management programmes is the interaction between the ageing management of systems, structures and components and the existing operation and maintenance practices. These existing practices are analysed and assessed to determine their effectiveness in controlling and mitigating ageing effects. In other words, the objective is to assess whether the causes and consequences of ageing (significant ageing mechanisms and effects) are adequately monitored, managed and mitigated by current maintenance practices. The methodologies should maximize the use of existing industrially available programmes, national and international studies, initiatives and databases. For example, some provisions of the nuclear regulatory authorities' guidance on plant life management or licence renewal may be satisfied by the actions taken by the nuclear power plants to comply with Ref. [4]. Also, the methodologies can make direct use of two key US regulatory documents:

(a) Standard Review Plan for Review of Licensing Renewal Application for Nuclear Power Plants [36];
(b) Generic Ageing Lessons Learned (GALL Report) [5].

The standard review plan provides guidance and methods used by NRC staff in reviewing licence renewal applications. The GALL report evaluates existing nuclear power plant programmes to document the basis for determining when such programmes are adequate without change and when they should be augmented for the extended operating period.

In the framework of licence renewal, demonstration that the effects of ageing are adequately managed is called an ageing management review. Specifically, the passive, long lived structures and components identified in the screening process will be reviewed to determine that the effects of ageing are being managed such that the intended functions of the systems, structures and components will be preserved consistent with the current licensing basis for the extended operating period. The results of the ageing management reviews should include a description of activities that are relied upon to demonstrate that the intended functions will be adequately maintained despite the effects of ageing.

In the Spanish approach to long term operation, based on the licence renewal rule, the ageing management review methodology utilizes the lessons learned from reviews at US plants and the previous ageing assessments at Spanish plants. That is, in preparation for the ageing management reviews, the plant, regulatory and industry bases and references are identified and collected. The plant programmes that will be credited in the ageing management reviews are identified and their effectiveness as ageing management programmes is demonstrated; the relevant plant operating experience is collected and reviewed and the structures and components are regrouped, as appropriate, to maximize the use of the GALL report. Presentation of the ageing management review results in the long term operation licence application.

Three methods may be used for the reviews, leading to the demonstration that the ageing effects are being properly managed:

(1) This method uses the ‘spaces approach’ to evaluate the qualified lifetime of the passive, long lived electrical component types and to determine that the qualification basis is adequate for the environmental conditions during the extended operating period, or that an ageing management programme will be required;
(2) This method utilizes the evaluation of the passive, long lived structures and components, ageing effects and ageing management programmes in the GALL report to demonstrate that the evaluations and conclusions

reflect the conditions, parameters and ageing management programmes at the plant, and to carry out any additional evaluations required by the GALL report;

(3) The third method uses a plant specific approach for those plant passive, long lived structures and components that are not reflected or evaluated in the GALL report to identify the ageing effects that will require an ageing management programme during the new period of extended operation.

The development of these activities in the framework of plant life management for long term operation can be seen as an advantage for using them in the current nuclear power plant maintenance and plant life management programmes, or for reorienting the plant life management programme in order to prepare the nuclear power plants for the requirements of long term operation.

Many of the ageing management programmes credited with maintaining nuclear power plant safety and reliable plant operation are existing maintenance programmes. For example, the US nuclear power plants that have been granted renewed operating licences for up to 60 years of operation credit existing maintenance programmes for ageing management, such as:

— Preventive maintenance programmes;
— In-service inspection programmes (non-destructive examination);
— System and component surveillance programmes;
— Coolant water chemistry programmes;
— Walkdowns and inspections.

Due to these existing maintenance programmes and the decades of success in managing ageing, as documented in operating experience reports, safe plant operation beyond the original design lifetime becomes a practical reality and has been approved by the NRC on a case by case basis.

Additionally, when revised ageing management programmes are needed to address new or emerging ageing effects it is often more efficient to modify existing maintenance programmes or practices to manage the new ageing effect.

5.3. MAINTENANCE RULE

From the point of view of the efficiency of plant life management it is essential to manage and properly assess the effectiveness of the maintenance performed on the systems, structures and components. Often, the maintenance programme is evaluated according to formal or quantitative criteria, based on the operating organization's work control practice. This, however, does not prove that the maintenance has achieved its goal, or that the performance and safety of the systems, structures and components after maintenance are at the required level.

It is therefore important to manage and assess the maintenance according to performance and safety criteria. In some Member States, specific regulatory requirements are implemented to control the efficiency of plant maintenance and ensure that the systems, structures and components can perform their intended functions. In the USA, Ref. [4] defines the rules for assessment of the maintenance. The maintenance rule is used for:

(a) Continuous performance monitoring of active system functions;
(b) Ageing management for active components and passive structures;
(c) Performance and condition monitoring activities with goals and preventive maintenance activities;
(d) Licence renewal.

Implementation of the maintenance rule ensures that:

(1) The performance of systems, structures and components is being effectively controlled by means of preventive maintenance;
(2) The performance of systems, structures and components is monitored using availability and reliability criteria;
(3) Periodic assessments of systems, structures and components take place, based on operating experience;
(4) Adjustments are made to balance availability and reliability while ensuring that safety levels are maintained or increased.

Assessments are carried out at every refuelling cycle (but not exceeding 24 months).

5.4. RELATIONSHIP BETWEEN MAINTENANCE AND PLANT LIFE MANAGEMENT

The plant life management programme for long term operation is dependent on good maintenance practices. Thus evaluation of maintenance practices is a part of the plant life management, making it possible to identify potential deficiencies in the monitoring or control of ageing of systems, structures and components. The result of the evaluation includes, when necessary, proposals for additional maintenance practices or improvements to the current maintenance practices needed to establish adequate and appropriate ageing management.

Accordingly, feedback in both directions is recommended, i.e. maintenance and ageing management and plant life management experiences, in order to complement each other. Also, from this interaction different plans can be established at the nuclear power plant level, such as a modernization and refurbishment plan, a repair and/or replacement plan and a specific main component monitoring plan.

In plant operation there are different ways of detecting the effects of ageing on systems, structures and components (preventive and corrective maintenance, inspections, testing, monitoring and observed performance monitoring of systems, structures and components). The mechanism that has given rise to the degradation of the reliability or safety of the systems, structures and component material can be identified through subsequent analysis of these effects. The selection of an efficient method for mitigating ageing in systems, structures and components depends on an accurate determination and evaluation of the degradation mechanism that caused the ageing. Therefore, the selected mitigation method defines the maintenance practice.

