IAEA Nuclear Energy Series

No. NR-T-3.33

Basic Principles

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Asset Management for Sustainable Nuclear Power Plant Operation

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ASSET MANAGEMENT FOR SUSTAINABLE NUCLEAR POWER PLANT OPERATION

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The Agency’s Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is “to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world’’.

IAEA NUCLEAR ENERGY SERIES No. NR-T-3.33

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FOREWORD

The IAEA's statutory role is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". Among other functions, the IAEA is authorized to "foster the exchange of scientific and technical information on peaceful uses of atomic energy". One way this is achieved is through a range of technical publications including the IAEA Nuclear Energy Series.

The IAEA Nuclear Energy Series comprises publications designed to further the use of nuclear technologies in support of sustainable development, to advance nuclear science and technology, catalyse innovation and build capacity to support the existing and expanded use of nuclear power and nuclear science applications. The publications include information covering all policy, technological and management aspects of the definition and implementation of activities involving the peaceful use of nuclear technology.

The IAEA safety standards establish fundamental principles, requirements and recommendations to ensure nuclear safety and serve as a global reference for protecting people and the environment from harmful effects of ionizing radiation.

When IAEA Nuclear Energy Series publications address safety, it is ensured that the IAEA safety standards are referred to as the current boundary conditions for the application of nuclear technology.

Asset management plays an important role in maintaining the competitiveness of nuclear power plants in a challenging and changing electricity market. Due to the deregulation in energy markets, there is an increased need for asset management. The essence of asset management is providing support to decisions seeking the optimum level of financial performance, operational performance and risk exposure. Decisions have to be made about operating and maintaining assets. Hence, the primary goal of asset management is informed decision making, rather than a focus on technical performance. Therefore, effective asset management facilitates both the competitive operation of nuclear power plants today and their sustainable long term operation.

This publication describes decision making in and implementation of asset management for sustainable nuclear power plant operation. It addresses aspects of asset management in nuclear power plants and presents shared experience and lessons identified, based on operational experience and knowledge. Although the publication is aimed at promoting asset management for nuclear power plants, the approach presented can also benefit other nuclear fuel cycle facilities, as they also constitute nuclear assets.

The IAEA is grateful to the experts and Member States for their valuable contributions in the drafting and review of this publication. The IAEA officer responsible for this publication was H. Delabre of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Nuclear power plants have proven their efficiency in reliably generating clean energy, while maintaining a high level of safety. The proactive management of assets is key to achieving cost effective plant operation. Currently, the utility sector faces the challenge of aligning the management of its assets with corporate objectives. This requires engineering and economic tools as well as value based decision support. The strategic plan of a company defines the high level goals and, based on this, business units set up their operational plans to achieve their targets.

With ageing facilities and a challenging economic situation, there is a need to improve efficiency to keep nuclear power competitive in a changing electricity market, all while maintaining a high level of safety. This has led to initiatives to improve asset management in nuclear power plants or in companies operating and maintaining these plants.

Both nuclear and non-nuclear industries have similar definitions of asset management. For example, the Institute of Asset Management has defined it as a balance of costs, opportunities and risks against the desired performance of assets and assets systems at different levels to achieve organizational objectives. This balancing might need to be considered over different time frames.

Given the increasing interest of Member States in improving the efficiency and sustainability of nuclear power, which can be achieved with nuclear asset management, there is a need to provide information in this area (see Fig. 1). International Organization for Standardization (ISO) standard ISO 55000:2014, Asset Management: Overview, Principles and Terminology [2], states that “Effective control and governance of assets by organizations is essential to realize value through managing risk and opportunity, in order to achieve the desired balance of cost, risk and performance.”

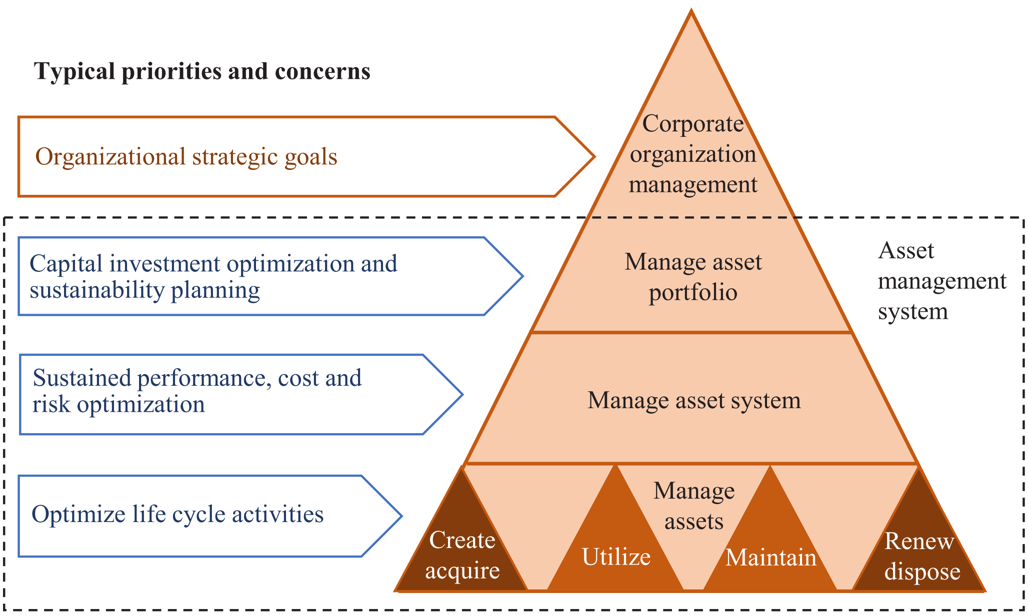

FIG. 1. Level of assets and their management, including typical priorities and concerns [1].

1.2. OBJECTIVE

The purpose of this publication is to provide best practices for asset management for sustainable plant operation. It offers the latest practices, lessons identified and operating experience associated with the fundamentals of asset management. The publication incorporates the key principles of international standards such as British Standards Institution standard PAS55-1:2008, Specification for the Optimized Management of Physical Assets [1], ISO 55001:2014, Asset Management: Management Systems — Requirements [3], and industry guidelines from the IAEA, the Electric Power Research Institute (EPRI) and the Nuclear Energy Institute (NEI). It is also intended to help Member States to develop strategies and/or plans for the asset management of their plants.

1.3. SCOPE

This publication provides information on various methodologies, good practices and approaches to manage assets in nuclear power plants currently in operation or in other operational nuclear facilities. Information on new build and decommissioning is also provided. It is intended primarily for users in:

- States with operating nuclear power plants;
- States in the process of building a nuclear power plant or in an advanced planning phase for construction;
- International organizations involved in the development and/or promotion of nuclear power;
- Owners and operators wishing to improve the management of their assets for a longer operational time frame;
- Other entities involved in the nuclear industry sector (suppliers and contractors to nuclear power plants, vendors, technical support organizations, developers and suppliers of operation and maintenance (O&M) materials and tools);
- International organizations which help States and nuclear power plants to enhance safety, increasing efficiency and improving performance;
- Member States in the process of introducing nuclear power in newcomer countries to help them manage their assets;
- Organizations involved in the establishment, implementation, maintenance and improvement of nuclear asset management;
- Organizations involved in delivering asset management activities and service providers;
- Internal and external entities which assess an organization’s ability to meet legal, regulatory and contractual requirements and the organization’s own requirements.

The main personnel from the entities listed above who would benefit from this publication include the following:

- Senior managers and supervisors in charge of efficiency and performance at their facility;
- Operation, maintenance and plant modifications managers from existing and operating plants to help them manage their assets to operate safely and efficiently throughout the life of the assets, and to help them establish a strategy for long term operation (LTO);
- Maintenance, budget and finance managers in companies operating and maintaining nuclear power plants;
- Plant operators or vendors in charge of the review and assessment of their organization;
- Specialists in engineering, procurement, manufacturing and construction contractors;
- Supply chain and support staff in charge of products and services;
- Experts from regulatory bodies in charge of the review and assessment of nuclear power plants.

Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.4. STRUCTURE

Section 2 shows how asset management provides value to an organization through a coordination of activities based on a line of sight to organizational goals, delivered through strong leadership. On this basis, it can be considered as a set of principles which an organization tailors specific to its needs. The publication provides concepts to contribute to the tailoring process, rather than a prescriptive framework.

Section 3 describes specific challenges that an owner/operator faces: maintaining a high level of safety; large capital investment; long operating life; multiple stakeholders; the regulatory framework; and a changing energy market. Guidance and support exist to ensure that operations are undertaken in a safe manner. Asset management provides an opportunity to control and optimize long term costs, and by doing so ensures that nuclear power remains a sustainable option in a clean energy market.

In Section 4, the potential of the asset management approach to coordinate existing and new activities (e.g. investment planning, maintenance planning, risk management) is described, as well as aligning these activities to ensure that they achieve the same purpose. This is achieved by providing line of sight of strategic goals, and challenges to tangible, executable activities, for example, maintenance delivery, business risk assessment, resource planning and competency management. It is important that these activities, and the supporting rational, are documented within the asset management (or wider organizational management) system.

Section 5 defines the expected value or improvements of asset management. Specific activities, or enablers, are required to support the delivery of the framework. These activities will be specific to an organization; however, they are typically across different departments and require strong, coordinated leadership.

Section 6 lists the methods that can be used to support the management of assets and provides some examples of the most important methods that an owner/operator can consider as part of their asset management framework, supported by references to the appropriate standards. These are existing methods that can be utilized across multiple sectors, with specific applications for nuclear power plants.

Section 7 lists methods, such as audit and benchmarking, to support required routine verification to ensure that the management system is appropriate for the organization and delivers the expected benefits and performance. Section 8 summarizes and concludes.

2. ASSET MANAGEMENT

ISO 55000:2014 [2] defines asset management as “coordinated activity of an *organization* to realize value from *assets*”, where an asset is an “item, thing or entity that has potential or actual value to an *organization*”. Asset management for nuclear power plants is defined by the NEI as “the process for making resource allocation and risk management decisions at all levels of a nuclear generation business to maximize value/profitability for all stakeholders while maintaining plant safety” [4]. According to these definitions, asset management has the potential to include a significant scope that encompasses plant safety, for example everything within a given organization and aspects such as its supply chain. The concepts of what constitutes an asset are discussed in more detail in Section 2.2.

Asset management identifies the activities needed to support operational objectives and to ensure they are aligned strategically. Typically, the supporting activities (or functions) may already be undertaken in an organization (potentially under a different name), and the process of asset management reviews and aligns these activities, rather than replace them. This alignment can help to coordinate many activities at a nuclear power plant, such as providing line of sight of organizational objectives and decision making throughout the plant's lifetime (design, construction, O&M, decommissioning). It also provides an understanding of how decisions support, or are influenced by, corporate objectives.

2.1. ASSET MANAGEMENT AND VALUE

Value can have multiple meanings, three of which are defined by ISO 55002:2018, Asset Management: Management Systems — Guidelines for the Application of ISO 55001 [5] as:

"a) value *generation* (benefits from use, ownership or custodianship of assets);
b) value *determination* (such as valuation of assets or the organization, for example, the sale price of the asset or organization, if you sell it);
c) values (principles that guide an organization's internal and external conduct)."

This publication refers to value in the context of value generation. In this sense, asset management can provide a platform of coordinated decision making across an organization, focusing on maximizing value throughout its lifetime. Value typically refers to the ability of an asset (structure, system, component, person, process) to deliver the required capability throughout the life of the plant. The focus is thus long term value rather than a sole emphasis on short term cost (see Fig. 2).

The value model provides a framework to structure thinking about the value of asset management and forms the basis for building models to support decision making in an organization. It is not developed further in this publication but is referenced as a useful tool for organizations to use as required. The value model includes the following aspects:

(a) External corporate/governmental value level:
   — Assured energy supply;
   — Reputation with regulator and public delivered through safe operations;
   — Reduced environmental footprint (e.g. low carbon generation);
   — Safe and cost effective electrical energy production;
   — Long term opportunities for highly skilled jobs and investment in the community.
(b) Internal organizational value:
   — Confidence in safe operations;
   — Consistent, informed decision making;
   — Safe and cost effective energy production and O&M;
   — Training and assignment of competent, experienced personnel throughout the lifetime of the plant.

2.2. DEFINITIONS

The definitions used in this publication are the following:

(a) Asset: The term can mean different things, and the perspective from which the word is used in this publication is important. At the highest (national) level, the asset is the nuclear power plant fleet that provides safe, low carbon electricity to the grid, ensuring security of supply (see Fig. 3).
(b) Asset management policy and strategy: The translation of organizational objectives into asset management objectives and coordinated activities from across the organization through which the objectives can be achieved. Typically, this connects the strategy with the approach to be taken to develop individual asset management plans.

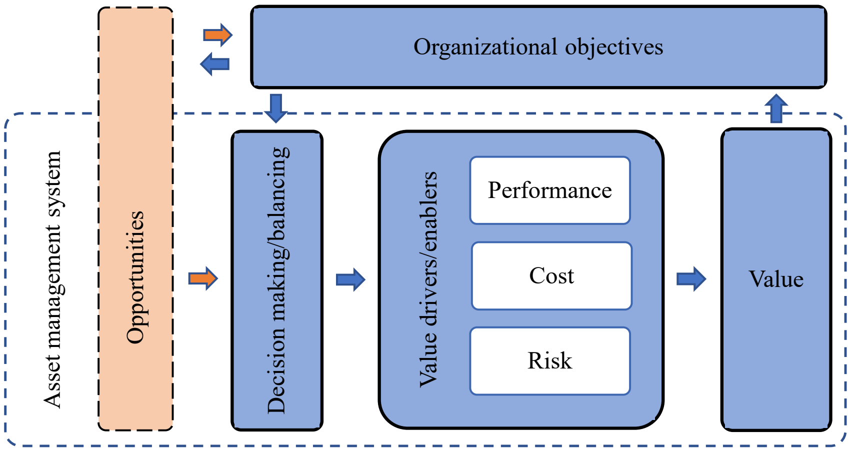

FIG. 2. The value model asset management to an organization. Source: fig. 1 of Ref. [6].

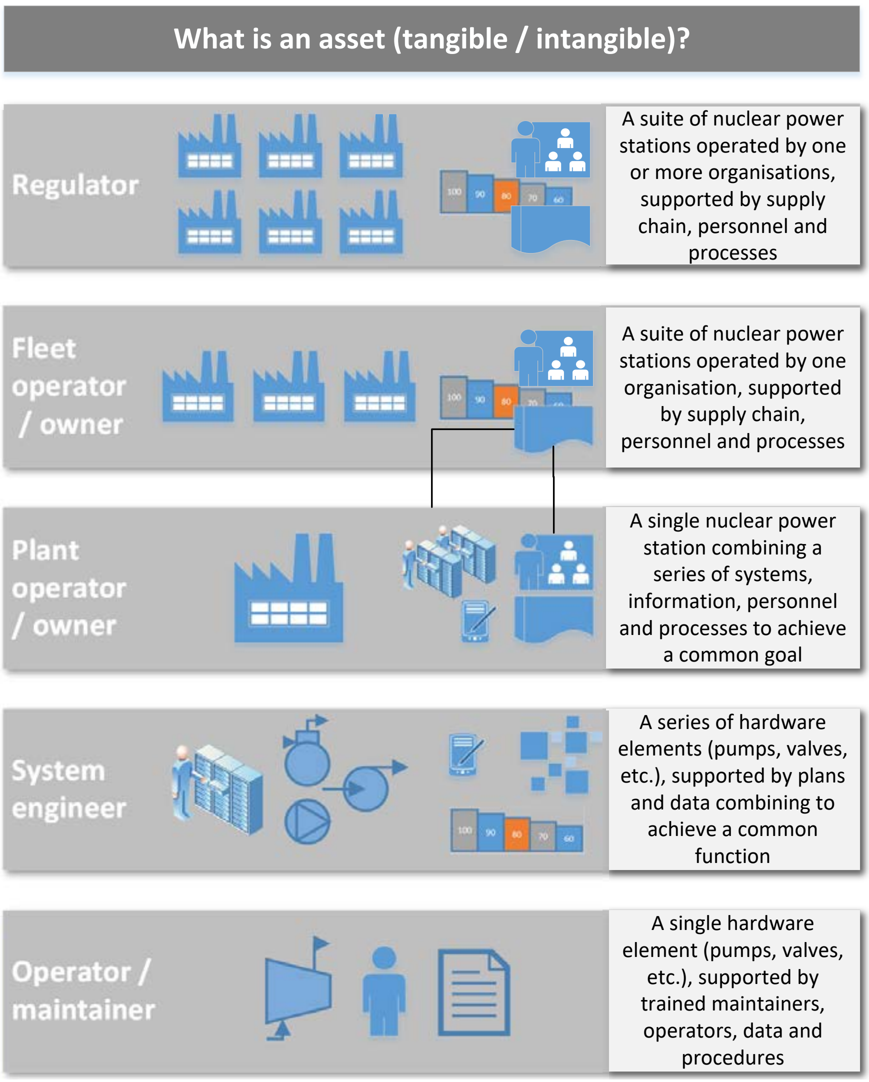

FIG. 3. Meaning of asset at various levels.

(c) Asset management objectives: A derivation of the overarching organizational objectives that are to be achieved through the delivery of the asset management system.
(d) Asset management plans: This term specifies, for an asset or group of assets, the activities that will be undertaken (e.g. proactive replacement, inspection, run to failure), associated responsibilities and resources, supported by timescales for these activities.
(e) Audit: An organization's process for reviewing and auditing the effectiveness of its asset management processes.

At the lowest level, an asset is the individual equipment item (e.g. pump) that fulfils a purpose, or even the component parts that make up the pump. In nuclear power plants, assets have historically been viewed as the structures, systems and components (SSCs) that comprise the plant. However, there is a growing recognition that this definition can extend to tangible items that add value such as processes, personnel or knowledge, and other items such as resources (i.e. people, materials), inventory, contracts, documents, software and information.

2.3. BENEFITS OF ASSET MANAGEMENT TO AN ORGANIZATION

The 'value' described in Section 2.1 and Fig. 2 is realized through the improved performance of the organization. There are several quantifiable benefits of implementing an asset management programme at nuclear power plants. They will be explained in detail further in the publication. Some benefits of asset management in the nuclear electricity generation include the following:

— Optimized life cycle costs;
— Identified and managed risk (financial and physical);
— Optimized maintenance activities;
— Reduced system failures;
— Reduced unplanned outages;
— Increased capacity factor;
— Increased generation output;
— Increased nuclear fleet performance;
— Maximized profitability while maintaining a high level of safety and sustainability;
— Extended lifetime operation.

2.4. ASSET MANAGEMENT AND UNITED NATIONS SUSTAINABLE DEVELOPMENT GOALS

A good asset management programme can give assurance that assets will fulfil an organization's corporate and social responsibility and indirectly support the United Nations Sustainable Development Goals (SDGs) [7] (see Annex V for more details). Effective asset management, as defined in standards such as ISO 55000:2014 [2], supports these goals because it requires the following from the organization:

"1) developing and implementing processes that connect the required purposes and performance of the assets to the organizational objectives;
2) implementing processes for assurance of capability across all life cycle stages;
3) implementing processes for monitoring and continual improvement;
4) providing the necessary resources and competent personnel for demonstration of assurance, by undertaking asset management activities and operating the asset management system."

Depending on the industry, asset management can contribute to the following SDGs [7]:

- Goal 6: Ensure availability and sustainable management of clean water and sanitation for all.
- Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all.
- Goal 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
- Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
- Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable.
- Goal 12: Ensure sustainable consumption and production patterns.
- Goal 13: Take urgent action to combat climate change and its impacts.

Asset management in the nuclear sector can contribute directly to affordable clean energy and climate action goals, and indirectly supports other SDGs, while maintaining a high level of safety in plant operation and integrating long term liabilities for waste and decommissioning.

3. ASSET MANAGEMENT FOR THE NUCLEAR POWER PLANT OWNER/OPERATOR

3.1. KEY TERMINOLOGY

In order to ensure that terminology is aligned with other industries, the definitions in ISO 55000:2014 [2] are used.

3.1.1. Asset management and business risk

In the nuclear industry, the word ‘risk’ is most often associated with nuclear safety risk. However, in asset management, risk is associated with business risk (i.e. the risk of not fulfilling business objectives). For most owner/operators, it is the risk of not producing electricity, since electricity production is the main creator of value for the business.