Evaluation of the maintenance practices also provides information about ageing and trends, the degree of uncertainty in their evaluation, and a determination of the efficiency of maintenance practices and their shortcomings. This is the basis for decisions on the plant life management or continuous safe operation measures to be applied. These measures may fall into the following categories:

(a) Repairs, replacements or modifications and optimized planning for the components most severely affected and/or for which the improvement in safety, availability or performance fully justifies the investment;
(b) Modifications to operating procedures and/or in-service conditions to make them less demanding on the systems, structures and components (e.g. temperatures, pressures, flow rates, water chemistry and neutron flux);
(c) Improvements to maintenance and inspection practices to achieve full efficiency for detecting evolving defects (e.g. higher resolution non-destructive testing apparatus);
(d) Implementation of additional monitoring to improve condition evaluation and trends, especially for poorly understood component degradation mechanism combinations (e.g. extended reactor pressure

vessel surveillance programmes with reconstituted specimens). This will reduce the effort required for collection and analysis of information and allow the use of realistic criteria for assessing ageing parameters in the overall life management decision making process.

6. RESEARCH AND DEVELOPMENT REQUIREMENTS FOR PLANT LIFE MANAGEMENT FOR LONG TERM OPERATION

6.1. ROLE OF RESEARCH AND DEVELOPMENT

Utilities, manufacturers, government support organizations and regulatory bodies, and international organizations, have been conducting or encouraging various kinds of research and development programmes relating to ageing, plant life management and safety since the start of the nuclear power age. The issues of materials, environments in which they perform and human factors are all important for safe and reliable operation. Two main schools of activity can be identified: materials research and human–machine interactions; or power production goals and safety issues,.

Research and development provides the descriptions of ageing phenomena which are necessary to predict and manage the ageing issues, addressing the following:

(a) Determination of the ageing laws as functions of in-service parameters (temperature, time, neutron irradiation, chemical composition, etc.) and, in particular, indication for each component of the ultimate tolerable ageing level and the expected length of time beyond which an unacceptable ageing level is reached;
(b) Definition of the surveillance programmes (e.g. improved reactor pressure vessel fracture mechanical evaluation);
(c) Guidelines for the choice of methods of in situ ageing level inspection (e.g. published reports);
(d) Definition of the potential mitigation or replacement methods for systems, structures and components.

The necessary information is usually obtained by research methods to produce the following results:

(1) Provide appropriate and realistic values for the mechanical, electrical and physical properties of aged systems, structures and components;
(2) Identify and define variables that can be conveniently utilized (water chemistry adjustments, neutron flux reduction, etc.);
(3) Improve knowledge concerning uncertainties, which may lead to an easing of overly conservative margins.

There is often a lack of quantitative precision in the results of ageing management methods due to uncertainties about the representativeness of materials, the operating environment, the applied stresses or even the test methods used to assess, for example, fracture toughness. Therefore, there is a need to search for appropriate methods and qualified techniques to address this problem.

In situ ageing assessment methods can be divided into two types, namely non-destructive methods and methods requiring sampling. Each of these types can yield information concerning either the mechanical properties or the microstructural state or evolution of a material that has been in service.

The sampling method aims at yielding a mechanical property, i.e. a value that, as a rule, can be used to assess remaining operational safety margins. However, sampling requires either a sufficient material thickness or subsequent repair of the component to replace the material removed. Sampling (e.g. scratch or boat samples) and repair are often difficult and may lead to radiation exposure for those involved. R&D work will always be necessary and relies on interdisciplinary approaches.

6.2. CONSTRUCTION AND USE OF DATABASES

Due to the large volume of data and documents needed for plant life management, databases are useful tools for information management. A typical plant life management database will include:

(a) Plant life management methodologies and technical references for each system, structure and component;
(b) Nuclear power plant operating data and experience, including transient history;
(c) Component design specification, identification code and manufacturing data;
(d) In-service inspection, surveillance and maintenance data;
(e) Ageing management programme details and implementation schedule;
(f) Accumulated R&D results;

(g) References to where similar effects have been found at other nuclear power plants (i.e. generic problems and issues);
(h) Root cause analyses of system, structure or component failures;
(i) Recommendations on future ways of avoiding the problem (mitigation actions);
(j) Any legal requirements;
(k) The IAEA–OECD/NEA Incident Reporting System (IRS) codes and the IAEA/OECD-NEA International Nuclear Event Scale (INES) ratings, where appropriate;
(l) Supplementary information.

Systematic data collection and verification provides a basis for effective oversight of the effectiveness of plant life management (trending and statistical analyses of system, structure and component failures), and may eventually help in assessments for long term operation. This approach also serves knowledge management policies.

The effectiveness of plant life management actions can be augmented with comprehensive databases and record keeping that provides operating organizations and regulatory bodies with the updated information necessary to ensure that an integrated plant life management programme is focused on relevant issues.

As an example, the Swiss regulatory body, HSK, maintains its own databank which records every safety relevant and reportable event or discovered deficiency of each nuclear power plant's systems, structures and components. The input data stem from event reports supplied by nuclear power plants. The event data are assessed by the nuclear power plant itself and a root cause analysis is provided. The input is then reviewed by HSK and a final opinion is reached. A main points description of the event and its circumstances is documented, as are the corrective actions taken. The lessons learned are recorded and are then applied in the future. Furthermore, the IAEA–OECD/NEA Reporting Guidelines — IRS is also used and documented in the HSK databank.

6.3. EUROPEAN COMMISSION PROGRAMMES ON PLANT LIFE MANAGEMENT

To ensure a safe and secure energy supply to the European Union, various Directorates General of the European Commission support plant life management of nuclear power plants by means of the following main instruments:

(a) The Directorate General Research, developing the EU's policy in the field of research and technological development, enforces multi-annual Framework Programmes which help to organize and financially support cooperation between universities, research centres and industries. The current sixth Framework Programme covers the period from 2002 to 2006 and has a total budget of €17.5 billion. In particular, the EURATOM Framework Programme budget for projects in the area of nuclear power plant life management is €50 million.
(b) The direct research activities of the Directorate General Joint Research Centre (JRC) supports EU policies. Especially for nuclear power plant life management activities the JRC promotes an integrated view on ageing mechanisms and optimization of R&D activities, together with the prevention, performance and risk informed based approach supporting the integrity assessment of reactor pressure vessel and internals, piping and fuel, as well as safety culture. The list of issues affecting plant life management is long, and more R&D efforts are required in order to understand and address them properly.
(c) Technical Assistance for the Community of Independent States (TACIS) and PHARE are key assistance programmes which have also dealt with plant life management.

Further details are given in Appendix II.

6.4. IAEA PROGRAMMES ON PLANT LIFE MANAGEMENT

6.4.1. Ageing management activities of the IAEA

Although in the early 1980s most people believed that routine maintenance programmes were adequate for dealing with the ageing of nuclear installations, in the 1990s the need for ageing studies and life management methodologies for nuclear power plants became widely recognized. Therefore the IAEA in 1985 initiated activities to promote information exchange on safety aspects of nuclear power plant ageing and to increase awareness of the emerging potential safety issues relating to ageing of nuclear power plant systems, structures and components.