That said, the nuclear risk needs to be considered as a factor in the business risk. If the operation of the plant is not safe, then there is no possibility of fulfilling the objectives and reducing the business risk to a satisfactory level. The plant needs to be safe and be able to demonstrate it to remain in business.

3.1.2. Asset tangible versus intangible

It is important not to limit the definition of assets to only physical assets. In the nuclear industry, there are other types of intangible asset. For example, there is the competence of personnel, dedicated human resources, data, knowledge, experience feedback and safety culture. According to ISO 55000:2014 [2], an asset is:

> “item, thing or entity that has potential or actual value to an *organization*...
>
> “Note 1 to entry: Value can be tangible or intangible, financial or non-financial, and includes consideration of *risks*...and liabilities. It can be positive or negative at different stages of the *asset life*…

“Note 2 to entry: Physical assets usually refer to equipment, inventory and properties owned by the organization. Physical assets are the opposite of intangible assets, which are non-physical assets such as leases, brands, digital assets, use rights, licences, intellectual property rights, reputation or agreements.

“Note 3 to entry: A grouping of assets referred to as an *asset system*...could also be considered as an asset.”

For asset management in nuclear power plants, intangible assets include safety, experience feedback, dedicated human resources, knowledge and competences.

3.2. BENEFITS OF ASSET MANAGEMENT FOR THE NUCLEAR POWER PLANT OWNER/OPERATOR

In recent years, the importance of asset management for plant operation has been recognized as a key factor both for safety and efficiency. Without efficient asset management, operations would not be profitable, at least not in the long term. This is true regardless of the efficiency of other processes in the organization.

A similar trend has also been seen in non-nuclear sectors. International standards continue to be developed for the implementation of asset management programmes, for instance PAS55-1:2008 [1] and later ISO 55000:2014 [2], as a complement to ISO 9000:2015, Quality Management Systems: Fundamentals and Vocabulary [8]. The international standards have not been specifically developed for nuclear power plants, or any other sector, but an owner/operator can benefit from the adoption of the principles of asset management in those standards.

Nuclear power plants have high level specific priorities for safety management and the regulatory framework. Nuclear safety is a key aspect of the asset value in a plant, in addition to efficiency and business risk management. It is the main priority to be maintained to ensure safe, reliable LTO. The owner/operator is responsible, at a minimum, for preventing and mitigating any impact on public health and the environment by managing assets within the regulatory domain. This requires conservative operational decision making. A nuclear safety issue might cause long non-production periods or even permanent shutdown of the reactor.

Asset management also supports the plant’s drive to be a safe and clean generation tool within a strong regulatory framework with stringent safety requirements, openness and transparency. In addition, the plant operates under the oversight of an independent regulatory body and benefits from international experience feedback and international reviews.

Nuclear power generation, though a low carbon baseload and massive power generation technology, remains highly capital intensive. The overall cost depends significantly on the cost of capital recurring expenses and needs long term cost recovery through the electricity market. To ensure affordability, the coordination of investment, maintenance and refurbishment requires careful balance. The key purpose of asset management is to provide a platform for decision making and for achieving the associated balance.

One major benefit of proper asset management for an owner/operator, apart from keeping track of plant status, is the forward looking approach for plant operation. In addition, asset management programmes include perspective and anticipation for LTO, which is one of the revenue sources for a significant industrial investment such as a nuclear power plant.

The owner/operator needs to consider a significant number of topics: for example, how long the plant will be operated within the safety demonstration framework; how the qualified suppliers of components are secured in the long term; how competent personnel are secured; and, more importantly, how the assets are maintained. These questions need to be addressed in the owner/operator’s strategy. It is then important to ensure that this strategy is implemented at the plant.

The owner/operator also has to consider the allocation of the investment from a fleet perspective (if applicable and relevant). A prioritization methodology is the key to ensure efficient allocation of investments in activities that provide the highest value and safety. Investment optimization is explored further in Section 6.

3.3. CHALLENGES FOR THE NUCLEAR POWER PLANT OWNER/OPERATOR

Every application of asset management is considered unique. As such, it is important to tailor the management system so it is specific to the objectives, business risks and benefits of the application. The operation of nuclear power plants is no exception and each existing plant represents a unique asset which contributes to safe and sustainable power generation. Some specific considerations for a plant include the following:

— A nuclear power plant is a large and complex asset in terms of investment.
— It has long asset design, construction, operation and decommissioning lifetimes.
— It involves multiple technical, regulatory and societal obligations during its operation.
— It manages multiple stakeholders (including governments, regulators and public opinion) who can have a major impact on its economic value.
— It needs to consider long term energy resources, waste and spent fuel management.
— It has maintained human resources through continual training and addressing knowledge management challenges.

Nuclear power plants face multiple challenges during their operation. As previously discussed, effective asset management provides a platform of coordinated decision making across an organization based on value and risk management. Historically within the nuclear sector, risk is intrinsically linked with safety and safe operation. In the context of asset management, however, risk management refers more widely to LTO and economic performance. Asset management programmes need to be developed on the basis that safe operations are a pre-condition, requiring constant and proactive vigilance, and need to provide a bounded domain within which informed decisions can be made aligned with corporate objectives. In addition, the asset management framework has to work with the safety case to permanently ensure that the safe operational domain is well understood and receives compliance.

While asset management frameworks can do little to influence the highly regulated and politically sensitive environment within which plants operate, they can be used to ensure that stakeholder needs are considered formally within the management system. An effective asset management system needs to coordinate these requirements, with clear line of sight, from, for example, IAEA publications (see Refs [9–12]).

3.3.1. Responsibility for safety

The operator or licensee bears the prime responsibility for safety to ensure continuously that the plant is operated to achieve the highest standards of safety that can reasonably be achieved, as required by the licence and the strict regulatory framework. It is the first principle prescribed in the IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [13], and involves the following:

(a) An integrated management system, as explained in IAEA Safety Standards Series No. GSR Part 2, Leadership and Management for Safety [14], leadership and development of safety culture at all stages of the organization, training operating teams and allocating resources devoted to safety, commensurate with the magnitude of the risks.
(b) Consideration of lessons from the feedback of experience or possible new issues due to material aspects or additional regulatory requirements.

(c) Periodic safety reviews or safety reassessments, which are important steps in the industrial process, with the aim of ensuring full compliance with the current design basis and to anticipate issues by identifying further improvements in defence in depth by taking into account ageing issues.
(d) LTO, which may require extensive refurbishment and safety upgrade programmes to be implemented, if economically justified and accepted by the national safety authorities; feedback of experience and predictability in the regulatory framework are key for sustainable LTO.

Such refurbishment and upgrade programmes cannot be compared with routine maintenance. They are more expensive and may therefore be considered and analysed as a major capital investment associated with extended plant lifetimes. Clearly, the levelized cost of electricity (LCOE) for LTO of an existing plant has to compare favourably with other electricity generation sources.

3.3.2. Long term liabilities

The management of long term liabilities including the management of spent fuel (storage, reprocessing, disposal), funding for dismantling and ultimate waste storage and repository are key elements and major challenges to be considered.

3.3.3. Evolution of electricity demand and the challenging electricity market

Electricity demand, energy market price and competitiveness, fair consideration for environmental benefit and clean energy are major issues for asset management frameworks. Nuclear power is critical to national energy infrastructures. It provides sustained economic benefits to the entire economy. It can play a key role in ensuring grid reliability. It is by far the largest source of clean and baseload energy. Some nuclear power plants can be flexible, adapting to changing demand, when dispatchable generation is needed to step up when generation from intermittent sources decreases.

Nevertheless, markets can threaten the viability of nuclear power when they do not fully value the services that nuclear power plants provide. This can lead to premature shutdown of nuclear units accompanied by negative economic consequences. It appears that plant assets can also be at risk, not only due to low growth in electricity market demand, low current natural gas prices or transmission constraints, but also due to public policies to promote or subsidize renewable energy sources outside of fair market considerations.

These electricity market issues are key for economic and sustainable nuclear power plant asset management. Accurate and fair price formation in the energy markets is particularly important because a baseload plant derives most of its revenue from the energy markets. Some valuable plant assets worldwide are currently threatened due to these market distortion mechanisms.

It is important that fair electricity market regulation permit full recognition of the value of clean, low carbon emitting and dispatchable generation, including capacity market, and accurate price formation to address legitimate environmental needs and price stability, and consistent with the economic signals coming from the market.

3.3.4. New regulatory requirements and improvements required for renewal of licences

Legal requirements for operating nuclear power plants and LTO also have to be considered as part of asset management. These legal requirements are mainly consistent with the international framework and recommendations, such as those in IAEA Safety Standards Series Nos SSR-2/2 (Rev. 1), Safety of Nuclear Power Plants: Commissioning and Operation [15], SSG-25, Periodic Safety Review for Nuclear Power Plants [16], and SSG-48, Ageing Management and Development of a Programme for Long Term Operation of Nuclear Power Plants [17] (see also Refs [18, 19]).

With regard to the LTO of operating nuclear power plants, two main regulatory approaches have been used. They have the same goals — to maintain and improve safety — but apply different methods and focus for LTO, as follows:

(a) LTO based on renewal of the licence, including a rigorous ageing management programme (e.g. US regulatory framework [20]):
  - This is a regulatory process that ensures that the current licensing basis provides and maintains an acceptable level of safety (including maintenance rules and quality assurance).
  - Each plant's current licensing basis is examined during licence renewal in the same manner, and to the same extent, as it was examined during the original licensing with the addition of ageing management activities.

(b) LTO based on periodic safety reviews and continuous improvement:
  - In this case, licence holders are to assess, verify at least every ten years (for most Member States) and continuously improve, as far as reasonably practicable, the nuclear safety of their nuclear installations in a systematic and verifiable manner.
  - In this approach, a high level safety objective which applies to new plants may be used as a reference to define reasonably achievable improvements to existing plants (e.g. European Nuclear Safety Directive [21], Western European Nuclear Regulators Association (WENRA) Nuclear Safety Directive [22]).

With regard to asset management, these regulatory approaches, depending on how they are implemented, may result in different licensing timelines, degree of predictability or uncertainties in terms of future conditions and timelines, or new requirements to be applied. These elements have major impacts on overall decision making for the owner/operator in terms of long term planning, investment, cost recovery and allocation of resources which are key for plant asset management.

Regardless of the regulatory framework, it is important to have stable and predictable regulatory conditions for safety for adequate investment planning and a safe and sustainable long term nuclear asset management.

3.4. STAKEHOLDER IMPACT ON ASSET MANAGEMENT

For a nuclear power plant, each of the following stakeholders is considered and the challenges addressed in the asset management, with dedicated analysis in terms of possible impacts and ways to make them predictable and with limited impacts on the operation, safety and economics.

3.4.1. Owner/operator, vendors and the supply chain

While making safety a priority, monitoring the economics of production is essential in maintaining the plant's equipment in good condition so as to ensure safe and reliable power generation.

3.4.2. Investors

Depending on the circumstances, investors may consider long term issues and the long term return on investment, but they may also consider immediate challenges and opportunities involving short term decisions.

3.4.3. Regulatory body

Regulatory bodies have an important responsibility in establishing standards and establishing the regulatory framework. Decisions can impact both the operation of a plant and the conditions required and can have a major impact on the economics of the plant.

3.4.4. Governments and local authorities

Government policy with regard to energy and the future of nuclear power plants (e.g. society and environmental issues, low carbon generation, environmental laws, national policy issues) can have a major impact on the economics or future lifetime of plants.

3.4.5. Customers

Customers are key stakeholders with regard to reliability and the price of electricity, including environmental considerations.

3.4.6. Public

Public acceptance is a key factor, which has to be built through transparency and confidence and which can impact the future of a nuclear power plant. As a result, the goal of asset management is to ensure that the plant's economic value is fully maintained and recognized, and that the owner/operator enjoys an efficient, predictable, safety focused regulatory framework as well as a fair market and economic, environmental and social conditions, commensurate with the benefit for the society.

3.5. LIMITATIONS OF ASSET MANAGEMENT FOR THE NUCLEAR POWER PLANT OWNER/OPERATOR

An effective asset management programme will not eliminate all business, safety and environmental risks, nor is it the intent of such a programme. For instance, as demonstrated by the accident at the Fukushima Daiichi nuclear power plant (see Ref. [23]), the likelihood of a high impact low probability event cannot be eliminated. Disruptive events involving technical, economic or political issues cannot be excluded. Failures of equipment can affect plants at any stage of their operation. As plants age, equipment may also become obsolete, which would increase the need for new investment for major equipment replacement or for large refurbishment.

Moreover, there are also challenges in implementing an asset management programme. The additional costs of such a programme, leadership support, competencies within organizations and management challenges can result in an ineffective asset management programme. Another limitation is that undue complexity could be introduced in the operating organization.

Despite these challenges, an asset management programme needs to focus on controllable activities, manage the interfaces and develop transverse projects. Asset management is not a panacea to eliminate risk but more to highlight business risks and to try to reduce them, both physical and financial, and have an organization wide approach to improving the asset value of nuclear power plants.

4. ASSET MANAGEMENT FRAMEWORK FOR THE NUCLEAR POWER PLANT OWNER/OPERATOR

4.1. NUCLEAR ASSET MANAGEMENT

The process required for an asset management programme for a nuclear power plant is comparable to other types of process. As with all areas, it is important to tailor the approach and the associated risks.

4.2. ASSET MANAGEMENT POLICY AND STRATEGY

In order to deliver a successful asset management system, the following areas need to be considered:

(a) Organizational objectives: Articulation of the organizational objectives to be addressed (fully or partially) through the asset management strategy.
(b) Scope and perspective: This includes both the physical boundary in terms of fleet, plant and SSCs, and also the scope of the management system as described in Ref. [24].
(c) Identify stakeholders: Regulators, consumers, competitors, partners and owners, among others, as described in INSAG-20, Stakeholder Involvement in Nuclear Issues [25].
(d) Needs and expectations: Based on the key stakeholders, their needs and expectations of the overall organization.
(e) Criteria for decision making: This provides a baseline for the risk evaluation for the organization, balancing probability of occurrence against impact which may be on the budget, safety, production or availability.
(f) Design basis: The design basis for the facility, in terms of life and power generation, and how this is reflected in terms of the current operational status.
(g) Life cycle: Consideration of the point in the life cycle of the plant (i.e. early/late life) and whether any key considerations such as life extension need to be considered or anticipated within the asset management framework.
(h) Processes and procedures: Whether the existing processes and procedures will support, influence or be influenced by the asset management framework.
(i) Budgets: Whether to include high level budgetary information in the strategy to ensure that investment decisions are linked to the entire asset portfolio.

The policy and strategy need to provide a basis from which the owner/operator can inform consistent investment decisions across the asset portfolio. For example, due to the ageing of nuclear facilities, ongoing training requirements may need to be compared against the replacement of hardware when considering investment decisions. The decisions will typically be linked to available funding and will have to balance business risk to profit, operations, whole life cost, safety, human factors and any other factors at the plant.

These considerations are typically communicated and evaluated through a business risk matrix, or articulation of the business risk inclination of the organization. This basis has to be used throughout the organization to ensure consistent investment decisions. There needs to be a transparent line of sight from the top strategies to all decisions, making it possible for the entire organization to be aligned and have the same understanding. The roles and responsibilities need to be clear, precise and distinctive:

— Why is this being done?
— What are the strategic goals of the organization?
— What are the needs of the stakeholders?

— What is the risk appetite of the organization?
— What should we do to meet the strategic goals?
— How do we carry out the actions to meet the goal?
— How do we minimize the cost of the desired service?

4.3. NUCLEAR POWER PLANT ASSET MANAGEMENT OBJECTIVES

In this publication, separate sections have been developed for the asset management strategy and objectives. The asset management objectives need to translate the owner/operator's strategy and asset management strategy into achievable objectives. For example, this may include:

— Key performance indicators;
— Cost per MW·h;
— Failures per annum;
— Maintenance compliance levels;
— Supply chain management indicators;
— System or equipment availability.

As already stated, safety has to be considered as a 'bounded domain' with conservative limits and decision making (i.e. the required level of safety needs to be fulfilled to achieve the asset management objectives). Safety indicators could be included; however, their use needs to be carefully considered and linked to the performance of the asset management system.

In the nuclear sector, there is a significant number of stakeholders, and plants operate within a potentially volatile economic market in which the nuclear provider is a large investment, and there is overhead with stable power output. However, newer, cheaper forms of energy can have an impact on the economic viability of the plant. The views of stakeholders, and their needs from the asset management system, can vary greatly, although they tend to align to maximize economic value. When articulating asset management objectives, the following stakeholder views should be considered:

— Owner/operator: Determines overhead costs and investment to continue operation, including the decision for life extension.
— Public: Competitive price per MW·h.
— System engineer: Determination of investment to maintain or improve performance.
— Plant asset manager: Determines the distribution of investment and if life extension is possible.
— Regulator: Oversight of long term, safe, reliable and affordable energy production.

4.4. ASSET MANAGEMENT PLANS

While asset management plans can be established for both tangible and intangible assets, this section concentrates primarily on the physical assets of the plant (i.e. the SSCs). The purpose of an asset management plan is to articulate how the asset will be supported to deliver objectives in line with the risk level and associated investment throughout the life of the asset. This includes the requirements that influence maintenance requirements, or provide additional maintenance impact due to support equipment, and any plans to respond to failed equipment.

The risk prioritization and categorization process will provide key information to identify the needs for maintenance and/or improvement of performance, supported by appropriate analysis. These needs can be assessed against specific analytical methods, such as failure mode, effects and criticality analysis (FMECA), fault tree analysis, reliability analysis and risk based inspection (see Section 6). The result of these analyses needs to identify a platform from which maintenance, information and investment plans can be developed. The following sections detail the relevant considerations or tools that can be used.

The asset management plan needs to link to the following:

- — Predicted equipment life;
- — Maintenance activities;
- — Maintenance strategy (e.g. run to failure, preventive, condition based);
- — Planned change programmes (i.e. maintenance, condition monitoring, replacement, refurbishment, replacement, upgrade);
- — Obsolescence management;
- — LTO;
- — Review and update process.

4.5. ASSESSMENTS

To ensure that the assets, processes and systems are working as intended, a well developed assessment process is needed which will help the organization close the plan–do–check–act cycle. The assessment process could be set up in various ways. However, the goal is to ensure that the asset management system is working in the expected and desired way. There needs to be a clear line of sight from the asset management system to the assessment process to verify the effectiveness of the asset management system and improve it based on the results. The assessment of an asset management programme and different aspects of it is discussed in Section 7.

5. ASSET MANAGEMENT ENABLERS

This section identifies the tools and processes that facilitate the implementation of an effective asset management programme.

Nuclear power plants have unique asset management provisions owing to the high levels of safety and reliability required. Effective asset management can be achieved with a risk based, planned approach, and embedding asset management features within the organization's culture. More importantly, having a consistent, long term approach to asset management, with checks and controls, is required to gain significant benefits from asset management programmes. Optimizing the return on a plant asset requires the management of the physical asset, human resources, the environment and safety, as well as financial investments, revenues and costs.

Figure 4 shows an adaptation of the nuclear value map as developed by EPRI as part of their risk informed asset management (RIAM) programme [26]. The RIAM programme focuses on factors that can be controlled and influenced by the management and staff of a nuclear power plant. Therefore, asset management enablers are aligned with influence factors at a plant that leads to long term value optimization. In addition, asset management standards such as PAS55-1:2008 [1] provide guidance, including checklists for requirements and good practices in physical asset management.

5.1. STRATEGIC PLANNING

Strategic planning from an asset management perspective requires the linking of organizational or corporate objectives to the asset management objective. It is important to document and use this strategic plan as a communication tool to implement effective asset management throughout the organization.

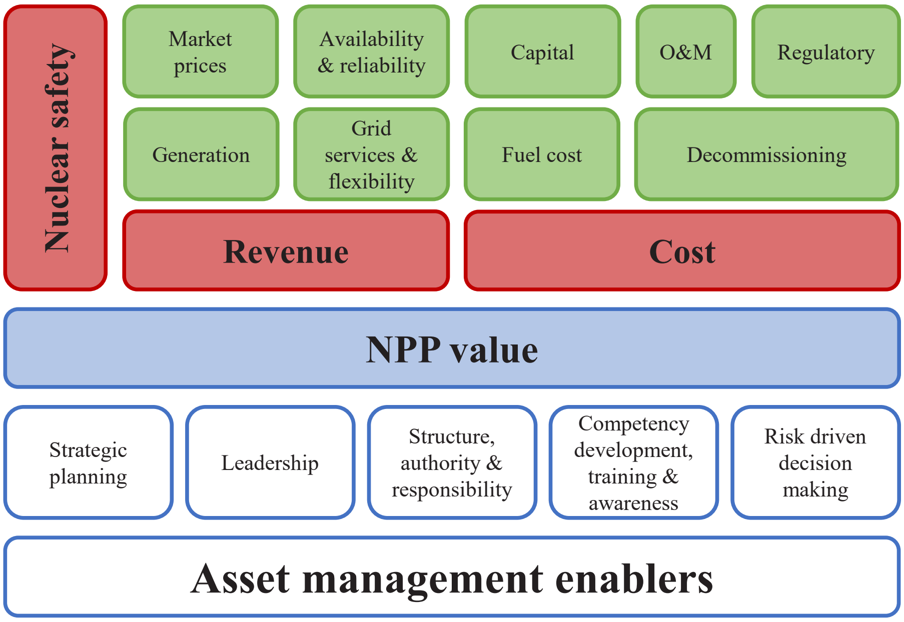

FIG. 4. Nuclear value map developed by EPRI [26].

EPRI has also developed an asset management toolkit for nuclear power plants, which identifies and evaluates existing tools to enable asset management [27].

Nuclear power plant operators can refer to ISO 55002:2018 [5] for guidance on setting up a strategic asset management plan when following ISO 55001:2014 [3] and framework. As a minimum, the organization needs to document the following:

— Why asset management is important and its relevance to the owner/operator;
— The stakeholders and their responsibilities;
— Bounding the definition of the asset and or the asset portfolio;
— Priorities;
— Performance indicators, including time frames.

The NEI has developed a structured methodology which identifies strategic decision making functions, including a standardized self-assessment tool to evaluate the owner/operator’s business practices (see Ref. [4]). The level 1 primary functions and level 2 ‘subfunctions’ listed in Ref. [4] are presented in Table 1.

Clearly, each function has to interact with another, requiring various departments in a nuclear power plant to communicate effectively. Leadership at the organization and the overall culture has to align to ensure that there is open communication, with appropriate authority and delegation.

5.2. LEADERSHIP

Leadership and organizational culture are important determinants of an effective asset management programme. While leadership buy-in is important, asset management need not be a top–down initiative. The responsibility of the leadership is to define and communicate the asset management objectives, facilitate integrated planning across various functions, empower resources within the organization and hold them

TABLE 1. NUCLEAR ASSET MANAGEMENT FUNCTIONS
(based on table 1-1 of Ref. [4])

Level 1 primary function	Level 2 subfunction
Strategic planning	Collect and evaluate stakeholder input Analyse strengths, weaknesses, opportunities and threats Identify strategies and alternatives Establish strategic and tactical goals
Generation planning	System demand forecast System resource forecast Gap analysis Generation plan development
Project evaluation and ranking	Project submission, categorization and screening Project evaluation Project review Prioritization and selection
Long range planning	Competitive analysis O&M cost planning Workforce planning Fuel planning
Budgeting	Competitive analysis Labour estimates Outage, project and fuel budgets Approval, reporting and communication
Plant/fleet valuation	Forecasting Scenario development Scenario, risk analysis and asset valuation

accountable to meet the asset management goals, and most importantly embrace change management. For example, clause 5 of ISO 55001:2014 [3] states the following three requirements of leadership:

— Demonstrate leadership and commitment with respect to the asset management system;
— Establish an asset management policy;
— Responsibilities and authorities for relevant roles are assigned and communicated.

With regard to the demonstration of leadership for safety and commitment to safety GSR Part 2 [14] states:

“**Managers shall demonstrate leadership for safety and commitment to safety.**

“3.1. The senior management of the organization shall demonstrate leadership for safety by:

(a) Establishing, advocating and adhering to an organizational approach to safety that stipulates that, as an overriding priority, issues relating to protection and safety receive the attention warranted by their significance;

(b) Acknowledging that safety encompasses interactions between people, technology and the organization...;
(c) Establishing behavioural expectations and fostering a strong safety culture;
(d) Establishing the acceptance of personal accountability in relation to safety on the part of all individuals in the organization and establishing that decisions taken at all levels take account of the priorities and accountabilities for safety.

"3.2. Managers at all levels in the organization, taking into account their duties, shall ensure that their leadership includes:

(a) Setting goals for safety that are consistent with the organization's policy for safety, actively seeking information on safety performance within their area of responsibility and demonstrating commitment to improving safety performance;
(b) Development of individual and institutional values and expectations for safety throughout the organization by means of their decisions, statements and actions;
(c) Ensuring that their actions serve to encourage the reporting of safety related problems, to develop questioning and learning attitudes, and to correct acts or conditions that are adverse to safety.

"3.3. Managers at all levels in the organization:

(a) Shall encourage and support all individuals in achieving safety goals and performing their tasks safely;
(b) Shall engage all individuals in enhancing safety performance;
(c) Shall communicate clearly the basis for decisions relevant to safety."

5.3. STRUCTURE, AUTHORITY AND RESPONSIBILITIES

Establishing and maintaining an organizational structure of roles, including responsibilities and key performance indicators are essential to have an accountable and effective asset management plan. Reference [28] discusses the organization and staffing lessons identified for improved performance evaluated the experience of the owner/operator's organizational structures and best practices to achieve safety and operational performance. It is helpful to repeat some of the highlights which are aligned with asset management standards:

(a) Organize and staff nuclear power plants using proven organizational design principles:
  — Clearly define the responsibilities and authorities of all organizational units.
  — Design the organization based on the company's vision, and related goals and objectives.
  — Organize work functions and processes to be efficient and effective.
  — Push decision making responsibility and authority as far down in the organization as practicable.
  — Increase the extent of control and minimize layers of management, where possible.
  — Minimize the number and size of administrative support units.
  — Design the organization to be sufficiently flexible to meet changing demands.
  — Train, qualify, develop and motivate staff to meet job requirements.
  — Match staff aptitude with job requirements.
  — Provide enough staff to accomplish all necessary activities that support the company's vision, goals and objectives.
  — Maintain everyone's focus on safety.

(b) Create a learning organization:
   - Establish an environment where change is looked upon as a normal state of affairs, and continuous self-assessment is encouraged.
   - Confirm the need for change and communicate the need to all affected persons.
   - Make a realistic assessment of the situation, and identify the best integrated, overall approach.
   - Set up an experience feedback programme and associated indicators to monitor progress.
   - Consider human related aspects.
   - Manage the change process.
   - Measure results.

(c) Design the organization to help achieve the production's potential of the plant.

(d) Encourage teamwork to improve performance:
   - Reduce interfaces and hand-offs.
   - Form multidisciplined teams.
   - Increase ownership of tasks and/or systems.
   - Increase job satisfaction and provide 'skill broadening'.
   - Team planning/empowerment.

(e) Establish partnerships with contractors and suppliers:
   - Outsourcing is quite common in nuclear power plants. From design and construction to O&M and final decommissioning, the owner/operator used to outsource activities to external vendors. To maintain control and ensure conformity to a plant's asset management system, outsourcing activities needs to be preceded by a risk assessment and action plan.
   - A variety of conditions have to be fulfilled to ensure the full functionality of the external supply system.
   - The decision making mechanisms have to remain under the control of the owner/operator.
   - The owner/operator has to require and control the fulfilment of the qualifying requirements for contractors and their employees.
   - The owner/operator has to maintain the know-how of the relevant departments and the qualifications of their staff at a sufficient level to be able to professionally assign and convey the delivered activities and to check the quality and the extent of their implementation.
   - The owner/operator has to monitor the status of the external contractor continuously (financial health, compliance with legislative requirements, sustainability and development of know-how).

Finally, and most importantly, asset managers need to be assigned throughout various divisions who are accountable for their own assets. Asset managers need to be involved with the programme from the beginning and need to help to define the scope of the asset management programme, including critical asset classes.

Some well known industry standards, such as the Institute of Nuclear Power Operations (INPO) standard INPO AP-913, Equipment Reliability Process Description [29], and the EPRI RIAM development plan [26], recommend that owner/operators seriously consider factoring in the asset management strategy.

5.4. TRAINING, AWARENESS AND COMPETENCE

The competence of personnel is a key element for a well functioning asset management system. The owner/operator needs to be properly trained, have a fundamental knowledge of asset management and have the appropriate level of competence for the relevant positions. People are one of the most important elements in order to generate maximum value from complex process industries, such as a nuclear power plant, independent of whether they are considered as assets on their own (ISO 55000:2014 [2]) or as an enabler (PAS55-1:2008 [1]). This is of course a general prerequisite and not nuclear specific. However, there are a few key elements worth mentioning with regard to the nuclear industry.

As in all organizations, it is important to have training plans in place for each specific role and position. For the nuclear industry, it is important to identify what is particularly relevant for the industry and how to add it to the asset management training programme. The most obvious perspective is of course nuclear safety and the impact it has on asset management.

Asset management is an evolving discipline, and the importance of formal training is becoming more relevant. This can be through holistic training in asset management, or specific training targeting key skills depending on the roles of the individuals. As such, international institutions and standardization bodies have specific training packages. Raising the awareness of asset management and its benefits within a nuclear organization, will help the following benefits to be achieved:

(a) The first benefit is that the general perception increases of how each employee's specific tasks is an important piece of the entire puzzle to meet the overall goals. The line of sight from strategic business goals to specific instructions will be clearer and hence the understanding of why things are done in a specific way. Furthermore, the possibility of finding improvements and identifying flaws will increase as people gain a better understanding of the entire situation.
(b) The second benefit is that raising awareness of asset management with senior management is important as their attention, commitment and actions will affect the rest of the organization.
(c) The third benefit is that it will be easier to set nuclear safety into its correct context. Safety is a fundamental condition for all nuclear operations. A better understanding of the processes and decisions to manage those large assets will increase the awareness of how safety is improved, or at least is maintained, while at the same time being business oriented and meeting commercial goals.

By developing a competence in asset management, the organization will have better possibilities and conditions to increase the returned value from the asset. Since value from nuclear power plants depends on the performance of the plant, it is important to understand the entire asset system and how it is connected together. It is also important to realize that asset management requires the perspective of, and coordination with, many parts of the business. Hence, general knowledge about asset management and what it comprises needs to be a general competence for most people working within the organization.

5.5. ASSET RISK MANAGEMENT

Risk management encompasses many aspects, including financial, commercial, physical, environmental, health and safety concerns. Nuclear asset management involves long term perspective and decision making with complex and multiple interfaces with stakeholders, including technical, financial, regulatory and public acceptance challenges.

Each risk has to be analysed in terms of physical and financial risk to define ways to prevent or mitigate them and ensure overall consistency in priorities and safety management. Methods have been developed in asset risk management.

Structured risk management is key to the effective management of assets and operations. Proper identification of risks ensures that the efforts of the organization are put into the right activities. It is important that major risks for the components and in the operations are identified and mitigated in due time. Risk analysis needs to be carried out through all the steps in the plant's life cycle. The risk based approach needs to be assessed within the following areas:

— Plant status and system health (e.g. damage identification);
— Maintenance activities (e.g. reliability centred maintenance (RCM));
— Inspection (e.g. risk informed in-service inspection (RI–ISI));
— Projects;
— Capital allocation (e.g. investments);

— Reactor safety (e.g. probabilistic safety assessment (PSA));
— Business risks (e.g. environmental hazards, regulatory, society, market).

Risk assessments need to be carried out using well established methods and to comprise at least an assessment of probability and consequence.

Plant status and system health are important factors in asset risk management (see Ref. [10]). The status of the components in the plants has to be surveyed and the likelihood of a failure identified. However, a complete risk assessment might not be necessary at this stage. Rather, a full risk assessment can be carried out in the case where poor system health leads to the identification of mitigating actions, such as replacement or maintenance investments. In these cases, the risk based approach can be adapted to the investment optimization. RCM and RI–ISI are also important tools in identifying system health, and the results from these work processes need to be integrated in the system health process. They are tools for risk analysis for components with the aim of prioritizing inspection and maintenance activities (described in Section 6.7.5).

There are several established models for project risk management. The models are usually qualitative, with assessment of probability and consequence on a scale of, for example, 1 to 5, or semiquantitative with assessment of 'real' values for probability and consequence. Monte Carlo simulations can also be used as a quantitative approach to calculate, for example, the most probable cost increase. Project risk analysis typically covers the risk type time (delay), cost (increase) and quality (lack of).

The risk based approach has, in recent years, grown in importance for investment planning with the aim of ensuring that capital is allocated to the activities yielding the highest value. In this context, value means both monetary and non-monetary, such as safety issues. The probability of equipment failure and the costs of production loss and repair is part of this risk analysis.

As mentioned in INSAG-25, A Framework for an Integrated Risk Informed Decision Making Process [9], PSAs and probabilistic safety targets provide risk metrics to support decisions relating to nuclear safety. This tool has been widely and successfully used in many fields, usually in addition to deterministic and other considerations, from evaluation of simple events for a component to complex analysis for a plant (in a formal PSA). For different types of event (physical phenomena, hazards, human behaviour), it evaluates the consequences quantitatively (failures, reactor core damage, radioactive releases). Hence, a risk management system can take advantage of PSA lessons, if the strengths and weaknesses of a PSA results are understood and considered (see Refs [30–33] for guidance on PSA).

Business risk can be defined in several ways but, in this context, is used as a summary of risks not directly related to assets. These could, for example include environmental hazards causing major costs for the company or politics that threatens future operations of the nuclear power plant. The most important step of risk management is the development of mitigating actions against the risks. This step is unfortunately often neglected or not treated sufficiently and the information from the risk analysis is often not fed back properly to the relevant parts of the organization. An important part of the asset management system is to develop procedures for feedback and initiation of actions, as well as follow-up of the results.

5.6. DECISION ANALYSIS

Section 6.2.2 of ISO 55001:2004 [3] emphasizes the importance of the decision process to determine and document the method and criteria for decision making. The decision making process is a key element of any organization, but it has a particular dimension for nuclear industry risks. INSAG-25 [9] provides the framework for a structured and adapted approach to nuclear industries and describes three main types of evaluation: traditional deterministic evaluations; probabilistic evaluations; and also a field of other equally important considerations (i.e. standards and good practices, operating experience, organizational and security considerations, radiation doses, economic factors). For each category, the key elements are to be identified and prioritized. As with ISO 55001:2014 [3], the framework in INSAG-25 [9] highlights the need for a process that is logical, comprehensive, transparent, reproducible and verifiable.

Any decision has to be informed and accompanied by limitations, uncertainties and sensitivity analysis when relevant. Decision making is intrinsically embedded in any organization, but depending on its size, history, and technical or financial issues, there may be several decision making processes in place for different types of asset. The important thing is to respect the main principles stated above for each process, and that the owner/operator foresees the articulation between all these processes (and the settlement of possible arbitrations).

6. SUPPORTING METHODS AND PROCESSES FOR ASSET MANAGEMENT

Asset management decisions are based on a combination of asset risks, safety requirements and financial optimization. The use of structured risk methods provides a stable foundation for the mobilization of resources for maintenance and investments, but this has to be combined with the requirement of owners for profitability and financial optimization. This section describes methods that can be used to support the decision making for the owner/operator.

6.1. FINANCIAL OPTIMIZATION PRINCIPLES

Optimizing the financial value of nuclear power plants is one of the key drivers in an asset management programme. With growing market competition and stringent budgets, the asset management programme needs to maximize the financial value of the asset. This section introduces some of the financial optimization techniques involved.

From a corporate finance perspective, the economic value, attached to a series of future cash inflows and cash outflows is very often measured by the net present value (NPV). This is the current value of all future cash flows generated by a project, accounting both for capital investments and operating expenditures (cash outflows) and cash inflows from the sale of products and services:

$$\mathrm{NPV}(i,N)=\sum_{t=0}^{N}\frac{R_t}{(1+i)^t}$$

where

t is the time associated with the cash flow;
i is the discount rate (i.e. the return that could be earned on an investment with similar risk);
R_t is the cash inflow at time t;

and N is the total number of calculation periods (e.g. years). NPV considers how capital and operating expenditure and cash inflows are distributed over the economic lifetime of an investment. This metric also considers financial risk associated with the investment, by applying a risk adjusted discount rate (sometimes referred to as the cost of capital) when discounting future cash flows. NPV can be calculated for a single investment but for the entire plant, and then covers all future costs and revenues from the plant. The NPV provides a measure of the economic performance and value of the plant for the owner/operator.

The investment's internal rate of return (IRR), defined as the value of the discount rate that results in an NPV equal to zero, is another key financial metric that can be used as a basis for valuing and comparing different strategies and investment alternatives. IRR calculations rely on the same formula as NPV. Once the IRR is determined, it is typically compared with a company's hurdle rate or cost of capital. From an economic standpoint, preference needs to always be given to the investment alternatives that maximize NPV— or the IRR compared with the cost of capital. The cost of capital reflects the expectations of risk and return in the future and is often referred to as the weighted average cost of capital (WACC):

$$\text{WACC} = \frac{D}{D+E}K_d + \frac{E}{D+E}K_e$$

where

D is the company's total debt;
E is the company's total equity;
K_d is the cost of debt;

and K_e is the cost of equity. The WACC depends on a company's cost of debt and the cost of equity. The company's discount rate used in the NPV calculation is usually equal to the WACC or higher. However, there are other values, apart from economic, that have to be considered for investment decisions, such as enhanced safety. The balance between the financial value and these 'other values' in investment decision making is described in Section 6.3.

Cash flow refers to a stream of money at a point of time. A distinction is often made between cash inflows (positive) generally attached to the sale of products and services and cash outflows (negative) representing expenses.

Discounting is a financial valuation technique used primarily to value a stream of future cash flows. It is based on the notion of time value of money: a dollar is worth more today than tomorrow (see Fig. 5). This figure describes the present and future value of US $1000, 100 years in the future, with various curves representing constant discount rates of 2, 3, 5 and 7%.

The LCOE can be used as a rough measure of production costs to compare between different assets or energy sources. It provides a figure for the production cost on average over time (i.e. it does not vary from one year to another):

$$\text{LCOE} = \frac{\text{Total life cycle cost}}{\text{Total lifetime energy production}}$$

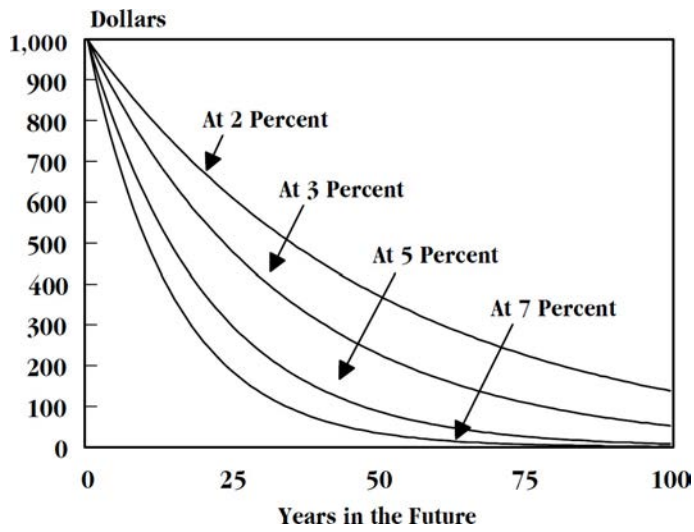

FIG. 5. The present discounted value of US $1000 [34].

The LCOE is commonly used as a basis for comparing electricity generation costs from different technologies. Its scope is limited to the plant (or ‘busbar’) and does not include grid level costs and externalities beyond CO_2 emissions (see Fig. 6). The LCOE depends primarily on construction costs and duration. Decommissioning expenditures can represent a significant amount. However, these costs are incurred tens of years after the beginning of operation and their impact on LCOE is rather limited. The revenue depends on electricity prices and the plant’s output (e.g. the plant’s capacity factor[1]). Excellence in asset management translates into increased capacity factors, lower O&M expenditure, longer operational life and improved economics of power generation.

6.2. LIFE CYCLE COSTS

To maximize value from an asset, the standards emphasize the importance in decision making of considering the entire life cycle of the asset. This avoids suboptimization, and the investment in the asset or the planned maintenance could be done at the point in time where the return on invested value is the greatest.

For the owner/operator, the issue of outages is of specific interest. By combining long term outage planning with maintenance and plant modifications, the risk of prolonged outages is minimized. Furthermore, the balance between maintenance and exchange and/or plant modification is especially important when plants age and their end of operation approaches. Hence, the maintenance alternative and its optimization becomes even more important when a plant enters LTO. A third perspective is the use and optimization of fuel. Since fuel is part of the production cost, having a lifetime strategy for fuel could affect costs.