Follow-up IAEA activities are focused on understanding the ageing of systems, structures and components important to safety and on their effective ageing management. To assist Member States in managing nuclear power plant ageing effectively, the IAEA has developed a publication on safety aspects of nuclear power plant ageing [32] and a set of programmatic guidelines [9, 32–35], component specific guidelines [14–22] and ageing management review guidelines. The component specific guidelines on ageing management provide descriptions of components and design basis, potential ageing mechanisms and their significance, operating guidelines to control or mitigate age related degradation, inspection and monitoring requirements and technologies, and assessment and maintenance methods. In addition, the IAEA has issued other publications which are focused on specific ageing issues [23–28].

The IAEA Technical Working Group on Plant Life Management of Nuclear Power Plants (TWG-LMNPP) is currently involved with all aspects of plant life management, as well as conducting Coordinated Research Projects (CRPs). Currently, over 30 delegates and observers from Member States and organizations report all activities to the TWG-LMNPP every two years. Conferences, international symposia and other meetings are held to provide information exchange and promote good practices.

6.4.2. Reactor pressure vessel integrity

Since 1975 the IAEA has implemented seven CRPs to develop a methodology to evaluate neutron irradiation effects on reactor pressure vessels, in cooperation with more than 100 organizations and institutes. Based on the results of the CRPs the IAEA developed the application guideline for the master curve approach which was first proposed by researchers in Finland [42] and published in Refs [25–28]:

- Irradiation embrittlement of reactor pressure vessel steels (phase 1);
- Analysis of the behaviour of advanced reactor pressure vessel steels under neutron irradiation (phase 2);
- Optimizing reactor pressure vessel surveillance programmes and their analyses (phase 3);
- Ensuring structural integrity of reactor pressure vessels (phase 4);
- Surveillance programme results: application to reactor pressure vessel integrity assessment (phase 5);
- Effects of nickel on irradiation embrittlement of LWR reactor pressure vessel steels (phase 6);
- Evaluation of radiation damage of WWER reactor pressure vessels using the database (phase 7).

The IAEA initiated two new CRPs in 2005 to verify reactor pressure vessel integrity under the following conditions:

— Master curve approach to obtain the fracture toughness of reactor pressure vessels in nuclear power plants (phase 8);
— Review and benchmark of calculation methods for structural integrity assessment of reactor pressure vessels during pressurized thermal shocks (phase 9).

6.4.3. Database for plant life management

The IAEA started work on an international database on nuclear power plant life management several years ago. This is a multimodule database as shown Fig. 15, the first module of which is called the International Database on Reactor Pressure Vessel Materials (IDRPVM), which is being used worldwide [43]. Four other modules have also been completed, and work on processing the data received and entering them into the databases is under way.

In addition, the IAEA is developing a Safety Knowledge-base for Ageing and Long Term Operation of Nuclear Power Plants (SKALTO) [44]. SKALTO is not a conventional database, but provides a road map to help obtain the necessary information.

6.4.4. Maintenance programmes and in-service inspection

Maintenance and in-service inspection are fundamental elements of plant life management, and their effectiveness strongly influences production and safety performance. The IAEA has prepared a publication dealing with the optimization of nuclear power plant maintenance programmes [45]. Its aim is to identify approaches and methodologies in Member States on how

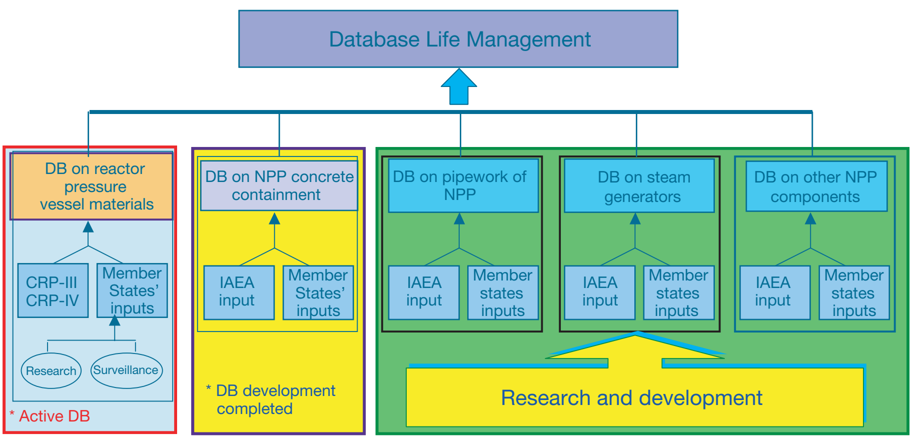


FIG. 14. The IAEA's multimodule plant life management database.

maintenance programme optimization contributes to the improvement of nuclear power plant performance and plant life management. It will recommend seeing the process of maintenance optimization as a continuing one, driven by the imbalance between maintenance requirements (legislative, economic, technical) and resources used (people, spare parts, consumable materials, equipment, facilities and collective doses).

A recent IAEA publication deals with good practices in in-service inspection effectiveness improvement [35]. Results of tests performed under various international research projects, as well as the appearance of real in-service defects in pressurized components (e.g. cracks in internals caused by stress corrosion or thermal fatigue) have demonstrated the need for improving in-service inspection effectiveness.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. CONCLUSIONS

(a) In view of the world's demand for electric power and the environmental impact of the use of fossil fuels, nuclear power plant life management for long term operation is a viable and economically attractive alternative. Since the initial capital costs of the long term operation phase will have already been amortized, long term operation will become a competitive power generation option.
(b) Since there are clear benefits to be gained in terms of both safety and economics, as well as ensuring supplies of power, plant life management is recognized as an essential part of nuclear power plant operation, and facilitates the achievement of long term operation.
(c) Long term operation is an operating organization decision. Plant life management will facilitate conditions for long term operation to become a realistic option in terms of safety and economics.
(d) Long term operation is technically feasible through appropriate ageing management and maintenance activities.
(e) Plant life management plays a key role in ensuring that safety and design margins are adhered to.
(f) Compliance with the current licensing basis will ensure that all safety and legal requirements are satisfied, or are even exceeded, and will facilitate long term operation. The periodic safety review, where applicable, will

remain an important tool to assess the safety of nuclear power plants. The outcome of the periodic safety review dictates whether or not a nuclear power plant will be allowed to continue operating.

(g) Principles for deriving plant life management for long term operation strategies must be based on current knowledge of the status of the nuclear power plant's systems, structures and components and the operating conditions to which they are exposed.

(h) General plans for plant life management may be made based on experience from nuclear power plants worldwide, but plant specific plant life management programmes are required for assessing the possibility of long term operation.

(i) Open and rapid exchange of information between operating organizations and regulatory bodies is necessary to facilitate timely, comprehensive and effective resolutions of all aspects of the long term ageing process and unexpected issues.

(j) The plant life management for long term operation strategy must, primarily, address those systems, structures and components that are relevant to safety and which potentially will decide the overall safe operating lifetime of the nuclear power plant. The status of large passive components (reactor pressure vessel and containment) will likely decide the technical lifetime of a nuclear power plant. Other systems, structures and components can be replaced within the framework of normal maintenance tasks. Cost factors may, however, limit such actions.