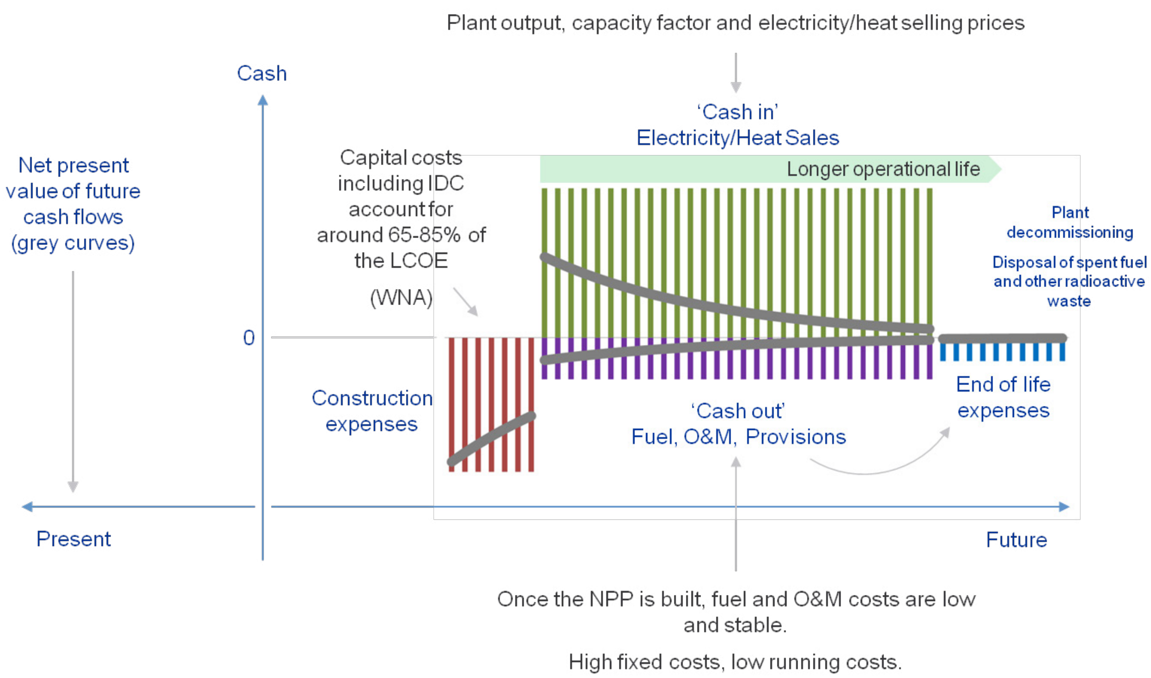

FIG. 6. Factors affecting the levelized cost of electricity.

[1] Capacity factors of nuclear power plants around the world have increased by 10 percentage points since 1990, from 70 to 80%. Levels of 90% and above have been achieved by plants in Asia, Europe and North America for many years.

A lifetime strategy facilitates the management of systems and components, allowing for the correct strategy for each. Depending on the importance of business risk (where safety is a major part), different strategies, such as run to failure, scheduled maintenance, condition based maintenance (or a combination of them), need to be chosen. The maintenance strategy could of course also be combined with a replacement strategy, making sure that the correct status is maintained for the remaining life of the asset, for example the business case could have condition based maintenance until a specified level of degradation is reached. If this degradation is reached before a specified time, replacement will be carried out. If the degradation is reached after the specified time, the risk of failure is accepted and maintenance is increased to be both scheduled and condition based. In the end, it all comes down to the risk evaluation by the asset owner/licence holder which determines what strategy to choose for each part of the asset.

An example of a tool that optimizes the life cycle cost is integrated life cycle management [35], developed by EPRI and Électricité de France (EDF). The methodology relies on the likelihood of failure curves database, maintained by EPRI, and a financial optimization model from EDF to determine the NPV of any specific replacement or refurbishment scenario, and to inform decisions on the purchase of spares and the time of replacement or refurbishment. The analysis can be performed on a specific component basis, a plant basis or a fleet basis. The data required for this analysis include the: cost of replacement or refurbishment; cost of capital; impact on maintenance costs of replacement/refurbishment; and the consequences of failure while in operation. Figure 7 provides an illustration of such calculations. In this example, the component's optimum replacement time is 2025 such that:

(a) Replacing the component before 2025 will result in increased life cycle costs and the likelihood of failure will be relatively low.
(b) Replacing the component after 2025 will also result in increased life cycle costs; the probability of failure will be relatively high; forced outages will be very likely; and the failure rate during operation will incur additional expenses, increasing life cycle costs significantly.

6.3. CAPITAL INVESTMENT

For an efficient asset management programme, it is essential that the capital investments are allocated to activities that offer safe and cost effective production. It is the responsibility of the licence holder to ensure that the allocated investments are sufficient to maintain the nuclear safety of the plant and to keep O&M costs low. Apart from 'has to do' nuclear safety issues, the investments need to be allocated

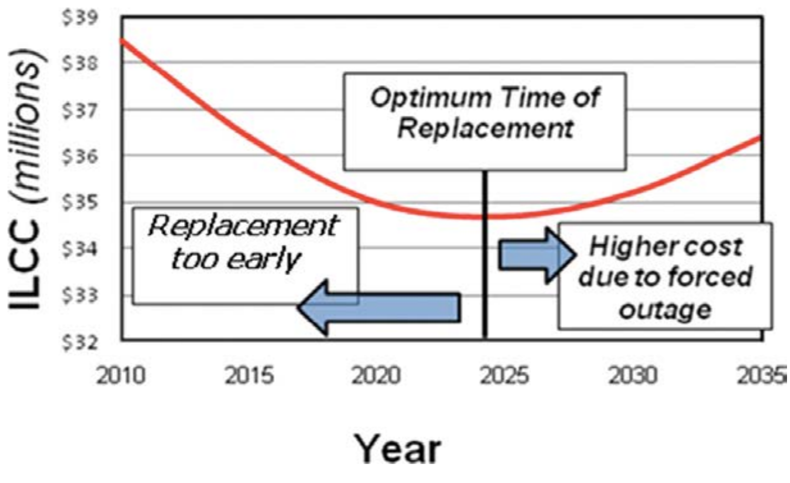

FIG. 7. Component replacement optimization. Source: fig. 1 of Ref. [36].

to activities that give the best value. It is not an easy task, since there are various needs at a nuclear power plant. The necessity for actions on ageing equipment needs to be balanced against other obligations, such as personal safety and reactor safety. For this purpose, risk based methods have been developed which evaluate the risk of not carrying out the investment. In this risk assessment, even reactor safety can be evaluated. However, it requires caution and indicates the involvement of the nuclear safety department at the plant. An important part of the risk based method is the development of the value framework and development of a risk matrix with risk types that cover all stakeholder needs in the organization. The risk types need, at a minimum, to cover personal safety, nuclear safety and economics.

Based on the risk assessment and cost–benefit analysis, the investments can be prioritized and allocated to the activities creating the highest value. In this assessment, it is important to ensure that the future plant status is considered (i.e. that savings in the short term do not cause a degraded plant in the future), causing low availability or even shortened lifetime. The risk based investment methodology is used widely in the conventional industry, but there are only a few examples in the nuclear industry, such as the methodology from Vattenfall (see Annex III).

6.4. REPLACEMENT COST

The strategy for capital investments used by the owner/operator depends on the energy mix (i.e. in the portfolio, profitability, remaining lifetime) and provides guidelines for replacement or maintenance. It also specifies how assessments at the plant/system level are carried out.

Replacement is generally more expensive than refurbishment or maintenance of the component, though the production risk is generally lower. A technical–economic analysis needs to be carried out for the investment, which considers the risk for future production losses compared with the investment cost. This is in line with the methodology for investment prioritization, as described in Section 6.3. In general, the alternative with the highest NPV needs to be chosen; however, the company’s strategic direction could override this decision.

Replacement cost has to be planned and included in the cash flow calculations to assess the economy of LTO. This is especially the case for extensive refurbishment of major equipment (e.g. steam generator replacement, turbine generator overhaul, main transformers, primary pumps, condenser, cooling tower). This can be done in a technical–economic study (see Ref. [37]).

6.5. OPERATION AND MAINTENANCE COSTS

Heavy power generation sectors, such as the nuclear industry, are characterized by a high cost of operation balanced with large power production. Hence, O&M costs are an important part of the business case for the plant. For the licence holder, it is important to optimize and balance the costs against targeted availability and the required nuclear safety level of the plant.

Setting targets for accepted levels of O&M costs (at different levels) balanced against the accepted business risk sets the risk evaluation by the asset owner; that is, depending on what level of business risk the asset owner is willing to accept, the level of accepted O&M costs is set. It is also important to ensure that those parts of the O&M that support the overall strategic goals are prioritized and that other costs not supporting the goals are cut. Furthermore, it is about putting the right levels of allowed costs for each part of O&M. Not balancing means ending up with a ‘deluxe’ solution for some parts and a very basic one for others. This is not necessarily a concern, but it could mean an increased risk to the business. For example, having the best generators in the world will not increase production if the turbine island cannot support it enough to make use of its whole potential. The same concept applies for everything relating to O&M: follow a balanced method to meet the overall strategy at the highest accepted business risk level.

To gain a better idea of where to focus available resources, the asset management standards emphasize the importance of letting the personnel who work close to the focus areas have the mandate to take decisions within each area. By pushing decisions and responsibility downstream, the knowledge and experience from the organization is used. One example is the use of system engineers according to INPO AP-913 [29], where the system engineer has been given a budget for his area.

The level of O&M costs needs to be set in accordance with the requirements of the planned life of the plant, the required reliability of production (setting the optimal level of reliability in terms of costs, production requirements) and safety. In the short term, it can temporarily reduce these costs without any impact on the status of the SSCs and their reliability and safety, but in the longer term, due to lower O&M costs, it may lead to a significant long term reduction in the reliability of operation, with an impact on the overall operating efficiency in the short and long periods.

With regard to the SSCs life cycle (required lifetime) and the planned (required) period of operation of nuclear power plants, it is therefore important to set O&M activities and the resulting costs to support these requirements (targets). O&M costs, as well as investment costs, are a significant component of the total cost of securing LTO of nuclear power plants, and it is necessary to assess their level within the overall costs and complex economics and efficiency of the LTO of the plant.

6.6. AGEING MANAGEMENT

Ageing management is probably one of the most important challenges for LTO. As a result of international concerns, research and much experience in this area, the technical aspects are expected to be addressed in the future. Yet, resources and costs remain key elements when deciding a lifetime extension of a plant. Ageing related phenomena have to be considered to maintain a satisfactory level of safety of the facilities over their extended time of operation (e.g. by 10, 20, 30 or more years). For example, in the United States of America, applications for second licence renewal extend up to 80 years. Plant status and system health are important tools for ageing management. The status of the components in the plants needs to be surveyed and components which are critical for safety and production have to be addressed.

In addition to the continuing work on system health, there are special material related issues in the nuclear sector that are life limiting, such as radiation embrittlement of the reactor pressure vessel (RPV). To avoid large production losses or even early shutdown, it is essential to keep track of potential unforeseen material ageing issues in the plant. This is especially important for the RPV and associated systems (e.g. reactor coolant pressure boundary), where it can be difficult or even impossible, to repair damages. Environment caused cracking, thermal ageing and radiation embrittlement are important degradation phenomena (see Ref. [38]).

Demonstration of the management of ageing is based on operating experience feedback, maintenance arrangements and the possibility of repairing or replacing equipment. Some components cannot be replaced (e.g. RPV, containment). Thus, specific research programmes and in-site inspection are needed. The most critical damage mechanism for the RPV is radiation embrittlement, which can be life limiting for pressurized water reactors. This mechanism can be mitigated, for example by fuel management in order to reduce the neutron flux (radiation dose) to the material, or installation of shielded fuel assemblies.

For ageing and obsolescence management of replaceable components (i.e. reactor internals, cables, steam generators), the long term decision making process needs to be based on maintenance history and end-of-life prognosis. The understanding of ageing mechanisms is the key to defining the lifetime strategy (e.g. routine maintenance or preventive replacement). Equipment qualification for extended operation beyond the licensed life can also become an important issue. Depending on the regulations in individual countries, this may require expensive replacements of SSCs, such as containment cables or various instrumentation and control equipment (see Refs [16, 18, 38–40] for further information about ageing management).

6.7. MAINTENANCE AND INSPECTION

6.7.1. Developing a maintenance strategy

Maintenance is key to managing the nuclear asset, preventing failures or defects in the performance of safety functions and avoiding costly halting of production. A routine maintenance strategy has the goal of maintaining the availability, performance and reliability of functions which are necessary for a safe and economic operation of the plant.

A maintenance strategy will depend on prior analysis of the possible modes of degradation or failure for each piece of equipment, the results of inspection, monitoring, testing and controls, application of codes and rules, collection of experience feedback and, depending on the importance to safety, the classification of each item of equipment. The anticipated lifetime of the plant is also a key factor when deciding the maintenance strategy and the possibility of replacing equipment. Most of the components are replaceable, but major ones like the RPV and containment building cannot be replaced. Nevertheless, operational conditions or limited adaptation or repair can be implemented if necessary. One of the most expensive actions for the LTO of pressurized water reactors is the replacement of the steam generators, but the plant can also benefit from increased thermal efficiency of the replacements.

Planning and preparation for maintenance are key for optimization of outages and assurance of maintaining the required safety functions as needed. Earlier safety and risk analyses have to be implemented to identify the quality and safety conditions for the maintenance activity and requalification after maintenance, for each equipment and at the system level.

Inspection and monitoring programmes of SSCs could facilitate the timely detection and characterization of significant degradation and the assessment of observed degradation to determine the type and timing of any corrective actions required. Inspection and maintenance programmes can be developed using risk based methodologies, such as RI–ISI and RCM (see Section 6.7.5).

Use of data for reliability analysis and integration into PSAs may be a useful tool in order to assess the overall safety significance of the main safety related equipment, and define priorities in the timely implementation of maintenance activities. PSA is further described in Section 6.11.2.

6.7.2. Computerized maintenance management systems

The integrated information management of the core assets (i.e. SSCs) of the nuclear power plant will involve not only the traditional computerized maintenance management system (CMMS) described in this section, but will also involve related functionality to manage secondary assets such as personnel, training, documents, materials, contracts, suppliers, operational experience and knowledge. Not all of these functionalities will exist in one computer system.

It is important to develop an overall information management strategy that recognizes that these systems interact with each other and information from one system is used in another. While this publication cannot describe the complete information management portfolio for a nuclear power plant, it concentrates on the CMMS, which is also called a work management system or an enterprise asset management system [41], which will contain a subset of the functionality (see Fig. 8).

For the management of maintenance at nuclear power plants, a set of software tools is used to help with maintenance processes and to keep them well arranged. The CMMS includes software and database systems for collecting and processing data for maintenance purposes. These systems are an indispensable tool for the optimization of maintenance, efficient use of resources and securing or supporting of reliability management[2] processes (including life cycle management) and configuration management. Computerized management systems collect, maintain, process and utilize operational and maintenance data for failure monitoring, identification of trends and forecasting of failures and, based on such data and trends, optimize

[2] A process of selecting equipment for equipment review for LTO in terms of its safety significance.

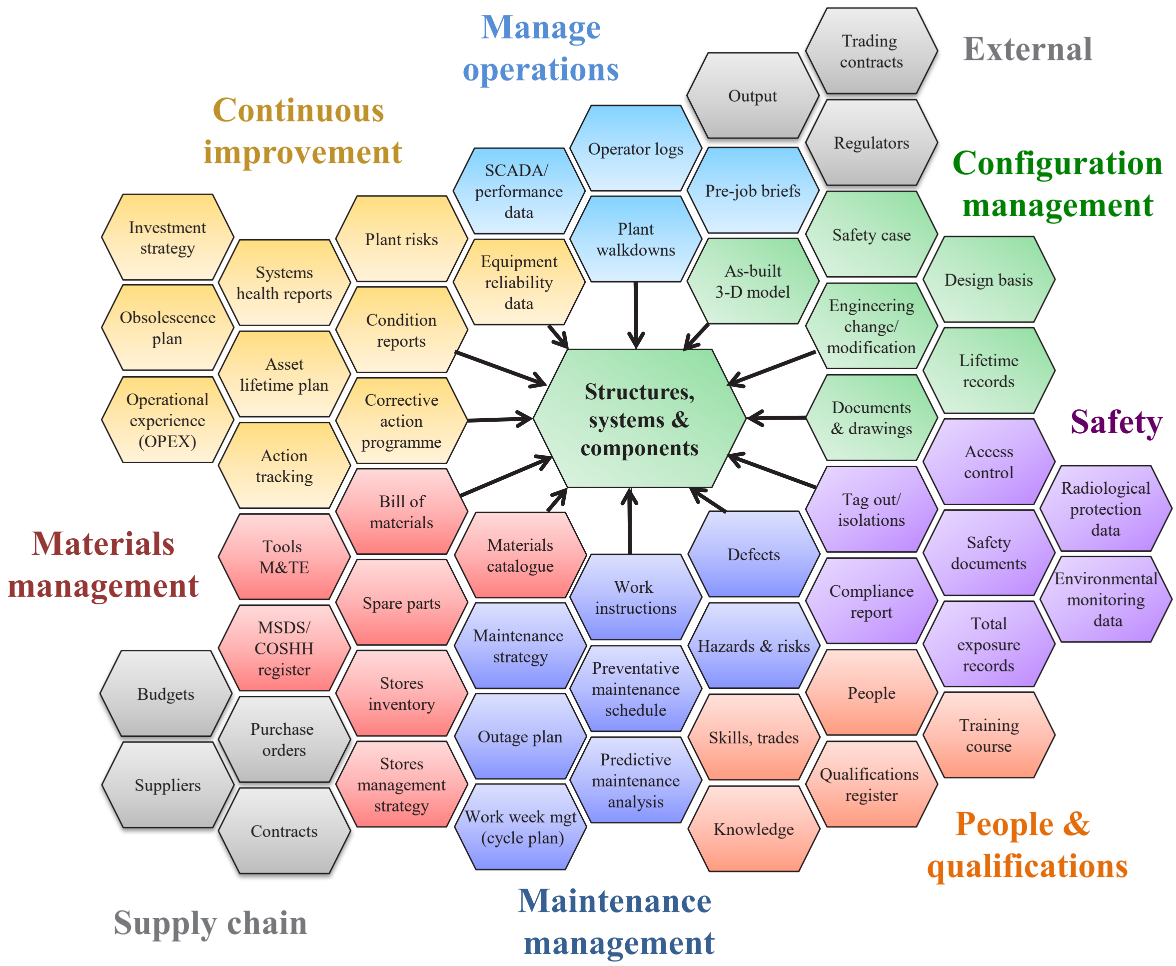

FIG. 8. Extended asset map [41].

intervals and methods of maintenance activities and inspections. RCM and RI–ISI can be supporting methods (see Section 6.7.5).

For the efficient use of software tools in maintenance, it is critical to set up the system appropriately and to employ an efficient approach to the maintenance of SSCs and to classify the SSCs according to their significance in terms of safety (not only nuclear safety but also radiological, fire and occupational safety) and in terms of production (a technological function whose loss leads to an outage or reduction of unit performance, or loss of production, including a prolongation of an outage by more than one day). SSCs are divided into categories with different approaches to maintenance and reliability, ageing management, life cycle management and configuration management.

The amount of information in the enterprise asset management database is optional and will be set up according to the individual needs of the nuclear power plant or individual unit. The basic attributes (i.e. identification, location, plant documentation) are usually contained in the system, while the other attributes can be stored in separate databases linked to the enterprise asset management system.

A properly set-up software system containing correct and up to date information supports the maintenance processes, workflow control, change management, and configuration management and other functionalities efficiently and at optimal cost. In the past, these systems were not available, so many nuclear power plants were built without them and CMMSs were applied during operation. This is not optimal as the entire operation time of equipment or component is not monitored. Nowadays, these systems are implemented at plants during the construction stage and this approach permits recording of O&M data from before the operational phase for reliability and lifetime management. To take full advantage of software systems, it is necessary to collect O&M data continuously for the long term and to store them in a central database or a network of databases for post-processing.

The CMMS works as the central point where all up to date data are maintained. This system can assess and compare the licensing basis, design basis and current conditions and help to fulfil monitoring and oversight requirements on equipment and components, the actual conditions of equipment and components and all maintenance programme changes.

When choosing a software system, it is advisable to acquire a standard system that is widely used, with well tried and tested functionality, ensured by long term service and further development, with the possibility of upgrading and expanding functionality based on separate but connected modules. By implementing such a system, the operator avoids several problems and waste of resources.

6.7.3. Equipment reliability

The equipment reliability programme for critical assets will often be based on a recognized approach, as described in INPO AP-913 [29]. The objective is to ensure that: (i) equipment performs reliably between statutory/refuelling outages; (ii) standby safety equipment operates properly upon demand; and (iii) the equipment is capable of satisfactory performance under all design conditions. The key elements of an equipment reliability programme help to formulate the asset management plan described in Section 4.4 (see Fig. 9):

(a) Identifying critical components: Critical equipment is identified based on its importance to the safety function, safe shutdown capability and power generation capability.
(b) Maintenance plan (strategy): Developed for each component based on criticality. The plan may be as simple as ‘run to failure’, or may involve continuous measurement to predict failure before it occurs.
(c) Performance monitoring/condition monitoring: Equipment and system performance criteria are established, performance is monitored, adverse trends identified and corrective actions implemented and verified for effectiveness.
(d) Failure analysis: Failures, and the causes of failures, are identified for critical equipment and measures are developed to prevent them.
(e) Measuring system and component health (asset health): Predictive maintenance technologies are implemented for critical equipment to detect equipment degradation and to optimize equipment performance.

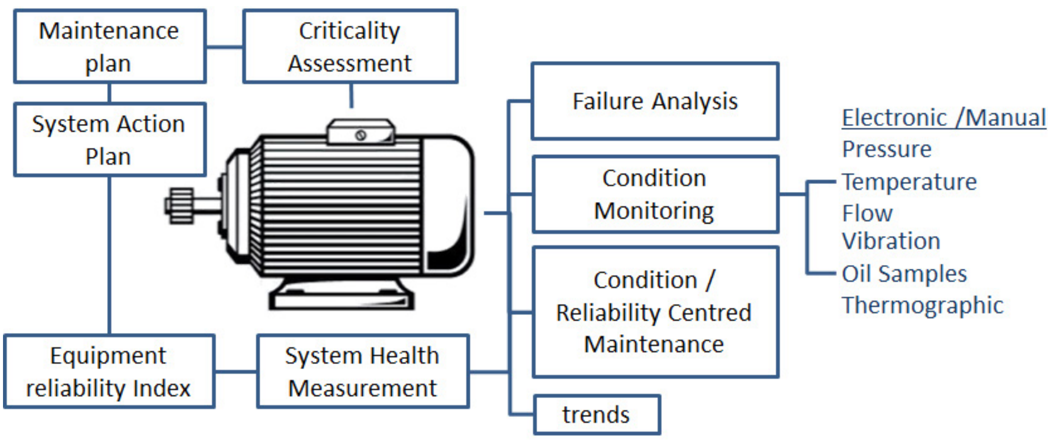

FIG. 9. Key elements of an equipment reliability programme [41].

(f) Equipment reliability index/system health indicator programme: A composite indicator used to gauge the overall performance of plant systems and components. It uses a combination of an overall score, colour coding and detailed scores for the supporting metrics to develop a targeted system of action plans to continually drive improvements in equipment reliability.

RCM can be a supporting method in the equipment reliability programme with the aim of optimizing the maintenance plan.

6.7.4. Reliability assessment tools

Several reliability assessment tools have been utilized by the nuclear industry. For instance, Ref. [42] is a supplement to other IAEA publications about RCM, and provides Members State experience in the application of the principles involved. RCM utilizes tools such as FMECA and reliability data analysis to identify and prioritize planned maintenance activities. Reliability tools need to, at a minimum, include the following features to more closely align with asset management requirements:

— Fault tree analysis;
— Life cycle cost analysis;
— Failure reporting and corrective action system;
— Failure mode and effects analysis;
— Remaining life analysis and life prediction.

6.7.5. Risk based inspection and maintenance

6.7.5.1. Risk informed in-service inspection

RI–ISI is a risk based approach for planning the inspection of pressurized equipment. The term RI–ISI is specific for the nuclear industry, while risk based inspection (RBI) is used in other industries. There are numerous suppliers of RBI and RI–ISI methodologies, which differ somewhat, but the principles are the same: a structured risk analysis with the aim of defining inspection intervals for pressurized equipment (e.g. pressure vessels, pipes). The risk analysis for RBI and RI–ISI is quantitative or semiquantitative. A fully quantitative risk analysis is based on calculation models for both probability and the consequence of a component failure, while for a semiquantitative model some steps are based on ‘engineering judgements’, for example for the consequence of a release of a toxic substance. Identification of inspection methods is often included in RBI and RI–ISI, but can also be carried out later in the maintenance planning step. The key components of RBI and RI–ISI are:

— Identification of possible damage mechanisms for the component (e.g. corrosion, erosion, stress corrosion cracking, radiation embrittlement, fatigue): engineering judgement.
— Identification of the probability of initiation of damage: engineering judgement.
— Calculation of the damage propagation rate and failure probability: based on calculation models (combining engineering judgement with statistics).
— Calculation of the consequence of failure.
— Calculation of risk: probability multiplied by consequence.
— Setting risk acceptance level.
— Calculation of inspection interval (based on acceptable risk).

The principle of RBI and RI–ISI is that an acceptable risk level is defined and that the inspection intervals are calculated so that the remaining risk is below the acceptable level. For high risk components, the damage has to be found before it causes failure. On the other hand, for low risk components a failure might be accepted, due to low consequence, and the inspection interval could be long or inspection even completely omitted.

The main difference between RBI in conventional industries and RI–ISI in the nuclear industry is the effort put in the consequence analysis and calculation of inspection intervals. In RBI, the consequence is often estimated roughly, or possibly calculated by simple models, such as release models for chemicals in the petrochemical industry. In the nuclear sector, consequence is based on the PSA, which is a detailed method for calculating the probability of core damage and the ultimate consequence of a radioactive release. The disadvantage of RI–ISI based on PSA is that the focus is on radioactive release, while direct personal injuries, for example caused by hot steam, are not treated as thoroughly. The inspection interval is calculated with simple and standardized models in RBI, while in RI–ISI it is calculated based on specific component data (i.e. based on damage tolerance analysis). This step often lies outside of the scope of RI–ISI in the inspection planning step.

The major benefit of using RI–ISI is a safer plant, since the inspection is focused on components causing the real risk and not a standardized inspection based on regulations. A positive side effect is also that the inspection costs can often be reduced since ‘unnecessary’ inspections can be avoided for components with low risk.

RI–ISI is a quantitative methodology and its application requires extensive work. The RI–ISI methodology is used widely in the United States of America. Its adoption in Europe is not as widespread, but most nuclear power plants use it for the categorization of equipment and the development of their inspection programmes. The method defines a consequence and probability index and presents it in a simplified risk matrix (e.g. 3 × 3). The probability index is based on the material and the environment and reflects the probability of a failure. The consequence index is based on the system the component belongs to and reflects the severity of a consequence (e.g. risk of core damage). The resulting risk index defines the extent of inspection.

6.7.5.2. Reliability centred maintenance

RCM is a risk based methodology for the planning and prioritization of maintenance activities. It can be part of the equipment reliability programme (see Section 6.7.3). It is used for rotating equipment (e.g. valves, pumps, turbine rotors), while RI–ISI is used for pressurized equipment. The principles of RCM are the same as for RBI and RI–ISI, but the calculation models differ. A major difference is that the focus is on fault modes for the equipment, which is generally identified by FMECA. The probability of failure is then based mostly on statistics, since there are generally fewer material issues to consider, for example valve failure is often due to the wear of steam seals, and not a material degradation mechanism. For some valves, however, corrosion and cracking mechanisms are important issues and need to be taken into consideration. Based on the size and media in the valve or pump, it might be included in the pressurized equipment regulations and is thus handled by RBI and RI–ISI and not RCM. This is true for the valves and pumps that are part of the reactor pressure boundary.

Streamlined reliability centred maintenance (SRCM) is a simplified method for RCM which focuses on the consequence of component failure, using criticality analysis. If the component is judged to be critical according to the defined criteria (i.e. reactor safety, personal safety, production), the component is selected for further analysis of maintenance activities. The maintenance interval and method are then selected based on standard templates from EPRI. Material and corrosion issues are considered, but no calculation models are used.

The disadvantage of SRCM is that it is consequence based rather than risk based, since the first filtering is carried out based on criticality only. This means that the benefits of a risk based method are lost. For example, can a non-critical component be ignored even though the risk can be high, based on a high probability of failure, and it might not be cost effective to be run to failure? The balanced prioritization of maintenance activities based on risk is also lost. The benefit of SRCM is, however, that maintenance activities are based on a structured analysis and provide a significant improvement compared to regular maintenance at quite a low work effort.

6.8. PLANNING AND SCHEDULING

INPO [43] identifies best practices in the scheduling and execution of preventive maintenance and non-preventive maintenance during operation, surveillance tests and any related support activities are recommended to follow best practices. The scope of the process includes:

(a) Identification and prioritization of work.
(b) Work week scheduling, where all work, including defects, to be performed in a specific execution week is identified and prepared well in advance. Equipment is also grouped into functional groups (see Ref. [42] for details).
(c) Preparation, execution and performance review of work (execution plan).
(d) Preventive maintenance delivery programme.

Some work can only be scheduled when the unit is on outage, so there are usually two teams scheduling work at a nuclear power plant. The two types of outage are unplanned (forced) and planned. Unplanned shutdowns, together with outage extensions and load reductions during power operations, will adversely affect the plant's ability to meet targets, as calculated in the business case, and good planning and preparedness seek to reduce the time off-load.

Outage strategy is addressed in many IAEA publications (e.g. see Ref. [44]) and depends on the type of reactor. This publication will not go into those details, apart from the observation that outage maintenance activities are planned years in advance and the CMMS has to be closely linked to a powerful planning tool.

6.9. FUEL MANAGEMENT

Fuel management can contribute to improving asset management, as it offers possibilities to adapt to electricity demand (long lasting trend) or for LTO. It is also a tool for reducing the risk of fuel procurement interruption by diversifying fuel suppliers. Adapting to electricity demand (long term and durable trend) involves the following issues:

— With high demand (long lasting higher market price), the focus is on production and implementing a longer fuel cycle (18 months) using higher enriched fuel or a higher proportion of fuel reloading to reduce the number of outages for reloading. This is the most frequent case for baseload generation.
— If the demand is low (long lasting lower market price), the focus is on cost optimization, with a balance between reduction of the proportion of fuel reload (more efficient average fuel burnup) versus more frequent outage for reloading. It contributes to ensuring the competitiveness of the nuclear power plant.

With regard to lifetime extension, fuel management is an important tool to reduce vessel embrittlement:

— Arrangement of the last cycle fuel at positions close to the vessel can reduce the neutron flux and limit the neutron embrittlement on sensitive points of the vessel (but with an increase in the peak factor at the centre of the core).
— Other possibilities are to add poison rods (with a burning absorber) within fuel assemblies at positions close to the vessel, or to use fresh fuel assemblies with burnable poison at positions close to the vessel.

6.10. COMPLIANCE MANAGEMENT

The compliance regime will depend on the regulatory requirement in each country. For example, technical specifications and limiting conditions for operations are used in the United Kingdom and the United States of America. Operating rules used in the United Kingdom and operational limits and conditions (OLCs) in other countries all specify the limits of operation (e.g. limits of normal operation, limits of design basis, safety limits). For instance, OLCs are developed to ensure that plants operated in accordance with design assumptions and intents. They contain operational requirements for different operational states, including shutdown. These operational states need to include startup, power production, shutting down, maintenance, testing and refuelling. The OLCs need to also define operational requirements to ensure that safety systems, including engineered safety features, perform the necessary functions in all operational states and in design basis accidents.

One of the roles of OLCs is to ensure the operability of safety functions necessary for safety in each of the operating modes (e.g. in-service, shutdown, outage for maintenance and refuelling): control; protection; safeguards; ability to apply incidental; accidental and ultimate procedures; and operability of equipment and systems which have to be available. OLCs can also require the performance criteria of equipment and systems to be checked during testing or monitoring, and which could trigger the need for maintenance.

In this framework, maintenance activities have to be planned in compliance with OLCs, both in-service (limited possibilities or timeline to intervene on redundant safety systems) and in shutdown, especially during sensitive operating modes (e.g. mid-loop operation for pressurized water reactors), during which some safety systems have to remain available (e.g. core cooling, confinement).

6.11. MANAGEMENT FOR SAFETY

6.11.1. Safety strategy

Nuclear safety is the key element in the operation of a nuclear power plant. Ensuring nuclear safety in the maintenance process and maintenance strategy can be achieved using the SSC classification according to the significance for ensuring nuclear safety in compliance with the following:

- IAEA Safety Standards Series No. SSG-30, Safety Classification of Structures, Systems and Components in Nuclear Power Plants [45];
- IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), Safety of Nuclear Power Plants: Design [46];
- IAEA Safety Standards Series No GSR Part 4 (Rev. 1), Safety Assessment for Facilities and Activities [47];
- WENRA reactor safety reference levels [48].

The SSC classification is used to determine the level of safety requirements or part of the mechanical code to apply for a given piece of equipment (e.g. seismic resistance, qualification, monitoring). It is based on the significance for the nuclear safety that determines which technology systems and, subsequently, which equipment and components in the identified systems are significant from the viewpoint of the performance of safety functions and therefore how such equipment and components are significant for safety. The identified equipment and components significant for safety then serve as an input for setting the appropriate maintenance level.

When it comes to the assessment of risk levels of plant operation, an operator needs to have a tool for deciding on an acceptability of a risk level for operation of individual units, allowing determination of the immediate risk according to the unit's current configuration. The unit configuration is determined by:

— Condition of components (inoperability due to degraded function);
— Status of redundant equipment/component and its operation;
— Operation mode of the unit (unit mode or states defined in the given mode);
— Planned inspections increasing the frequency of the initiation event;
— External factors.

6.11.2. Probabilistic safety assessment

When a failure is detected, PSA can help to estimate the time remaining before a shutdown to repair, and in some cases how to reach the state required for the replacement. Risk analysis and monitoring can be based on, for example, the living probabilistic safety analysis (LPSA). LPSA is a regularly updated PSA that reflects the current condition of the project, the plant's operational features and characteristics. The LPSA may have several functions, for example it can be used for the evaluation of the nuclear power plant project in terms of the operational risk of individual units, evaluation of proposed and implemented design modifications or operational and emergency procedures. In maintenance, inspections and outages management, the risk monitoring can be processed for the purposes of monitoring of the risk profile before and when performing on-line maintenance of safety significant equipment.

Safety criteria for the operative assessment of operational configurations are based on the core damage frequency level. Usually, PSA results are embedded in the definition of allowable time for repair and transient as defined in the OLCs in the event of unavailability of equipment or in the amount of time allowed for maintenance with equipment unavailability. PSAs have been widely and successfully used in many fields, usually in addition to deterministic and other considerations, from evaluation of simple events for a component to complex analysis for a plant (in a formal PSA). They are very efficient tools to define the possible incidental and accidental sequences of events and possible consequences with estimated probabilities.

Starting from the frequency of initiating events (i.e. transients, breaks) and taking into account the probability of success or failure of safety systems, which depend on systems reliability (from experience feedback) and operator behaviour (from test on simulators), PSAs enable analysts to derive the probability of core damage (level 1 PSA), external consequences taking into account the containment behaviour (level 2 PSA), and the impact on the public and environment, taking into account emergency planning (level 3 PSA).

PSAs are used as a complement to deterministic and conservative safety approach (which relies on design rules and studies of conventional incident or accident) to identify all possible sequences and to check the overall consistency. Possible and cost efficient risk reduction measures include the following:

— Evaluation of the design basis and identification of weak points;
— Safety reassessment to prioritize issues, elaborate cost–benefit analysis and decide on their treatment;
— Support the elaboration of OLCs and optimization of maintenance programmes.

With regard to asset management, PSA studies are a useful tool to identify risks and critical sequences to assess the overall level of safety. They facilitate the checking of the consistency of operational decision making for asset management and optimization of resource allocation for maintenance, operational measures or possible modifications. In strategy and maintenance planning, PSA outputs can be used in nuclear power plants for the following purposes:

(a) Detecting nuclear power plant vulnerabilities and proposing corrective actions: The PSA method makes it possible to determine relatively efficiently the systems, equipment and activities that most contribute to the risk of failure of safety functions within the operating nuclear power plant. Based on this, appropriate corrective actions are proposed. These corrective actions include, in maintenance particularly, changes in the way the equipment is operated and the method and intervals of equipment testing and the modification of the O&M procedures. This can include, for example, changes in the periods (intervals) of maintenance activities and inspections, identification of entirely new activities and inspections, or their modification and adjustment. All changes made to the maintenance programme are then recorded in the maintenance template for the equipment or component in question and in the operating procedures.

(b) Assessment of equipment inspection intervals and equipment unavailability due to testing and repairs: The PSA model can be used to evaluate the effect of changes in equipment test intervals (i.e. RI–ISI methodology) and the effect of prolonging or shortening equipment unavailability due to testing and repairs. Based on the observed impact on the value of core damage frequency, the acceptability of these changes is assessed or the appropriate adjustments are proposed.

(c) Risk informed outage assessment: PSA outputs are used to establish type maintenance schedules, schedules of individual shutdowns of all units, and to compare the planned outage risk with the actual progress in the safety assessment of previous outages. Mapping and analysing the possibility of on-line maintenance (OLM) is also related. OLM means shifting maintenance activities of safety and safety related systems (that have defined limits and conditions ensuring safe operation of the nuclear power plant) from outages to the power level, resulting in an increase in safety (overall risk reduction) and shorter outages.

Nevertheless, PSAs rely intrinsically on the initial quality of data, with their unavoidable uncertainty levels, and are also limited in terms of considering possible dependencies between systems or human behaviour, common cause failure modes and possible recovery actions. As such, the results need to be considered with care and completed by technical and conservative analysis in compliance with requirements as defined in the OLCs. Thus, human analysis remains important to consider results from PSAs (see Refs [31–33] for guidelines).

6.11.3. Safety culture

Safety culture is a key value in each nuclear organization. The concept was introduced in INSAG-4, Safety Culture [49]. Safety culture helps to reduce human errors at every level of the company and thus protects the assets of the company. Major undesired events (unplanned or longer outages) or accidents are rarely the result of one mistake but instead a series of errors. This is why a wide ranging safety culture is so important. INSAG-15, Key Practical Issues in Strengthening Safety Culture [50], provides pragmatic and practical advice for strengthening safety culture in seven topics:

— Commitment;
— Use of procedures;
— Conservative decision making;
— A reporting culture;
— Challenging unsafe acts and conditions;
— The learning organization;
— Underpinning issues: communication, clear priorities and organization.

6.11.4. Knowledge management

Communication about safety culture can provide general knowledge for all workers of nuclear facilities and suppliers, but to operate nuclear power plants over the long term maintaining expertise is a challenge for safety issues. Thus, research and education are values to consider in an asset management framework. In this context, para. 7 of INSAG-16, Maintaining Knowledge, Training and Infrastructure for Research and Development in Nuclear Safety [51], states that the goal is:

> "to emphasize the importance of maintaining capabilities for nuclear research and education, especially with regard to safety aspects, so that nuclear safety may be maintained in IAEA Member

States, and to alert Member States to the potential for significant harm if the infrastructure for research, development and education is not maintained.”

6.12. SUPPLY CHAIN MANAGEMENT

The supply chain process for a nuclear power plant is geared towards ensuring that it is kept running and so needs to be aligned with the maintenance plans: both the work week management plan and the outage plan (see Section 6.8 on planning and scheduling). Each material item will have its own strategy:

- Will it be kept in the site warehouse?
- Will there be a corporate warehouse?
- Will items be held in the supplier’s warehouse or purchased as required?

The strategy depends on the criticality for the plant of services, purchase and delivery lead times, and costs. Keeping items in stores in case they are required has a cost associated with it, and this needs to be balanced with the risk of not having the item available. For critical components, only compliant plant spares have to be procured, stocked, repaired and installed in the plant. Over the life of the plant, material items may become obsolete or alternatives are sourced for resilience or other reasons (see Ref. [38]). The site needs to maintain control of the substitution of spares and materials which are not in accordance with the original design for use at the plant.