(k) Utilities or operating organizations contemplating plant life management with a view to continuing nuclear power plants' operating lifetimes past their original design lifetimes will have to demonstrate to regulatory bodies that the systems, structures and components continue to fulfil their intended functions. A correctly conceived and implemented plant life management programme will be a pivotal discussion point and a decisive argument to use, as far as the technological aspects are concerned. Transparent, logical and state of the science plant life management practices may also find application in political arguments for cases where nuclear power plant operation exceeding the original design lifetime is being proposed.

(l) Plant life management should be an integral part of the nuclear power plant's overall maintenance, replacement, monitoring and regular servicing schedules, whereby it is recognized that plant life management focuses mostly on large passive components that cannot be replaced (reactor pressure vessel, containment), or whose replacement is not economically viable. All other components are deemed to be technically and economically replaceable should safety and reliability issues arise, for example I&C. However, reactor pressure vessel heads, PWR steam generators and BWR core shrouds, if replaced, represent significant costs that must be amortized during the rest of the nuclear power plant's lifetime.

(m) Plant life management requires full, concise and accurate documentation of all systems, structures and components including design, materials, treatments, manufacturers and modifications. Comprehensive documentation allows operating organizations and regulatory bodies to follow the progress of ageing (and the effectiveness of any mitigating actions) in nuclear power plants.

(n) Plant life management programmes require sufficient, well trained nuclear power plant personnel with a questioning and interactive attitude.

(o) Knowledge management is a priority for nuclear power plants, not only for normal operating lifetimes but especially for long term operation. Lessons learned are essential aspects to be integrated into a nuclear power plant's life management for long term operation strategy, and become a part of knowledge management and retention.

(p) R&D is essential in such an evolving sector as nuclear power plant ageing research. The ageing phenomena need to be investigated continuously, as do mitigating measures, by enhancing the evaluation technology and inspection techniques. Actual plant data need to be collected, as does knowledge obtained from R&D results. Regulatory bodies and operating organizations must be aware of R&D results concerning the ageing of systems, structures and components and their impact on safety and economic issues.

(q) If nuclear power plants operate longer, provision should also be made well in advance for the storage/disposal capacity of spent fuel and other associated radioactive wastes.

7.2. RECOMMENDATIONS

(a) Plant life management programmes should be implemented as early as possible, ideally at startup. Irrespective of whether operation after the original design lifetime is contemplated, plant life management has the potential to improve current safety and reliability (availability) of systems, structures and components.

(b) It is advantageous to manage and assess maintenance actions based on the performance or reliability and safety criteria of systems, structures and components. Information feedback should take place in both directions, i.e. maintenance and ageing management and plant life management experiences, so that these complement one another.

(c) Initiate, from the beginning, an efficient process for the exchange of information between operating organizations and regulatory bodies.

(d) Research concerning ageing effects should be continued in all relevant fields concerning nuclear power plant materials and the way they are affected by the environment to which they are exposed. The reactor pressure vessel and its internals, primary pressure boundary piping and pressurizers are vital to the safety and to the economic viability of a nuclear power plant. Mitigation measures will be optimized using validated inputs from research, since knowledge about the ageing mechanisms will provide ways to avoid, mitigate or reduce their impact.

(e) Operating organizations must take steps at an early stage to ensure that sufficient and well trained personnel are always available. The efficiency of knowledge transfer could be augmented through full documentation of the systems, structures and components and regularly updated databanks.

(f) Nuclear power plants should implement a plant specific knowledge management programme based on generic issues concerning the loss of implicit knowledge when experienced personnel leave. Temporary job duplication is one way to facilitate efficient transfer of knowledge and duties.

(g) Wherever possible, when subcontractors are used, the nuclear power plant's own personnel should be present to observe, learn and record the work processes employed. This furthers the plant's own knowledge bases.

(h) Nuclear power plant owners should be aware of the age distributions of their staff and plan well ahead to allow for training of replacements.

(i) A good practice for transferring technical excellence is to involve young nuclear power plant employees in major replacement projects under the leadership of experienced personnel. Young employees will thus be motivated to acquire essential knowledge through participation. A process should be in place to ensure that all personnel who leave a nuclear power plant are fully debriefed with respect to their knowledge gained and their accumulated experience.

(j) Nuclear power plant operating organizations must ensure that updated documentation pertaining to the nuclear power plant's systems, structures and components is readily available. It is a good practice to create a personnel team to manage all the plant's documentation, especially that related to systems, structures and components and long term operation.

(k) All necessary documentation should be validated to confirm the current plant configuration. Documentation management is an important task within plant life management and some operating organizations have a configuration management service dedicated to this activity.

(l) It is a good practice to reinsert tested reactor pressure vessel surveillance specimens (either as fragments or reconstituted) to expand the capability of the programme to allow for improved science and technological developments relating to mechanical property characterizations.

(m) All tasks concerned with plant life management for long term operation that may involve radiation exposure of personnel must first be planned and carried out according to ALARA principles. Dry runs on mock-ups will optimize the actions to favour ALARA principles.

(n) It is important to recognize that the reliability of secondary systems, structures and components will also become important as nuclear power plants operate for longer periods. Although such systems, structures and components may be adequately managed for ageing effects (e.g. replacement), their contribution to overall costs have to be considered in the business justification of long term operation. Extensive replacements and modernization tasks may become commonplace in the future.

(o) Keep the implementation of ageing management programmes or plant life management programmes as quality assurance processes.

(p) Assess whether long term operation beyond the original design lifetime might have an unacceptable impact on people and the environment and identify supplementary requirements that might be necessary in addition to those habitually applied, to guarantee the protection of the nuclear power plant workers, the general public and the environment.

Appendix I

EXAMPLES FROM MEMBER STATES OF GOOD PRACTICES IN NUCLEAR POWER PLANT LIFE MANAGEMENT

I.1. ARGENTINA

A comprehensive plant life management programme is in place, as are various focused research programmes. At present, solutions are being sought for the reactor pressure vessel surveillance programmes since issues remain concerning representative neutron irradiation conditions (temperature of irradiation and thermal neutron effect, etc.).

The objectives of plant life management are to assess the plant's status, monitor ageing, and develop an ageing management programme. The method used involves characterization of the current status of systems, structures and components, screening to identify critical systems, structures and components, revision of design requirements, materials, manufacture, assembly information and revision of design modifications. The licensing review is based on the current licensing basis.

Local and external operating experience is analysed. This enables comparison of the behaviour of the systems, structures and components. Databases are also maintained regarding the in-service inspection data and maintenance activities.

An assessment of degradation mechanisms and conditions for passive equipment is carried out. The impact of the degradation mechanisms on systems, structures and components is assessed, as are the methods used to counteract them. The type of monitoring required to verify the condition of equipment over time and acceptance criteria are defined.

I.2. BELGIUM

Operating licences are granted for indefinite periods, subject to periodic safety reviews every 10 years (legal requirement). The political decision is to shut down after 40 years, but only if energy supplies are guaranteed. The operating organization has opted for a long term ageing management strategy. The aim is to ensure safety functions of systems, structures and components for the entire lifetime of the nuclear power plant and to maximize availability. Primary mechanical equipment, secondary equipment, civil structures, I&C and electrical equipment are being studied. Known problems are being followed up (reactor pressure vessel embrittlement, flow accelerated corrosion/ erosion corrosion, obsolescence, etc.). New issues such as primary water stress corrosion cracking of Inconel 182 welds, reactor pressure vessel underclad defects and degradation of internal structures in cooling towers fall under ageing management. Priorities are items vital for nuclear safety, classical safety, availability, repair costs in cases of failures (also collateral costs) and consequences for the environment (also the political image of nuclear power).

I.3. BULGARIA

The licensing requirements are that a high level of safety must be present over the entire lifetime and that a programme for lifetime management, including ageing monitoring, is in place. A safety assessment report and periodic safety reviews are mandatory. Licences are valid for 10 years and the operating organization can apply for licence renewal based on the safety assessment report. The programme for lifetime management and ageing monitoring of the Kozloduy nuclear power plant includes selection and prioritization of systems, structures and components, understanding of degradation mechanisms, optimization of repairs and identification of where future modernization is needed (backfitting). It is important to determine the current material state, even in the absence of archive material (benchmarking problems).

I.4. CZECH REPUBLIC

Long term operation plans are in place and have been approved. The main aims are to achieve the original design lifetime, and then to operate up to 60 years. For metallic components the VERLIFE procedure is used to verify the lifetime of the Dukovany nuclear power plant. Operational safety reports (rather like periodic safety reviews) are produced every 10 years. The main activities have been specific tasks on components, non-destructive examination qualification, risk based in-service inspections, equipment qualification, plant life management and long term operation programmes, and design basis management and reconstruction. Improved surveillance programmes have been instituted for reactor pressure vessels, as have pressurized thermal shock calculations and assessment of the reactor pressure vessel state. The modified surveillance programme for the WWER-1000 allows better characterization of irradiation conditions with dosimetry and temperature monitors. Reconstituted specimens are included. The programme can be extended as an ‘integrated surveillance programme’ using the Temelin nuclear power plant as a host reactor for other WWER-1000 units since it fulfils the conditions set forth in Ref. [4]. Data will be further verified using the IAEA reference steel JRQ. A very comprehensive plant life management programme is in place.

I.5. FRANCE

Plant life management was recognized as a key issue for safety and economical operation. Operation for up to 60 years is currently under analysis. A major issue was the reactor pressure vessel head replacement programme because of control rod drive penetrations, leakage through primary water stress corrosion, and cracking of Alloy 600. Forty-one heads have been replaced to date. The steam generator replacement programme, where the steam generator lifetime was less than the nuclear power plant lifetime, was carried out. This became necessary due to Alloy 600 cracking. A systematic ageing management review is carried out every 10 years. Alloy 182 and 82 weld, associated J welds and bottom mounted instrumentation areas will need treatment (laser or plasma peening on the J weld). Plant life management takes into account all safety relevant systems, structures and components and the approach is based on the IAEA guidelines. This is seen as good practice.

I.6. GERMANY

Safe operation is and remains a priority. German nuclear power plants are designed for 32 effective full power years. There are no plans for long term operation since nuclear power is scheduled to be phased out for political reasons. Periodic safety reviews are carried out every 10 years. The Deming process ‘plan–do–check–act’ is used for degradation management. This is seen as good practice. Basic reports on mechanical and electrical components, civil structures (buildings), auxiliary systems and technological aspects, as well as ageing of personnel, are made.

I.7. HUNGARY

Ongoing programmes include licence renewal activities, supported by international expertise and the IAEA. The fouling of steam generators has been solved. The copper condenser has been replaced with a stainless steel condenser and the water chemistry correspondingly altered (higher pH possible). A low leakage core configuration is in place to lessen the neutron fluence on the reactor pressure vessel. The former are seen as good practices. The pressurized thermal shock issue for units 1 and 2 is open and research is being carried out. The importance of cladding is recognized in pressurized thermal shock evaluations. Reconstitution of reactor pressure vessel surveillance specimens is performed to extend the database. A power uprate to 500 MW is currently under way.

I.8. JAPAN

Based on inspection results, the regulatory body gives permission for further operation at the end of each refuelling cycle. Periodic safety reviews are carried out every 10 years. These were originally voluntary activities by the plants but became mandatory in December 2003. About 50% of the nuclear power plants have been operating for more than 20 years, 7 for more than 30 years. The plant life management study has a two phase approach for the 3 oldest nuclear power plants.

- Phase 1: Explore the possibility of 60 years of safe operation and evaluate integrity of safety related components and non-replaceable components.
- Phase 2: Establish procedures for plant life management, assuming 60 years of operation, and implement the concept and policy as defined in phase 1. Evaluate the integrity of all reliability and safety related components and begin maintenance for long term operation. The Japanese programme covers reactor pressure vessel internals, piping and pumps, cables and concrete, pressurizers, steam generators, cables, etc. The seismic force for evaluation is based on the latest Japanese standard, which is different from the design and construction basis. Thinning of feedwater piping is also analysed with respect to seismic resistance. The strategy is to maintain sufficient human resources and to develop codes and standards for long term operation. Research and development will focus on intergranular stress corrosion cracking of stainless steels, erosion corrosion, radiation embrittlement, thermal ageing of two phase stainless steel, stress corrosion cracking of nickel base alloy, and materials fatigue behaviour in the operating environment. Relevant codes and standards include rules of fitness for service (Japan Society of Mechanical Engineers (JSME)). In preparation are standards for periodic safety review by AESJ, a standard plant life management by AESJ (with reference to IAEA documents) and a standard pipe thinning management by JSME.

I.9. REPUBLIC OF KOREA

A plant life management programme has been set up based on operating experience and research and development. Long term operation is approved only when the safety basis is satisfied. It is sought to increase the safety level to meet international requirements. This is a good practice to allow comparison and favour proactive improvements having a quality assurance base. Korean regulatory bodies are preparing a regulatory guide for continuous plant operation. Ongoing studies include life management aspects, backfitting rule execution with reference to US practice, steam generator management and management of carbon steel piping thinning. Attention is being given to the ageing of electrical cables.

I.10. RUSSIAN FEDERATION

The Russian Federation is aiming, in principle, for long term operation and will add further nuclear power capacity by completing nuclear power plants under construction and building new units. Future prospects for the WWER-1500 will be investigated, which is only at the design stage at present but projected to operate for 60 years. For long term operation the regulatory body requires that the rules in place for safe operation of systems, structures and components are complied with. The residual lifetime of non-replaceable safety related equipment must be justified and sufficient for the extended operating period. This is seen as a good practice or requirement. Work has been done to assess the possibility of operating first generation WWER-440 reactors beyond their design lifetime. Licences have been obtained to operate the Novovoronezh (units 3 and 4) and Kola (units 1 and 2) nuclear power plants beyond their design lifetimes. Improvements have been made in degradation monitoring and in updating guidelines for reactor pressure vessel integrity and residual life assessment. Reactor pressure vessel cladding properties are important. Nuclear power plant life extension is important in the Russian Federation and the regulatory basis exists for it. Ageing management of non-recoverable components is a regulatory requirement.