As spares become obsolete there is a need to adequately specify requirements to facilitate repair and replacement to the appropriate standards. The technical evaluation may include evaluation of the following:

- Rebuild/repair;
- Cannibalization of other items (i.e. by taking parts from several items to create one good item);
- Substitution (which will require an equivalency evaluation);
- Reverse engineering by manufacturing an item from requirements and specifications;
- Design change.

Obsolescence can also occur not only when spares become obsolete from their supplier but also when the nuclear power plant makes a strategic decision to use alternative equipment. Note that in this case, any remaining stores need to be disposed to reduce storage costs.

6.13. CHANGES AND IMPROVEMENTS FOR LONG TERM OPERATION

The investments necessary for the LTO of nuclear power plants are important, and pose risks to the financial survival of many operators. In general, the costs associated with such longer operations are lower than the commissioning of new nuclear plants.

The most necessary investments are related to maintenance issues to preserve the state of the installation with unchanged requirements (including ageing). However, LTO means often increasing requirements following continuous improvement, state of the art knowledge of safety cases or periodic safety reviews.

6.13.1. Meeting new requirements

New requirements generally result from significant operational lessons learned from other reactors (e.g. lessons learned from the accident at the Fukushima Daiichi nuclear power plant) or comparisons to the requirements applied to more recent reactors. The evaluation of their impact on the installation is to be weighed in terms of their interest in safety. In fact, a too complex exploitation or design can harm the global interest in safety, which is why a rigorous process has to be followed to analyse all the impacts. This is a pathway to the Principle 5 of SF-1 [13]: "**Protection must be optimized to provide the highest level of safety that can reasonably be achieved.**" SF-1 [13] continues:

> "3.21. The safety measures that are applied to facilities and activities that give rise to radiation risks are considered optimized if they provide the highest level of safety that can reasonably be achieved throughout the lifetime of the facility or activity, without unduly limiting its utilization.
>
> "3.22. To determine whether radiation risks are as low as reasonably achievable, all such risks, whether arising from normal operations or from abnormal or accident conditions, must be assessed (using a graded approach) a priori and periodically reassessed throughout the lifetime of facilities and activities. Where there are interdependences between related actions or between their associated risks (e.g. for different stages of the lifetime of facilities and activities, for risks to different groups or for different steps in radioactive waste management), these must also be considered. Account also has to be taken of uncertainties in knowledge.
>
> "3.23. The optimization of protection requires judgements to be made about the relative significance of various factors, including:
>
> — The number of people (workers and the public) who may be exposed to radiation;
> — The likelihood of their incurring exposures;
> — The magnitude and distribution of radiation doses received;
> — Radiation risks arising from foreseeable events;
> — Economic, social and environmental factors.
>
> "The optimization of protection also means using good practices and common sense to avoid radiation risks as far as is practical in day to day activities.
>
> "3.24. The resources devoted to safety by the licensee, and the scope and stringency of regulations and their application, have to be commensurate with the magnitude of the radiation risks and their amenability to control. Regulatory control may not be needed where this is not warranted by the magnitude of the radiation risks."

The principles of risk informed decision making, described in INSAG-25 [9], are particularly well suited to analyse all the key factors associated with design changes. This includes a global look at the installation and other issues facing the owner/operator (maintaining compliance, ageing, obsolescence), with a pertinent look at the resources to be allocated. Indeed, the process described in para. 17 of INSAG-25 [9] enables "a comprehensive and balanced understanding of an installation's risk spectrum allows effective use of resources to address the more risk significant aspects while conserving resources that would otherwise be applied to less risk significant aspects."

Paragraph 8 of INSAG-25 [9] states that this "process brings transparency to complex decisions involving several key factors", and these "factors may be of different forms and can be weighed differently to reflect their relative importance to the situation under consideration." In this situation, uncertainties and regulator's requirements have to be considered.

The understanding and use of the reasonably achievable concept may differ between States. There is a wide range of national legislation, licensee applications or regulator acceptance on that concept; however, INSAG-25 [9] provides the key elements to implement and achieve such a concept for every operator.

In 2017, WENRA [22] provided guidance on art. 8a of the EU Nuclear Safety Directive. The framework of the guidance for implementation of reasonably practicable improvements is built on six aspects, with parallels to INSAG-25 [9]:

- Consideration of defence in depth;
- Role of PSA;
- Equivalence of outcomes and proportionality;
- Decision making;
- Timely implementation of safety improvements;
- Role of cost.

Studies demonstrate that new requirements are fulfilled with the actual design of the plant. Sometimes design changes are implemented at the installation for optimization and cost reduction. It may be appropriate to integrate or anticipate problems associated with ageing and obsolescence on components and systems (see Section 6.13.3 on plant modifications).

6.13.2. Addressing safety cases

A safety case is defined as a safety issue to be addressed with regard to existing applicable requirements, as opposed to design changes which need to meet new requirements. Non-conformity (of components or studies), unavailability of components or new knowledge are the main types of safety case.

For all licence renewals or periodic safety reviews, checking of the conformity is one of the key points to consider in an application for LTO. The objective of the review is to demonstrate and fulfil the applicable requirements. The challenge is to decide the best options when gaps are detected with regard to the remaining lifetime of the plant and the level of the issue.

The principles of INSAG-25 [9] are also well suited for the analysis of all the key factors associated with safety cases, even if the number of key factors is probably lower than those for design changes:

- Standards and good practices;
- Operating experience;
- Deterministic considerations;
- PSA (see Section 6.11.2 on PSAs when a failure is detected);
- Organizational considerations;
- Security considerations;
- Other considerations (radiation dose, economic factors, research results).

When design changes are to be implemented on the installation, some optimization needs to be addressed (see Section 6.13.3 on plant modifications).

6.13.3. Plant modifications

Plant modifications are defined in para. 4.1 of IAEA Safety Standards Series No. NS-G-2.3, Modifications to Nuclear Power Plants [52] as "as any permanent or temporary alterations to structures, systems and components, process software, operational limits and conditions, or operating procedures. This includes any replacement or refurbishment of existing structures, systems and components". It also covers any proposed experiments and non-routine tests, which change the state of the plant in a manner that may affect nuclear safety (see Refs [53, 54] for a description).

The plant modification process has to ensure that the principle of configuration management is maintained. In an operational plant, the configuration data (whether or not held electronically) in the plant databases have to conform to the physical configuration of the plant and to the design and licence requirements. The plant modification process therefore has to include the following:

— Changes to documents, and other data, including the 3-D model;
— Changes to the physical plant;
— Changes to the safety case or design basis;
— Planning of the change;
— Information and training of operators.

The process also has to ensure the design integrity of the plant. It is important not to introduce, through plant modifications, a safety regression at the installation, either during the implementation and requalification phase, or during the operation phase. Indeed, the overall benefit of these changes has to remain positive. Analyses carried out during assessments of issues generally consider this risk; it is preferable to extend this type of analysis at the time of the final design.

In addition, it is common to implement several LTO modifications on the same systems and components (e.g. ageing, obsolescence, new requirements, new knowledge) When a plant modification is necessary, its design may sometimes be optimized to address several issues in a timely manner to minimize costs.

Finally, the design of an LTO modification has to consider the remaining life of the installation. The nature of the equipment, or the complexity of its operation, needs to be put into perspective to define the best options according to the situations (+10 years, +20 years or longer) if this remaining life can be evaluated without having to consider too many uncertainties. It is important to keep in mind that after 30 or 40 years of operation, the plant has acquired substantial experience which has to be maintained so that the appropriate level of changes can be necessary for continued safe operation.

6.13.4. Maintaining the design integrity of nuclear installations

Whatever changes or improvements are implemented in the plant, every nuclear organization needs a full understanding of those modifications, and their impact throughout the lifetime of the installation. This is described in INSAG-19, Maintaining the Design Integrity of Nuclear Installations throughout their Operating Life [55].

6.14. STAKEHOLDER INVOLVEMENT

Stakeholders are part of the assets of a nuclear power plant and thus stakeholder involvement is a key aspect of an asset management strategy. Paragraph 5 of INSAG-20 [25] states four main purposes:

> "(a) to advocate open, transparent, factual, timely, informative and easily understandable multilateral communications among members of society and those who are operating or regulating nuclear facilities or developing a nuclear project; (b) to establish that substantive stakeholder communications contribute to the safe operation of nuclear facilities; (c) to present the major attributes of an effective communication programme; and (d) to discuss ways and means for the efficient and rational involvement of stakeholders in the consideration of nuclear issues."

When stakeholders are well engaged, they will take better care of the assets of the company and strive to optimize them.

7. ASSESSMENT OF ASSET MANAGEMENT PROGRAMMES

This section introduces several methods of reviewing the implementation and benefit of an asset management programme.

7.1. PURPOSE AND OBJECTIVE

The objective of assessing asset management programmes is to ensure compliance of each component with the objectives of the owner/operator. This means that all asset management components fully and functionally support the corporate objectives of the owner/operator and the objectives of each plant.

The purpose of asset management assessment is to identify the strengths and weaknesses of the system and the areas for possible improvement, the establishment of corrective actions, their implementation and appraisal through future evaluations. The effectiveness and appropriateness of the asset management strategy needs to be periodically reviewed based on the performance of the system. An assessment of the effectiveness of leadership and commitment associated with the delivery of the strategy needs to be an integral part of the asset management strategy.

Forms of asset management assessment can vary, from self-assessment of individual levels and components of asset management, through benchmarking (external, internal), to international external audits based on international missions. Figure 10 shows the linkage between asset management objectives, strategy and plans and different types of audit performance. This linkage gives the line of sight for each level of the asset management framework. The clear line of sight provides an opportunity to offer feedback and improves the asset management system on the correct level, based on the result of the assessment. A high level of transparency also facilitates the possibility to use results from one level to improve the other levels.

7.2. SELF-ASSESSMENT

Self-assessment is the method used by managers/guarantors to assess and identify opportunities for improvements within their own organization, department, process or activity. It is an effective tool, providing high quality and objective information on the state of the systems, projects and processes. The basis of self-assessment is to compare the current performance of a company, department, process or activity with standards, best practices and managerial expectations to find and treat areas for improvement.

The evaluator of the self-assessment is also the person responsible for the area to be evaluated. A key condition for successful self-assessment is to be open and, at the same time, critical of one's own activities. Therefore, an appropriate environment, including a clear declaration of deficiencies, has to be established before the self-assessment.

Internal audits can be considered another type of self-assessment. In this case, the auditor is a person working outside of the evaluated area but is still from the company and is well acquainted with activities within the evaluation area.

The contracting authority needs to clearly define the scope and extent of the self-assessment as well as the standard to which the evaluated activities will be compared. It is also important to pay attention to the right selection of the leader and members of the self-assessment team. A self-assessment team is formed from employees of different expertise who are well acquainted with the assessed activities and processes.

First, the self-assessment facts are collected. It is advisable to carry out the observation of the evaluated activities and to discuss the facts with the participants of the process. The identified facts have to be subsequently verified in the management documentation. The next part of the self-assessment is

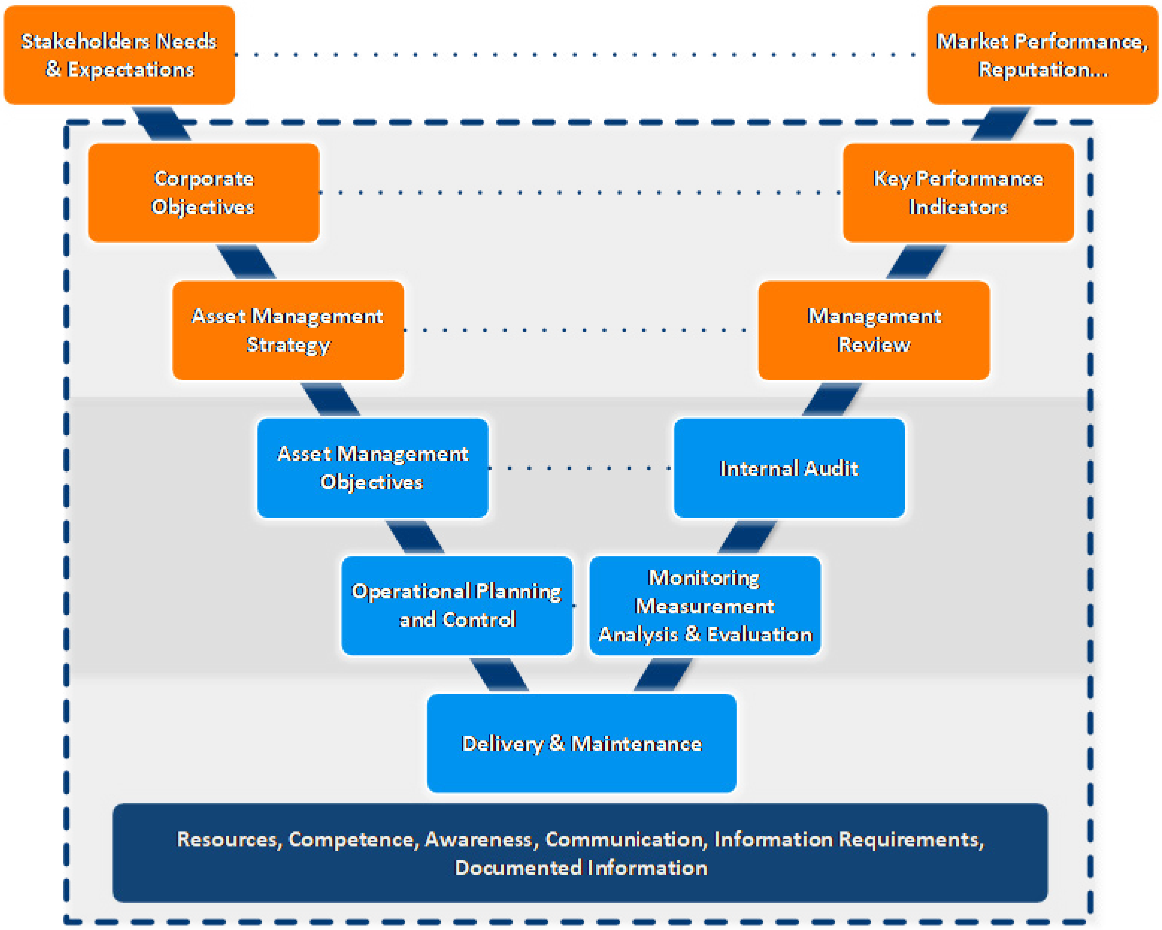

FIG. 10. Asset management assessment process.

sorting out the findings, defining the problems as areas for improvement, determining the root causes of the problems, and elaborating a structured proposal for improvement. Self-assessment outcomes have to be reviewed by the sponsor of the self-assessment (see the Vattenfall case study in Annex III for further details on the use of self-assessment).

7.3. BENCHMARKING

Benchmarking is another tool that can be used to assess and improve the settings of the entire or partial asset management system, and can be also considered as a tool for self-assessment. The comparison can be comprehensive; that is, it can include benchmarking of all components of asset management (e.g. strategy and maintenance planning, life cycle management, maintenance implementation, preparation and management of outages and work), or it can be a comparison of only partial areas which the operator identifies for improvement or where the operator does not achieve the desired results and quality. The detailed level of benchmarking can focus on a specific technological system, equipment, activities and methods, such as categorization and classification of certain SSCs, setting of specific parameters of maintenance of SSCs (e.g. periods of activities and inspections), implementation of individual ageing management programmes, their extent and mitigating the effects of degradation mechanisms.

It is possible to use external benchmarking (between nuclear power plants or units of different operators) or internal benchmarking (between plants of the same operator). However, this makes sense only if the comparison involves comparable units in terms of their concept and performance (e.g. pressurized water reactor, boiling water reactor, Canada deuterium–uranium reactor) working in the same load regime (baseload or flexible operation) and with similar or better aggregated indicators of asset management, such as unit availability or their reliability, and the specific maintenance and investment costs, so that the comparison is useful and can lead to improvement in the areas being benchmarked.

A prerequisite for performing any type of benchmarking is a thorough knowledge of compared processes, procedures and overall context. Based on this understanding, a benchmarking framework can be created. Outputs of benchmarking are proposals for improvement that need to be further elaborated into specific systems or partial changes and projects. After their introduction and implementation, these changes need to be assessed and, if the expected outcomes have not been achieved, corrective actions have to be proposed and implemented.

7.4. EXTERNAL ASSESSMENT

External assessment of asset management can be performed through national or international analysis, audits and missions aimed at a comparison of activities and processes practiced by an operator at a nuclear power plant with national or international requirements or good practices. Specific recommendations and suggestions for improvement are formulated as an outcome of such audits and missions. In the case when unique excellence outcomes in some areas are identified, these are described as strengths and can be labelled as good practices after a subsequent multilevel assessment by the IAEA and become an example and recommendation for other nuclear power plant operators. Implementation of recommendations and suggestions from the assessment and also following good practices lead to increasing levels of the assessed areas.

To maintain achievements of international and national requirements, it is advisable to organize periodic expert missions: either complex, thorough and profound focusing on many processes and areas; or as a mission focused specifically on a selected asset management area. After the regular mission, a follow-up mission takes place over a period of several years, most often after two years. Follow-up missions evaluate the level of implementation of recommendations and suggestions.

Explicit asset management missions or peer reviews are not yet being performed by the IAEA, but asset management elements can be addressed under the existing scope of peer reviews, such as Operational Safety Review Team (OSART) missions and Safety Aspects of Long Term Operation (SALTO) missions. The SALTO peer reviews are comprehensive safety reviews addressing strategy and key elements for safe LTO, including their economic viability. With regard to OSART missions, the IAEA currently provides reviews in 15 areas, of which the following relate to asset management: O&M, technical support, LTO, commissioning and the transitional period from operation to decommissioning. External assessment can also be performed by the certification process for international asset management standards (e.g. see ISO 55000:2014 [2]) to verify that all activities are carried out in accordance with the standards.

8. SUMMARY AND CONCLUSIONS

Nuclear power generation continues to play a major role in meeting the world's electricity demand. In a rapidly evolving power generation mix of wind, solar, energy storage and traditional fossil generation, clean and emissions free nuclear power, with a low marginal cost of generation, will allow States to develop intensive and adaptable low carbon power generation, meet their sustainability goals, and support United Nations SDG [7] of affordable clean energy and sustainable cities and communities.

For several decades, the outlook for nuclear generation was positive, with States evaluating new builds as well as the LTO of existing nuclear facilities. More recently, however, the prospect of nuclear has come under pressure from myriad sources, including lower wholesale electricity prices, higher O&M costs of operating nuclear facilities, cheaper wind and solar generation technologies, lower natural gas prices in some regions, slower electricity demand growth, more stringent safety regulations, ageing assets, the need for flexible non-baseload power, and to some extent negative societal and governmental perception.

This publication demonstrates how to apply the concepts of asset management to facilitate sustainable, nuclear power plant operations. Most mature organizations already employ methodologies that can be used to implement an asset management programme: asset integrity management; RCM; fitness for service; reliability availability maintainability; FMECA; RBI; root cause analysis; and the RIAM programme.

Most programmes have traditionally focused on physical assets at power plants; however, asset management, as described in this publication, expands their purview beyond the equipment at a nuclear facility. This is an important distinction. It is important not to limit the definition of assets to the physical equipment but to expand the definition to intangible assets, such as safety, human capital (personnel), data, software and other technologies, and knowledge.

Asset management identifies the activities needed to support the operational objectives and strategically ensures they are aligned. It provides an ability to understand how decisions support, or are influenced by, corporate objectives.

The goal of asset management is to ensure that the economic value of the nuclear power plant is maintained, including the safety level and benefit of clean generation, and is recognized by society and the markets. The expected outcome of an asset management programme is to ensure that nuclear power plants enjoy an efficient, predictable and safety focused regulatory framework, a fair market, and an equitable economic, environmental and social environment commensurate with the benefits to society. As this publication describes, along with some of the case studies listed in the annexes, there are several expected outcomes of an asset management programme for nuclear power plants:

— Make the right decision;
— Function effectively;
— Realize value from assets;
— Optimize life cycle costs;
— Identify and manage risk (financial, physical);
— Optimize maintenance activities;
— Extend lifetime operation.

The effectiveness of asset management in ensuring that the owner/operator realize these benefits is based on the execution of enabling activities, such as business risk assessment, resource planning and competency management. These activities need to be delivered with strong, coordinated leadership through all levels of the organization, and with the recognition that decisions made through asset management are based on the overall value to the business rather than the performance of an individual system while maintaining safe operations. Building on the nuclear industry approach to maximize availability and safety, risk based methodologies are essential to support the prioritization of activities to balance all key factors and deliver effective asset management and cost effective and safe operations.