I.11. SLOVAKIA

A major goal is the creation of nuclear power plant monitoring programmes to continuously evaluate the operational influence of several degradation processes on systems, structures and components, allow trending of degradation and mitigating actions. The selection criteria are based on the significance of systems, structures and components from the safety perspective and their replaceability. This is seen as good practice. Irradiation embrittlement, corrosion (by means of loops), fatigue, hydrogen, thermal and temper embrittlement, and microstructural changes are all monitored.

I.12. SPAIN

The lifetime management methodology of UNESA (the Spanish utilities association) has been used since the early 1990s. The strategy is to first secure the nuclear power plant's original design lifetime and to keep open the option for renewal of operating licences beyond the design lifetime. The other main aim is to maintain and improve nuclear power plant safety and availability. Plant life management is seen as a way of furthering long term operating goals. Efforts continue to better understand materials in BWRs and PWRs, to improve detection of ageing, to develop predictive models of component behaviour and to develop mitigation and repair methods. Research is focused on stress corrosion cracking of hardened stainless steels, irradiation assisted stress corrosion cracking in stainless steel of BWRs and PWRs, reactor pressure vessel embrittlement, irradiation damage and thermal embrittlement. Alloy 690 thermally treated as a replacement for Alloy 600 in reactor pressure vessel heads is also being studied internationally. This is a good example of pooling resources to achieve a common goal. The José Cabrera nuclear power plant was to be shut down in 2006 and there is a proposal that materials may be taken from it to benchmark models of material behaviour. This is also seen as good practice.

I.13. SWITZERLAND

There is a policy of continual monitoring, inspection and, where needed, replacement of systems, structures and components. The ageing surveillance programmes have been in force since 1991. They are based on a wide range of sources derived from national and international experience. The use of wide knowledge bases is seen as a good practice and quality assurance. The ageing surveillance programmes are living documents which can be revised to reflect new knowledge. It is foreseen that the nuclear power plants will be able to operate for as long as legal requirements for safety levels are upheld. Research continues in fracture mechanics, stress corrosion cracking and special monitoring methods.

I.14. USA

As of mid-2005 there were 104 nuclear plants in the USA with operating licences. US nuclear plants are initially licensed to operate for 40 years. The 40 year term reflects the amortization period generally used by electric utilities for large capital investments. It is not based on safety, technical or environmental issues. NRC regulations permit nuclear plants to renew their 40 year operating licences for additional 20 year periods for each renewal. Existing utility inspection and maintenance activities (e.g. maintenance rule programme), component replacement and refurbishment (e.g. nuclear asset management or life cycle management), equipment surveillance and testing, and NRC oversight ensure that nuclear facilities continue to meet safety standards, no matter how long they have been operating. Because of these sustained maintenance programmes, the safety, reliability and economics of nuclear power plant operation in the USA have shown a continuous and sustained level of improvement since the 1980s. As a result of the high levels of safety and performance, since 2000 the NRC has renewed the operating licences of 33 reactors, is reviewing the licence renewal applications of another 16 reactors and expects to receive applications for 30 more by 2010. This represents more than 75% of the total number of operating nuclear power plants in the USA, and most of the remaining reactors are expected to renew their operating licences as well. The decision to renew an operating licence is fundamentally an economic one. It involves estimates of future electricity demand, the cost of other electricity supply options, and the cost of continued operation of the nuclear power plant. Based on the positive safety and economic outlook for US nuclear power plants, current estimates are that most of the existing nuclear power plants will operate for 60 years and several are considering operation for even longer periods.

Appendix II

EUROPEAN COMMISSION PROGRAMMES SUPPORTING NUCLEAR POWER PLANT LIFE MANAGEMENT

II.1. JOINT RESEARCH CENTRE SAFELIFE ACTION

To improve research activities dedicated to nuclear power plant life management since 1993, the Joint Research Centre (JRC) has recently undertaken an integration effort creating the SAFELIFE action on nuclear power plant life management. Nuclear power plant life management is seen as a multidisciplinary issue requiring a subsequent application of the various disciplines involved, which include crack detection, residual stress evolution, integrity assessment, material properties degradation, irradiation assisted stress corrosion cracking and maintenance practices.

SAFELIFE action integrates the efforts and projects of the JRC, as well the competences of the various European Networks dealing with research on ageing issues of components and structures in nuclear installations.

The most important of these networks of experts are AMES, NESC, ENIQ, NET, SENUF, and the recently started AMALIA, dedicated to core internals and irradiation assisted stress corrosion cracking. These are described in the following sections.

The information and competence with the Tacis programmes also plays a key role in plant life management issues such as irradiation embrittlement issues, material degradation assessment and monitoring, surveillance, structural integrity, fracture mechanics studies, qualification of in-service inspection methodologies for crack detection and, recently, risk aspects.

Aspects of managing and mitigation of accidents, neutron beam methods for residual stress measurements and other issues related to directives on pressure equipment are also dealt with.

The major technical tasks encompass the key primary components, including:

(a) Reactor pressure vessel;
(b) Primary piping;
(c) Internals and welds.

Aside from the major technical tasks a series of horizontal tasks are necessary, including research on:

(1) Maintenance methods;
(2) Development of risk methodologies in ageing nuclear power plants;
(3) Degradation monitoring, non-destructive methods and testing;
(4) Human factors and safety culture.

SAFELIFE aims to contribute to the development of European guidelines for lifetime assessment of nuclear power plant components, development of key facilities to support European Network activities and training, contribution to and operation of nuclear safety related European Networks and integrated projects, and development and promotion of a related Network of Excellence in the framework of the European research area.

SAFELIFE also includes tasks dedicated to improved fracture mechanics assessment procedures, relevant to pressurized thermal shock assessment for both PWR and WWER plants.

II.2. BACKGROUND OF THE AMES NETWORK

The AMES (Ageing Materials European Strategy) network was set up in 1993 to bring together the European organizations having the greatest expertise on assessment of nuclear reactor materials and research on ageing management.

To fulfil the strategy developed by the AMES network, in line with the priorities of the European industry, several key projects in the field of reactor pressure vessel irradiation embrittlement were executed during the fourth and the fifth EURATOM framework programmes. Their general purpose is to understand the influence of various embrittlement mechanisms in reactor pressure vessel ferritic steels; develop new techniques; improve dosimetry; and improve the prediction of irradiated material fracture toughness.

A considerable modelling effort has been undertaken, including an attempt to justify embrittlement behaviour. This is of interest for WWER-440 reactors, but could be extended to WWER-1000s. The AMES steering committee includes 24 organizations belonging to the EU and associated countries.

II.3. NESC — NETWORK FOR EVALUATING STRUCTURAL COMPONENTS

NESC has worked over the past 10 years to:

(a) Create an international network to undertake collaborative projects capable of validating the entire structural integrity process;
(b) Support the development of best practices and the harmonization of standards;
(c) Improve codes and standards for assessment of structural integrity and to transfer the technology to industrial applications.

The network brings together some 30 operating organizations, manufacturers, regulatory bodies, service companies and R&D organizations in large scale experimental projects. Like AMES and others it is operated by the JRC as operating agent supporting the steering committee and the organization of the network and its projects. The JRC also contributes its own R&D expertise for experimental and analytical work.

The network projects are generally focused on large scale experimental activities capable of being benchmarks. A strong multidisciplinary element is aimed for, combining various aspects of structural integrity assessment, in particular inspection, characterization of materials, fracture mechanics and instrumentation. Two projects have been completed and three are currently running. The set of coordinated experimental and analytical studies making up each project is funded primarily through ‘in kind’ contributions, whereby participating organizations contribute work and are then entitled to have access to the contributions of others to any given project. Members have also benefited from the shared cost actions of the European Commission’s Research Framework Programmes. In many cases these small dedicated research projects have been pilot or seed projects for subsequent larger network supported actions. Examples of areas being explored for future NESC activities include verification of the warm pre-stress assessment methods and fracture analysis of flaws in repair welds.

II.4. EUROPEAN NETWORK ON INSPECTION QUALIFICATION (ENIQ)

The ENIQ also began its activities in 1993. Its main tasks are:

(a) Assessment and qualification of non-destructive testing systems;
(b) Inspection qualification schemes;
(c) Harmonization of codes and standards;
(d) Risk informed inspection.

The network has a total of 64 participating organizations. The ENIQ led European Non-Destructive Evaluation Forum (ENDEF) has elaborated a strategy on measures to improve in-service inspection in WWER and RBMK reactors

II.5. ASSESSMENT OF NUCLEAR POWER PLANT CORE INTERNALS (AMALIA)

The objective of AMALIA (started in 2004) is to allow safe and economically viable operation of existing nuclear power plants, in particular:

(a) Identification of critical parameters governing the degradation of core internals (by mechanisms such as stress corrosion cracking, swelling or irradiation creep);
(b) Identification and validation of countermeasures to mitigate the degradation of core internals of existing reactors and preventive design of new reactors;
(c) Validation of models able to predict safe operational limits of core internals subjected to irradiation assisted stress corrosion cracking and related degradation mechanisms;
(d) Review the capabilities within its member organization together with the existing knowledge base from previous work programmes;
(e) Assess the availability of stocks of irradiated and unirradiated materials that might be made available for work programmes, as well as material that might be recovered from operating or decommissioned reactors;
(f) Studies of impacts from life extension programmes on irradiation damage and irradiation assisted stress corrosion cracking;
(g) Exchange of information and data with other international and national programmes on the basis of ad hoc agreements;
(h) Studies on other/new materials than the steels used in the old power plants;
(i) Studies on stress corrosion cracking degradation of materials (for current and new generations of reactors);
(j) Studies on creep and swelling degradation of materials for current and new generations of reactor;
(k) Surveys of national regulatory requirements and identification of existing, planned and required standards at the European and wider international levels with relevant core internals material damage and mitigation methods.

II.6. AGEING PSA NETWORK

Within the Institute for Energy (IE) of the Petten joint research centre a new Network on Incorporating Ageing Effects into Probabilistic Safety Assessment (PSA) was initiated in 2004. Its main objective is to develop and operate a network of interested parties from Europe and beyond on incorporating ageing effects into PSA and use of ageing PSA applications.

The technical objectives are:

(a) Evaluation of available methods and approaches to incorporation of ageing effects into PSA;
(b) Identification of necessary information on ageing issues to be addressed in PSA tools for specific PSA applications;
(c) Demonstration of the impact of different levels of ageing information included in a PSA model on the overall PSA results;
(d) Discussion of reliability models and data to be used for modelling of ageing effects in PSA models;
(e) Demonstration of approaches and feasibility models by means of case studies;
(f) Identification of further research needs.

II.7. EURATOM FRAMEWORK PROGRAMME 6

The goal of present and future EURATOM framework programmes is to build an integrated structure for European nuclear research, fostering the formation of clusters of excellence and competence. Besides technical and scientific achievements, key goals are the preservation and management of knowledge, encouraging the formation of new generations of students and researchers in the field.

The 2003–2006 EURATOM framework programme 6 budget for activities, including nuclear power plant life management, is €50 million.

II.8. PERFECT (PREDICTION OF IRRADIATION DAMAGE EFFECTS IN REACTOR COMPONENTS) INTEGRATED PROJECT

The PERFECT integrated project is the last of a series of projects addressing the issue of simulation or radiation damage as summarized briefly below:

(a) The REVE (reactor for virtual experiments) project aimed at demonstrating the possibility of simulating irradiation effects. It was a successful in-kind cooperation of 17 European (11), US (3) and Japanese (3) organizations.
(b) The European organizations built the first virtual reactor, reactor pressure vessel-1. This reactor is capable of simulating irradiation effects in reactor pressure vessel steels of light water reactors. Its input parameters and output data are the same as those of experimental irradiation programmes (neutron spectrum, temperature, etc.) and subsequent tensile testing (deformation rate, etc.).
(c) Reactor pressure vessel-1 provides acceptable quantitative data; however, it has to be greatly improved to become a fully predictive tool for industrial applications.
(d) SIRENA (fifth framework programme), aimed at extending the approach developed within the REVE project for pressure vessel steel to Zr–Nb alloys. Its objective is to first simulate neutron irradiation effects in the Zr–Nb alloys used to manufacture fuel assembly cladding, and subsequently the stress corrosion cracking behaviour of these irradiated alloys in an iodine rich environment. Seven organizations are participating in the SIRENA project.

The project is run by a consortium of 30 partners (18 universities) led by Electricité de France, with a budget of €18 million (€7.5 million is the budget provided by EURATOM). The official start was in January 2004, and the projected duration of the project is 4 years.

The key objectives of PERFECT can be summarized as follows:

(1) To build RPV-2, supplemented with a toughness module for the modelling of irradiation induced evolution of fracture toughness of RPV steels;
(2) To build INTERN-1, supplemented with an irradiation assisted stress corrosion cracking module for the simulation of irradiation effects in stainless steel, including irradiation assisted stress corrosion cracking;
(3) To 'validate' these tools and to carry out a European collective exercise on material behaviour using numerical tools;
(4) To disseminate knowledge and experience beyond PERFECT: Euratom fusion, other international organizations;
(5) To carry out training activities, seminars and workshops in an international environment (can be EU funded) and make use of the Marie Curie grant system.

II.9. COVERS

Several WWER units (440 and 1000 MW) are in operation in the EU and several are in operation or under construction in neighbouring non-EU countries such as Ukraine and the Russian Federation.