This publication is not an implementation template. Case studies explore how some operators have implemented asset management programmes in their organizations and continue to assess and monitor their respective programmes. Standards such as PAS55-1:2008 [1], ISO 55000:2014 [2] and NEI AP-940 [4], provide details on how best to implement asset management programmes. These standards define minimum competence for asset management and have their limitations. However, a properly applied asset management programme will lead to improved prediction of industry uncertainties, prevention of equipment failures and higher regulator confidence, as well as optimizing economics of operation.

In several countries, nuclear power plants, owners and their investors have been caught off guard and are now reacting to changing conditions. An asset management strategy that includes the entire nuclear plant organization, which is flexible and agile to evolving market conditions and considers long term value rather than a sole emphasis on short term cost, needs to help the nuclear asset owner/operator tackle today's uncertainty and prepare for long term challenges. A well established asset management programme can provide several quantifiable benefits and can support long term safe and economic operation of a nuclear power plant.

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Annex I

CZECH REPUBLIC: ČEZ CASE STUDY

This annex focuses on long term operation (LTO) at ČEZ as an example of the benefit of asset management.

I–1. LONG TERM OPERATION OF THE DUKOVANY NUCLEAR POWER PLANT

I–1.1. Nuclear energy programme in the Czech Republic

As the project lifetime of Czech nuclear power plants approaches the end and new built projects will take at least 20 years, LTO acts as an important bridge between the plants currently in operation and future ones. With respect to commitments to reduce CO_2 emissions resulting from the 2015 Paris Convention, it is important that electricity production from nuclear power plants does not fall from the current 40%, as there is a limited possibility to use other sources of energy that are low in CO_2 production due to natural conditions (i.e. number of solar days is lower compared to more southerly regions, limited wind potential).

A further argument for LTO is the Government's demand for permanent self-sufficiency in electricity production and not to increase dependency on imported energy sources such as gas and oil. The State energy concept is therefore to increase the share of electricity production from nuclear power to 50% by 2040.

ČEZ gives LTO provisions great attention and variants of LTO length are comprehensively assessed regularly in terms of the condition of plant technology, LTO economy and possible risks and uncertainties threatening LTO. The department for asset management at ČEZ conducts a technical–economic study of LTO of both plants every five years. This annex briefly describes the study on the Dukovany nuclear power plant, prepared in 2014–2016.

I–1.2. Analytical support of long term operation

A technical–economic study is a complex assessment tool combining technical and economic approaches to evaluate the feasibility of LTO. The study had to cover significant input changes, including post Fukushima measures, new atomic law requirements, electricity price development and LTO action plan measures as recommended by the State Office for Nuclear Safety (SÚJB). It is a basic source of information for strategic decisions on operation of the Dukovany nuclear power plant after 2027. The result of the study are economic calculations based on the outputs from the cost driver's assessment in the technical part of the study — net present value (NPV) of the variants of the LTO (+20 years, +30 years) as the main parameter for the selection of the optimal variant, sensitivity analysis of the main parameters and the main risks associated with LTO. The output of the study is to determine the optimal variant of LTO and to define the basic assumptions and conditions for its collateral.

I–1.3. Technical part of the study

The methodology is based on IAEA-TECDOC-1309[1] and assesses all life limiting and cost important structures, systems and components based mainly on existing results of assessment management plans,

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Cost Drivers for the Assessment of Nuclear Power Plant Life Expansion, IAEA-TECDOC-1309, IAEA, Vienna (2002).

human resources and expert estimates and the assessment of other cost drivers, such as operation and maintenance, high level waste and spent fuel management, decommissioning and maintaining expertise.

The result of the assessment is a set of all the necessary measures (or actions) for the various LTO options considered, including the determination of their costs and the dates of implementation. Costs are determined economically conservatively; that is, if the problem can be solved in a variant, the most expensive option is chosen for the economic calculation. The implementation dates were also set with regard to the cycling of the shutdowns. These measures are presented in the overall LTO investment plan of the plant.

I–1.4. Economic part of the study

The objective of the economic part is to determine the NPV of the assessed LTO (+20 years, +30 years) variants, including the decommissioning phase (until 2085), as the main parameter for their comparison and selection of optimal variants.

Various scenarios of electricity price developments were used in the calculation to evaluate new opportunities across ČEZ. Within the reference price scenario (central scenario), downside and upside scenarios with the greatest impact on evaluation outputs as part of the variance resistance test were also evaluated based on the outputs of the sensitivity analysis of the main parameters (e.g. availability, nuclear fuel costs, cooling water costs, fee for the permanent storage of spent nuclear fuel, personal expenses, maintenance costs, capital expenses, decommissioning costs). The economic model calculates the cash flow discounted by the weighted average cost of capital in individual years. The amount of discounted cash flow is then the NPV of LTO operation.

I–1.5. Risk analysis

An integral part of the study is the identification and evaluation of the risks to the LTO of the Dukovany nuclear power plant in the evaluated LTO variants. It is methodologically processed in accordance with applicable international standards for risk management and ISO 31000:2018.[2]

The risk register contains 111 risks, 74 opened. Some of the analysed risks are critical — high score in inherent level (without application of measures) for both LTO variants. Their impact may be to terminate the operation of the units before the target date, either because of the withdrawal or non-renewal of the operating permit or the low or negative economic efficiency of the operation. A significant portion of the risks, even critical, are growing over time: 15 high risks at inherent level and 5 after application of measures were identified for LTO+20, 26 high risks at inherent and 11 after application of measures were identified for LTO+30. LTO+20 is less affected by the risks and from a risk point of view is the optimal variant. For all risks, proposals for corrective actions were presented.

I–1.6. Conclusions of the study

The optimal variant in terms of NPV, resistance downside scenarios, uncertainties and risks is the operation until 2035–37 (50 years), with the possibility of longer operation if the development of the main determinants (electricity prices, investments and their impact on availability, uncertainty and risk) is positive. To ensure the efficient operation of the horizon optimal variant is in addition to ensuring the required state of technology and project and mitigating the most serious risks, it is necessary to fulfil other basic prerequisites and necessary conditions in key areas:

- Ensuring enough sufficiently qualified and motivated staff;
- Ensuring the highest level of professionalism and quality of all management processes;

[2] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Risk Management: Guidelines, ISO 31000:2018, ISO, Geneva (2018).

— Ensuring a functional and comprehensive knowledge management in nuclear processes;
— Maintaining a high level of acceptability of nuclear energy and the operation of the Dukovany nuclear power plant by the public;
— Long term conservation and increasing the capabilities and stability of key suppliers.

Fulfilling conditions contribute or lead to the mitigation of some critical risks.

I–2. ASSET MANAGEMENT LOOP: RESOURCE ALLOCATION PROCESS FOR PLANTS OPERATED BY ČEZ

Operation planning and resource allocation reflects the importance of nuclear power plants in the ČEZ portfolio, focusing primarily on ensuring nuclear safety, availability and creating conditions for the LTO of nuclear units. The approach described below applies equally to all operating units, considering their status and individual needs. The proposal for the allocation and confirmation of the claimed resources takes place independently of other sources of the ČEZ production portfolio.

The long term concept (LTC) is the key document prepared by the department for asset management and is prepared with representatives from the plant and from key departments (i.e. nuclear safety, nuclear engineering, fuel cycle, human resources, group asset management, market analysis and forecast, new built projects). Part of the input is either submitted or commented on by Nuclear Research Institute Řež, which acts as the technical support organization in the operation of nuclear power plants in the Czech Republic. The main LTC inputs include the technical–economic study of LTO and the map of risks and opportunities. LTC is implemented through a mid-term plan for the plant site and annual assignment for the site. The mid-term plan focuses on safety, operational and technical and economic requirements imposed on plants and is prepared together with representatives from the plant and from the key departments. In addition to key operational parameters, the mid-term plan also sets goals relating to projects and modifications that are critical for safe and successful operation. The annual assignment for the plant site reflects the LTC and the mid-term plan in greater detail, setting limits on operational costs and capital expenditure for asset management, all translated into safety, process, technical and financial key performance indicators.

Assurance of safe operation and LTO maintenance are not possible without continuous identification, assessment and mitigation or minimization of risks. Risk analysis is one of the key inputs in the allocation and defence of resources. Risk maps are generated from several key input sources, such as the plant's status report, health report, non-compliance and event monitoring system and inputs from departments providing support to nuclear operation. Updating risk maps is ongoing, and prioritization takes place on a quarterly basis or as required at the director level (e.g. divisional director, nuclear safety director, plant directors, plant engineering director, asset management director). The risks are subsequently split, integrated into the plans and addressed according to the severity and impact on the plant.

Financial aspects of risk management are translated resource allocation requirements and are part of budgeting process. The budget is prepared in two phases. The first is prepared in the middle of the calendar year and is indicative; the second is the final entry for the board of directors. Other key inputs for the budget process are the maintenance plan, the production technology revitalization plan and the requirements from current legislation. The budget proposal is discussed in a workshop with the group asset management and central controlling departments.

ČEZ established advisory committees to create the conditions suitable for meeting the interests of ČEZ to maximize the value of the portfolio assets. These committees provide technical advice and support in assessment of financial claims coming from the nuclear departments.

Plant equipment is categorized based on the impact on nuclear safety, which in turn determines the extent and frequency of the maintenance to be performed. Based on the requirements set out in the maintenance strategy, a maintenance programme is created, which is the key input for the budgeting process and procurement of the maintenance services. Procurement conditions consider requirements on supplier qualification that have to be not only translated to contracts but also to requirements for ongoing vendor evaluation and qualification processes. An integral part of this activity is the assessment of the effectiveness of maintenance activities in-house or through outsourcing. The maintenance strategy reflects the legislative requirements imposed on the supplier through requirements for their qualification and performance evaluation. Supplier compliance with the qualification requirements is ensured through regular monitoring of compliance with legislative requirements linked to activities critical to nuclear safety. Vendor performance monitoring also takes the form of a broad spectrum assessment. It is a feedback tool used to optimize processes in maintenance and device modifications.

The evaluation of the maintenance programme, supplier performance (supplier activity reports, conclusions and findings of the audit activity), the plant equipment status (status reports, health reports), approved production technology revitalization plan and new requirements represent the basic source for an update of the plant equipment maintenance and modification programme. Qualified safety and financial evaluation of these requirements represent key input for the resource allocation necessary for the budgeting process. Finally, it creates the space for additional requirements on random maintenance and smaller investment activities. There are three key areas of assessment:

- Plant operation is compliant with the licence and other legal obligations;
- The overall plant performance has a positive trend (based on performance indicators from the World Association of Nuclear Operators);
- The economics of operation is in line with shareholder expectations (earnings before interest, taxes, depreciation and amortization, NPV of LTO support operation sustainability).

Annex II

FRANCE: ÉLECTRICITÉ DE FRANCE CASE STUDY

This annex focuses on long term operation (LTO) at Électricité de France (EDF) as another example of the benefit of asset management.

II–1. NUCLEAR POWER PLANT FLEET AND ORGANIZATION

In 2018, EDF operated a standardized fleet in France: 58 pressurized water reactors from one vendor and one licence through the 900 MW series (34 reactors); the 1300 MW series (20 reactors); and the 1450 MW series (4 reactors). In total, 75% of the fleet was built between 1979 and 1990, the oldest reactor is 40 years old and the average age of the fleet is 30 years. Thus, LTO programmes and plant life management have been key issues for years.

The principles of asset management as mentioned in ISO 55000:2014[1] are implemented in EDF processes, from strategic levels to working levels. If the main goals are shared inside the company, the nuclear operating branch is organized following several programmes (e.g. ageing management, obsolescence, maintenance and optimization, refurbishment for major components) and projects (e.g. periodic safety reviews, post Fukushima improvements) that are quite autonomous to contribute in maintaining or improving the value of the assets.

II–2. ECONOMIC AND TECHNICAL ASPECTS

If engineering asset management processes are specific to each utility or programme for the utility, they rely on the same needs with regard to life cycle management and investments decisions. All actors in the decision chain, from system engineers identifying necessary maintenance tasks to decision makers validating high value investments, need to be able to justify, optimize, prioritize and schedule these investments. To do so, it is necessary to quantify the value of an investment or a set of investments, and this value needs to take into account both the economics dimension (costs, production losses) and the technical aspect of physical assets (supply chain, reliability). Therefore, it is important to model both the:

(a) Technical system: Model describing the relationship between all physical components and covers the reliability models of all physical assets, the global asset architecture describing the relationships between subsystems, the maintenance programmes and the supply chain, among others. The model complexity will depend on the scope of the analysis, from a model representing a single elementary asset with a single failure mode up to a complete plant.
(b) Economic system: Model describing how the technical assets impact the economic dimension. Each technical event may generate cash flows (positive or negative) and these have to be valued to evaluate a life cycle strategy. For this model, the complexity will also depend on the scope of the study, from a single cost generated by a failure up to complex economic behaviour such as insurance covering part of generation losses or tax shield issues relating to spare parts.

The main indicator used to evaluate the value of one or several investments with regard to physical assets is the net present value (NPV), which can be defined as the difference in the life cycle cost of the

[1] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Asset Management: Overview, Principles and Terminology, ISO 55000:2014, ISO, Geneva (2014).

assets induced by these investments, in other words how the costs, forced outages, spare supplies and all other cash flows will be modified by new investments. If the NPV is a very important indicator, it is also important to be able to calculate other financial indicators, such as the internal rate of return, the payback period to give maximum inputs to decision makers.

II–3. EDF SUITE OF TOOLS TO SUPPORT ECONOMICS DECISION IN PLANT LIFE MANAGEMENT

EDF has developed several tools to support life cycle decision making.

II–3.1. VME

VME stands for Valorisation de la maintenance exceptionnelle and is the abbreviation used for an EDF tool that enables to model complex systems, with the complexity being technical and economic, meaning the physical assets can be modelled in the most realistic way with all redundancies, and hidden or not failure modes, among others. The economic context the physical assets are in can also be as realistic as needed (e.g. insurance, seasonality effect on the price of energy). Indicators are calculated thanks to a Monte Carlo simulation giving access to a wide variety of risk informed indicators (e.g. units availability, NPV standard deviation, value at risk). Events of the model can be deterministic or probabilistic. This scientific tool has been designed with a user friendly graphical interface to implement data and analyse results.

II–3.2. IPOP

The main purpose of investments portfolio optimal planning (IPOP) is to optimize the selection and planning of major investments for a nuclear power plant or fleet of plants. It is based on a simple data structure with a top to bottom architecture from the plants to the spare parts stock. The average NPV of a given investments portfolio is used to perform the optimization, considering a wide variety of constraints such as a budget limit, a delay between two investments or a maximum number of investments per year.

Once the investments portfolio is optimized, it is possible to evaluate risk informed indicators such as a value at risk or a probability of regret (i.e. probability of a negative NPV). Indicators can be provided at different levels (i.e. component, family of components, plant, fleet). This tool is part of the integrated life cycle management software of the Electric Power Research Institute as its economics module.[2]

II–3.3. OPTAL

OPTAL stands for Optimisation du placement des arrêts long terme and is the acronym used for an EDF tool that smooths the scheduled outages long term planning in order to minimize the outages during winter time while taking into account industrial constraints (i.e. maximum fuel utilization, delay between specific inspections, avoidance of simultaneous outages on one site). This operation is very important as most of the heavy maintenance tasks will be planned during scheduled outages. This tool can be used to optimize the unavailability factor of the fleet or limit the number of long planned outages.

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[2] ELECTRIC POWER RESEARCH INSTITUTE, 2005 EDF/EPRI Collaboration on Life Cycle Management and Nuclear Asset Management, Rep. 1011925, EPRI, Palo Alto, CA (2006).

II–4. EDF CASE ON THE MAINTENANCE OF A COMPONENT

The three tools designed at EDF (VME, IPOP, OPTAL) are complementary: they can be used in interaction during all the phases of the life cycle management of assets in nuclear power plants as described in Fig. II–1.

For instance, to answer questions about the best maintenance strategy for a major component, such as a pump, installed in a fleet of plants. The pump is made of three main subcomponents (motor, valve part, impeller) with multiple failure modes of different types (e.g. ageing or not, hidden failures, degradation mode) of different providers:

— Is the preventive replacement of one subcomponent profitable?
— Is the mass replacement programme at the fleet level schedule by a project profitable?
— May this programme be optimized?

The spare parts management issue is based on the availability of the spare parts (at the manufacturer and at the plant), the time to order and build new spare parts and the need of subcomponents on the plant.

VME models can deal with subcomponent failure modes and spare parts stocks for each component but can also manage all the components of the fleet in gathering all the components models. Due to the complexity of the case (i.e. several subcomponents and failure modes, supply chain process), a detailed model has been developed with VME for a single generic component. The obtained average NPV evolution with time is a classic one, with a single deterministic investment (NPV decreasing in 2020) and avoided losses piling up years after years to make the replacement profitable.

A second VME model has been developed by duplicating the previous one as many times as the number of components within the fleet. All the individual models have been instantiated by specifying the age of the components. All the single component models have been linked together to take into account the supply chain process defined at the fleet level. The average NPV at the fleet level is the sum of

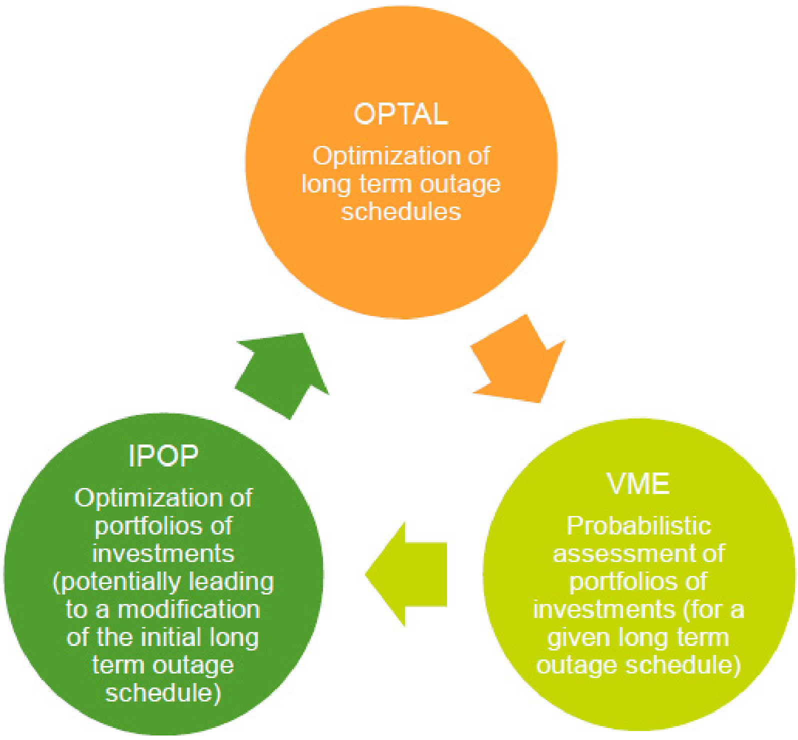

FIG. II–1. Interactions between tools.

the single component NPVs obtained with the specific ages and replacement dates. They sum up to a Gaussian curve that would tend to prove the independency of all components. This independency is an indirect proof that the numbers of spare parts (main components, subcomponents) are sufficient to avoid shortages in the supply chain throughout the replacement programme.

Once the strategy has been validated with VME calculations, both at the component and fleet levels, the investments programme was optimized using IPOP. The evolution of the replacements schedule has led to the improvement in the global NPV (may be increased by about 10% in the case study).

This case presents the suit of tools that may be used to support decision making with regard to investments for the life cycle management of nuclear power plants. The three main tools used deal with different dimensions of asset management issues from a local single component dimension, for which VME has proven to be a powerful tool to build very detailed complex models, up to a macroscopic fleet level dimension, for which IPOP is used to optimize and prioritize investments across heterogeneous issues. OPTAL enables the integration of planned investments into a robust outages schedule. EDF R&D is still working on the development of the improvement of these tools, especially on their capability to deal with risk informed decision making.

Annex III

SWEDEN: VATTENFALL CASE STUDY

III–1. VATTENFALL CHALLENGES

In 2014, the profitability of Vattenfall nuclear power plants dropped markedly following a dip in electricity prices combined with a high investment demand due to lifetime extensions. Hence, Vattenfall decided in 2015 to shut down two of the reactors at Ringhals in 2019–2020. For the two remaining reactors at Ringhals and the three reactors in Forsmark, the aim is 60 years of operation, with the last plant closing in 2045.