For the coming years there is a plan to implement within the current sixth framework programme a coordinated action on WWER safety, dedicated to reactor safety and related issues. This will offer a more extended framework for addressing the most critical issues in a harmonized way. The global aim of COVERS is "To establish a viable RTD structure with a view to enhance the scientific and technical cooperation of actors involved in WWER safety research, in close cooperation with operating organizations, manufacturers, regulatory bodies and other end users". The operation of all units has always been safe and efficient and there is a need to maintain this situation and improve on it.

II.10. PROPOSAL FOR A NUCLEAR POWER PLANT LIFE MANAGEMENT NETWORK OF EXCELLENCE (SIRENET)

In parallel with SAFELIFE JRC action, a Network of Excellence (NoE) on nuclear power plant life management has been proposed by JRC. The NoE is designed to be the centralized vehicle for R&D prioritization on nuclear power plant life management, bringing together the existing European networks, R&D organizations on nuclear power plant life management, with the needs of regulatory bodies of nuclear power plants, operating organizations and supporting industrial parties.

SIRENET (sustainable integration of European Research in residual lifetime prediction methodologies — network of excellence) is a current proposal to the EG-RTD Euratom programme and involves approximately 25 R&D and industrial organizations. The overall theme is the development of a set of best practice procedures for residual lifetime prediction of aged safety related systems, structures and components for all reactors in operation in EU member states, such as LWRs (BWR, PWR, VVER) and GCRs, specifically:

(a) Creation of an efficient organizational structure to undertake collaborative and integrated R&D, based on the collective long term commitment of the partners;
(b) Development of agreed roadmaps for advanced approaches;
(c) Synthesis of existing data and knowledge, with special emphasis on projects within the Euratom framework and national programmes;

(d) Development of leading edge knowledge and tools;
(e) Demonstration of predictive capability;
(f) Preparation of the technical basis for qualified and harmonized procedures;
(g) Implementation and exploitation of procedures for the benefit of end users.

II.11. TACIS AND PHARE PROGRAMMES

Since 1991 the European Commission has financed a number of Tacis, Phare and EURATOM R&D projects in order to support and ensure safe operation of WWER plants. In these projects and actions the main attention and support has focused on the WWER-440/230 and WWER-1000 reactor pressure vessel embrittlement issue and integrity assessment.

Two new TAREG projects have recently started (TAREG 2.01/00 and TAREG 2.02/00). They will be implemented simultaneously and in close cooperation with the Russian Federation and Ukraine, since the results of the second project are to be integrated in the final assessment of the first project.

The aim of the first project is to generate the conditions for an extensive understanding of the situation regarding the reactor pressure vessel integrity assessment, with particular emphasis on the embrittlement of material. This project includes the validation of the global programme on the basis of a consistent state of the art evaluation of the current knowledge, including a comprehensive identification of the most critical and urgent open safety issues.

This task is being carried out within an international group (senior advisory group) specifically set up for this purpose. Furthermore, this project is defining the conditions for improving the results of the WWER-1000 and 440/213 reactor pressure vessel surveillance results, the corresponding experimental programme being implemented in the twin project and made available later. These results and their consistency with others shall be evaluated with the aim of reaching conclusions on specific topics such as validation or reassessment of the neutron embrittlement prediction laws, the quality of the surveillance programmes, further assessment of spectrum and flux effects on the neutron embrittlement and direct measurement of fracture toughness in comparison with the application of the codified Charpy-V/K_{Ic} correlation. This project also includes preparation of the technical syntheses needed for performing EOL reactor pressure vessel integrity assessments, aiming to assess the most sensitive events. The IE of the JRC from the European Commission has been designated as the main contractor for this project.

The second project shall be seen as an experimental ‘support project’. It includes in depth analyses, as well as complementary investigations and tests which are being considered as necessary for upgrading the available surveillance results. A significant number of reconstituted standard and precracked Charpy-V surveillance specimens will be prepared according to the needs defined in the TAREG 2.01/00 project. The impact tests and the fracture toughness measurements according to the ‘master curve’ approach are also being performed in that framework.

Specific consideration is given to the implementation of the reconstitution technique in Ukraine and the qualification of the Ukrainian specialists. Further tests for underpinning advanced methods for the evaluation of the fracture toughness are also proposed. They are partly dedicated to further validation of the ‘local approach’, but also provide for complementary assessment of the shape of the temperature dependence fracture toughness curve. No additional reference irradiation is proposed at that stage since it has been considered more efficient to rely on upgraded surveillance results. The detailed programme will not enter into force until the senior advisory group has agreed to it. The results of this project will later be included in the final stage of the first project. A tender is foreseen, which is intended to identify the most appropriate western contractor.

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CONTRIBUTORS TO DRAFTING AND REVIEW

Bezdikian, G.	Electricité de France, France
Francia, L.	UNESA — Spanish Utilities Association, Spain
Inagaki, T.	International Atomic Energy Agency
Jeong, I.S.	Korea Electric Power Research Institute, Republic of Korea
Kang, K.S.	International Atomic Energy Agency
Katona, T.	Paks Nuclear Power Plant, Hungary
Kim, T.R.	Korea Electric Power Research Institute, Republic of Korea
Nishida, Y.	Nuclear Engineering Ltd, Japan
Sevini, F.	EC Joint Research Centre Petten
Tipping, P.	Swiss Federal Nuclear Safety Inspectorate, Switzerland
Young, G.	Entergy, United States of America

Consultants Meetings

Vienna, Austria: 15–18 February 2004, Paks, Hungary: 27–28 June 2005

Techncial Committee Meeting

Vienna, Austria: 22–26 November 2004

PERIODIC SAFETY REVIEW OF NUCLEAR POWER PLANTS SAFETY GUIDE
Safety Standards Series No. NS-G-2.10
STI/PUB/1157 (60 pp.; 2003)
ISBN 92-0-108503-6 Price: €15.50

GUIDELINES FOR APPLICATION OF THE MASTER CURVE APPROACH TO REACTOR PRESSURE VESSEL INTEGRITY IN NUCLEAR POWER PLANTS
Technical Reports Series No. 429
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ISBN 92-0-108104-9 Price: €15.00

GUIDANCE FOR OPTIMIZING NUCLEAR POWER PLANT MAINTENANCE PROGRAMMES
IAEA TECDOC Series No. 1383
IAEA-TECDOC-1383 (148 pp.; 2003)
ISBN 92-0-112703-0 Price: €15.00

The nuclear power industry will only be able to survive if plant safety is maintained and plant economics are favourable. This publication therefore addresses plant life management and ageing issues for light water reactors in terms of long term operation and licence renewal issues, not only from an operational and safety standpoint, but also in the context of plant economics in terms of the cost of electricity, including initial and recurring capital costs. It points out the importance of nuclear power plant life management in facilitating the technical and economic goals of long term operation in terms of the requirement to ensure safe, long term electricity supplies in the most economically competitive way possible.

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA
ISBN 92–0–101506–2
ISSN 0074–1914