The electricity price is expected to continue to be low due to added capacity of renewables in the Nordic power system. To assure profitability of Vattenfall nuclear power plants, a production cost target has been set at approximately €19/MW·h. A high demand on profitability enhances the need for efficient ageing management and cost efficient solutions. In this process, the principles for asset management according to PAS55-1:2008[1] have been a helpful tool.

III–2. INTRODUCTION TO PAS55-1:2008 IN VATTENFALL

Vattenfall power producing units are organized in three different business areas: BA Heat, BA Wind and BA Generation; the latter including nuclear power plants as well as the hydropower plants which stands for above 90% of the electricity production in Sweden.

Vattenfall group has since many years worked with PAS55-1:2008 and later on with the development into ISO 55000:2014[2]. Vattenfall Distribution (powerline) in Germany as well as BA Heat in the Netherlands have been certified against PAS55-1:2008 in recent years. Within Vattenfall nuclear operations, the work with PAS55-1:2008 started in 2014. A self-assessment against the standard was performed by the corporate staff functions for the Forsmark and Ringhals nuclear power plants, the result is summarized in the 'cobweb' in Fig. III–1.

The self-assessment showed several deficiencies against the standard, but also several areas where the organization was well developed. The main deficiencies were found within the following areas:

(a) Lack of 'line of sight' in the organization — insufficient connection between the corporate strategy and the plant strategies.
(b) In general, a lot of analysis is performed, such as ageing management, risk analysis, and safety analysis, but often the feedback from the performed analysis to the planning step is insufficient.
(c) Insufficient connection between plant risks and investment plans.

Based on the self-assessment, it was decided at the corporate level that the principles of PAS55-1:2008 need to be implemented for nuclear power plants, but there was no ambition to become certified. This ambition was later confirmed by the plants.

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[1] BRITISH STANDARDS INSTITUTION, Specification for the Optimized Management of Physical Assets, PAS55-1:2008, BSI, London (2008).

[2] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Asset Management: Overview, Principles and Terminology, ISO 55000:2014, ISO, Geneva (2014).

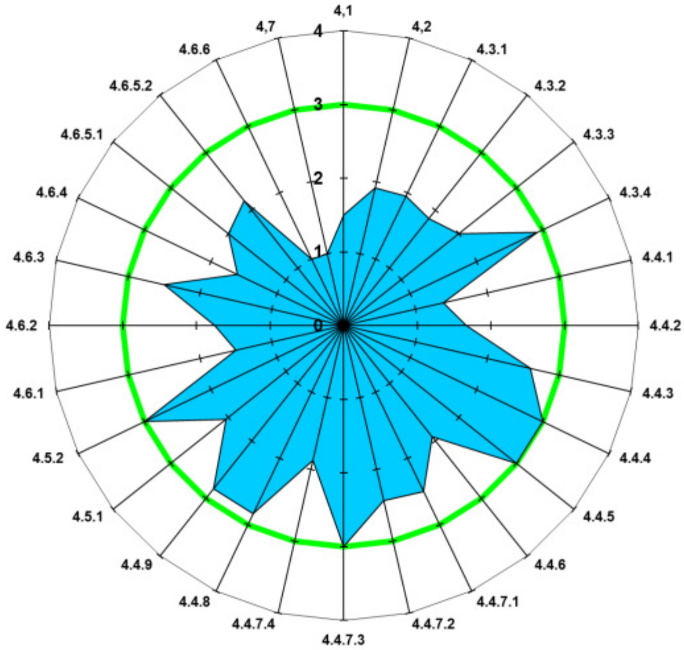


FIG. III–1. Cobweb for PAS55-1:2008 self-assessment of the Forsmark and Ringhals nuclear power plants. Note: The green circle marks the wanted position (3).

A project was initiated at the corporate level to facilitate this work with a focus on improving risk assessments, investment prioritization and strategy development. The project covered the following major areas:

— Development of a corporate asset management policy and asset management strategy;
— Development of a nuclear risk matrix for prioritization of investments;
— Execution of a pilot for optimization of the investment plans, utilizing a project portfolio management (PPM) tool.

III–3. ASSET MANAGEMENT POLICY AND ASSET MANAGEMENT STRATEGY

An important deficiency notified in the self-assessment was the lack of 'line of sight' — the intentions at the corporate level were not known or understood in the nuclear operations. Even though there was a corporate strategic plan present, it was poorly communicated. To improve this, an asset management policy and asset management strategy was developed for BA Generation. The communication of the corporate strategic plan was improved in connection to this work.

The asset management policy and asset management strategy aligns with the BA Generation strategic plan and provides directives and guidelines for the nuclear and hydropower plants. Based on these documents, the nuclear power plants have developed their own specific strategies. The asset management policy was developed on the corporate (BA Generation) level and provide the owners view on reactor safety and profitable operation of the plants. This policy is supposed to be reflected in the nuclear power plant strategic plan.

The asset management strategy was developed in cooperation with the business units, apart from the nuclear power plants, including also nuclear back end and hydropower plants. The asset management strategy contains guidelines for safe and effective asset management of the nuclear and hydropower plants according to the principles in PAS55-1:2008. Areas covered are, for example, nuclear safety, lifetime assessments and long term operation, investment planning, maintenance principles, risk assessments and suppliers' strategies. Since the business area covers two different energy sources — nuclear and hydro — there have been some difficulties to develop common asset management strategies and thus some nuclear specific parts have been developed. However, the principles of PAS55-1:2008 with regard to risk assessments and optimization of assets, among others, are independent of the energy source.

III–4. NUCLEAR RISK MATRIX

Due to financial pressure, which has implied reductions in available investments, a risk based method was developed to describe the consequences of these cost reductions. This method was later decided to be developed for the whole investment plan to assure a clear rationale for each investment in the portfolio. Part of this work was to perform a pilot for investment optimization by utilization of a PPM tool.

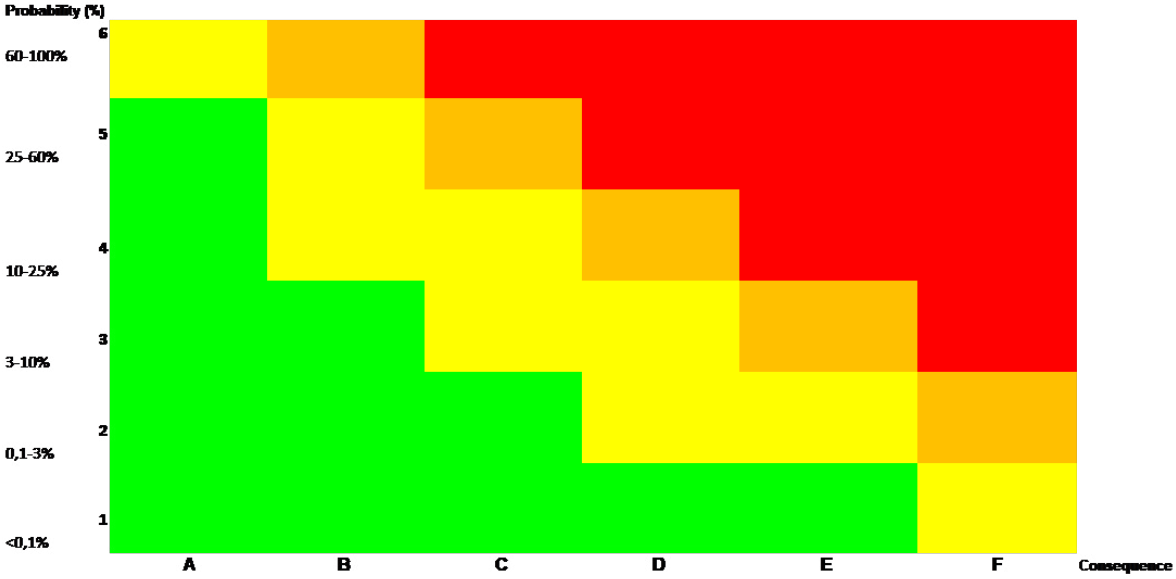
The first step was to develop a nuclear risk matrix. The principles of the risk matrix are that it needs to describe what the consequences would be if the investment were not implemented. The risk matrix needs to cover all types of consequence that can appear and has to be accepted by the organization. For the nuclear business, there were six consequence categories defined:

- Economy (production loss, direct costs);
- Personal safety (injuries, radiation, working environment);
- Reactor safety;
- Regulatory (radiation protection authority and 'others') and public reputation;
- Environment;
- Infrastructure and IT.

The most important, and difficult, part was to calibrate the risk matrix such that all consequence categories are valued equally (i.e. an economic category F needs to be as severe as a reactor safety category F). This means that the value of a reactor safety risk in category E is equal to the value of 45–75 days of production loss, which is the corresponding value of the economic category E. Note that this value needs only to be used for investment prioritization purposes, to compare different investments, and not to provide an exact value of a reactor safety issue or personal safety. It is important to communicate this within the organization and to ensure that the principles of the risk matrix are well understood, otherwise it might imply sensitive discussions about, for instance, the value of a loss of life.

The risk matrix was developed with all stakeholders involved, such as asset management, maintenance, health and safety and reactor safety representatives. It took roughly four months to develop a first version of the risk matrix which could be used for the pilot with the PPM software. The risk matrix was further developed after the pilot and later on approved by the nuclear management team; the time frame of this work was about one year. The risk matrix for nuclear with examples of risk categories is presented in Fig. III–2. The colouring of the risk matrix is based on calculated risk value (based on the economic consequence).

The principles for the risk matrix are that red and orange risks are defined as high and not accepted, yellow risks are defined as medium and need to be handled according to ALARA (as low as reasonably achievable) and green risks are defined as low and should generally not be mitigated. Note the yellow squares in the corners of the risk matrix (6A, 1F), which would be green if only the risk value were considered. This means that a risk with a high probability, up to 100% (6A), needs to not be accepted without an ALARA evaluation; that is, is it reasonable to let this risk basically happen or is the cost for mitigating actions low enough to be worth while? For 1F, the reasoning is that a risk with such a high consequence needs to be mitigated if the probability cannot be shown to be very low (i.e. far below 0.1%). This is especially important for personal safety and reactor safety where a category F needs to be avoided to highest reasonable extent.



	A	B	C	D	E	F
Environment	no impact	Release within target (ground/water/air) OR Mild environmental impact which is relatively easy to sanitize	Small release above target (ground/water/air) OR Limited environmental impact, possible to sanitize/restore	Release above allowed limit (ground/water/air) OR Environmental damage which can not be fully restored or sanitised	Release with limited environmental impact (ground/water/air) OR Large environmental impact which is only partly possible to restore and difficult to santize	Release with extensive environmental impact (ground/water/air) OR Extensive and permanent environmental damage, not possible to sanitize
Economy	Temporary reduction of power, <0.25 d	Production loss <7d	Production loss 7-21d	Production loss 21-45d	Production loss 45-75d	Production loss >75 d

FIG. III–2. Vattenfall nuclear risk matrix, with examples for two risk categories.

III–5. PILOT FOR OPTIMIZATION OF THE INVESTMENT PLAN

Based on the developed risk matrix, a pilot for investment optimization was carried out on the Forsmark 3 investment plan for the coming five years (which is the business planning period within Vattenfall). The PPM software that was chosen is based on the development of a value framework in which the risk matrix plays a central role. The utilized software is mostly spread in North America, with clients mostly within the hydropower and electric transmission and distribution business. There are also a few clients within the nuclear industry in North America.

The pilot was carried out by consultants from the company providing the PPM software and risk assessments were carried out in workshops for one week at the Forsmark nuclear power plant. Expert groups were formed to carry out correct risk assessments. The expert groups covered maintenance, operations, engineering and safety requirements personnel. Apart from the risk, it was considered whether maintenance costs would decrease when carrying out the investment. In the workshop, the following questions were raised for each investment:

- — What would the consequence be if the investment were not implemented (i.e. reactor safety, economic)?
- — What is the probability that this event will appear during the next year, five years ahead, tens years ahead, until end-of-life?
- — Will there be any cost benefits if the investment is implemented (i.e. reduced maintenance costs, increased power output)?
- — What will the residual risk be, probability and consequence after the investment has been implemented.

Based on the input from the workshop, the PPM tool was used to do simulations and calculate the optimal investment plan in the five year time frame. The optimization is based on the simple principle that investments which gives the highest value — cost–benefit ratio (i.e. highest risk mitigation per invested crown) — are prioritized first. Note that value also covers the value of non-monetary consequences (i.e. safety, environment) and is based on the value of the corresponding economical consequence.

Several optimization scenarios were tested with the PPM tool, such as economic constraints and high risk constraints, and the tool proposed a modified investment plan. Even without economic constraints the tool proposed a modified investment plan based on the cost–benefit analysis (i.e. investments with low value were postponed and investments with high value were advanced). There are several possibilities for adding constraints in the tool and these can be combined as desired.

The resulting investment plan was reviewed and deemed to be correct and could be derived to the input data and risk analysis. The results from the pilot were used to do some modifications of the five year investment plan. However, all factors were not considered in the optimization, such as available resources and outage planning. Thus, the results from the optimization tool have to be refined and adjusted, nevertheless it provides a good baseline.

III–6. LESSONS IDENTIFIED AND FUTURE WORK

The main take away from the pilot in Forsmark nuclear power plant was that the risk based method makes sense and provides a rationale for each investment. The interest from the expert team members was high and the results were valuable. Based on the pilot study, it was decided that the Vattenfall nuclear operations, both Forsmark and Ringhals, would continue with the risk based approach and carry out risk assessment for all investments in the five year plan. However, instead of the PPM software a manual spreadsheet based method has been developed. The manual prioritization method is based on the risk colour of the investment and the calculated cost–benefit ratio (i.e. risk reduction divided with investment sum).

The major benefit with the risk assessment is to provide a risk overview for the investment portfolio, which explains the need for investments in a transparent manner and provides a rationale for each investment. The general principle is that all ‘green’ investments needs to be postponed, exemptions could be made if the cost–benefit ratio is greater than one, and all other investments needs to be carried out as planned. If there are demands for cost reductions, the ‘yellow’ investments need to be evaluated based on cost–benefit ratio and can be postponed if the ratio is lower than one. Red and orange risks are not accepted, and these investments will be carried out regardless of demands for cost reductions. Exemptions could be made for pure economic risks if the owner is willing to take the production risk connected to the postponement of the investment.

The experience from the manual spreadsheet method is that it has significantly improved the quality of the investment planning work. In particular, it has increased the awareness in the organization that activities have to be prioritized and that the actual risk needs to be quantified and weighed against the costs for mitigation. The spreadsheet method works well but has some draw backs when it comes to re-planning due to demanded cost reductions, since this is more complicated to do manually and that the risk is only evaluated ten years ahead instead of the until end-of-life in the PPM tool (which is due to practical difficulties to keep track of large amounts of data in spreadsheets).

The long term ambition is to implement a PPM tool for the Vattenfall nuclear power plants and it will be needed also for other purposes than investment prioritization. Currently, the risk assessment method is only utilized for investments, but the ambition in long term is to cover also maintenance activities. However, the condition for that is implementation of a PPM tool, due to the large number of activities.

III–7. ASSET MANAGEMENT AT RINGHALS NUCLEAR POWER PLANT

Ringhals nuclear power plant, owned by Vattenfall AB (70.4%) and Sydkraft Nuclear Power AB (29.6%), is the largest plant in northern Europe. The site is located on the western coast of Sweden and operates four units, one boiling water reactor commissioned in 1976 with 881 MW of installed capacity and three pressurized water reactors commissioned in 1975, 1981 and 1983 with the installed capacities of 904 MW, 1063 MW and 1160 MW. The two oldest units are planned to operate until the end of 2020 and 2019, while the remaining units have a planned lifetime of 60 years (i.e. to 2041 and 2043).

With ageing facilities and a challenging economic situation, Vattenfall Ringhals, as other utilities, has identified the need to improve efficiency to keep nuclear power competitive in a changing electricity market, all while maintaining high level of safety. This has triggered initiatives to improve asset management thinking.

III–7.1. Assessment against ISO 55000:2014

Just as the main owner, Vattenfall, has made an assessment against PAS55-1:2008, Ringhals carried out its own asset management assessment in the end of 2016. The basis for this evaluation was ISO 55000:2014. The results were comparable to those of Vattenfall and resulted in an action plan with the goal to use the standard as a tool for improvement but without the ambition to get a certificate. Main areas to work with were:

— Roles and responsibilities;
— The interface towards the owners;
— Focus on the whole life cycle of the plant;
— The line of sight from top strategies down to carried out activities in the plant;
— The connection between risk and investment and maintenance plans.

III–7.2. Investment planning and nuclear risk matrix

As described above, the Vattenfall corporate staff functions and the individual plants have together developed a prioritization tool for investments. The previously used prioritization model lacked the ability to compare and balance different types of risk. For example, an investment with connection to some type of nuclear safety issue, regardless of severity and the strength of the link to it, always scored highest priority. The result was that almost 80% of all identified needs had highest priority. With the new risk matrix prioritization tool, there is a much greater transparency and there is now a possibility to prioritize between those 80% ‘highest priority’. Another benefit is the possibility to compare different types of risk, for example a risk for production loss compared to an environmental risk or a nuclear safety issue.

III–7.3. Line of sight and the focus on the whole life cycle

Ringhals has handled the findings connected to the headed subject in one package and worked both top–down with the line of sight; that is, how are the overall strategies traceable and supported all the way down to every single task carried out in the plant, and by emphasizing the importance of always thinking of and addressing the complete lifecycle for all decision making (see Fig. III–3). The pyramid describes the strategy on different levels. Overall strategies on top, detailed plans in the bottom and the different levels and details between. The content and purpose of each is described below.

III–7.3.1. Strategic direction

The strategic direction for Ringhals nuclear power plant reflects requirements from the owners. It defines the vision, strategical goals and strategical areas for Ringhals nuclear power plant and provides the goals and missions and sets the boundaries for its business. An important input is the asset management policy and asset management strategy provided by the main owner, Vattenfall.

III–7.3.2. Plant strategy

The goals and main strategies from the strategic direction is completed with boundaries and goals for fulfilment. The life cycle perspective is added, and the strategical direction is applied on a plant level. The strategy interprets the strategic direction with regard to the plant's ability to produce, be maintained and further develop.

III–7.3.3. Engineering area strategy

There is one strategy for each engineering area, mechanical and process, electrical, instrumentation and control, reactor coolant pressure boundary, core and fuel, infrastructure and construction. For each area, the chosen life cycle strategy is described (i.e. why and how this strategy is the most economical and efficient way to fulfil the plant strategy).

The engineering area strategy is developed based on known conditions at the time of writing, thus making the area's best assessment based on these conditions. It needs to be reviewed once a year. The strategies are developed commonly by the engineering, maintenance and operations department. The

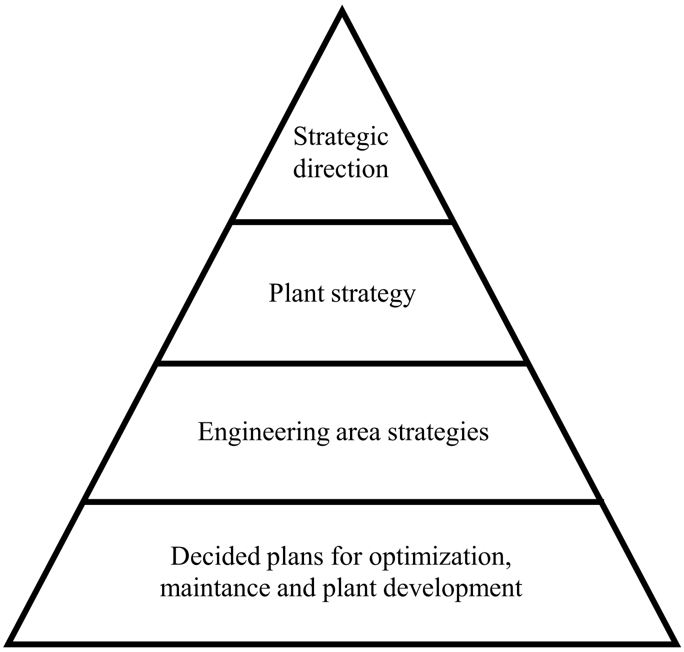


FIG. III–3. Strategic hierarchy at Ringhals nuclear power plant.

engineering area strategy serves as a platform to keep, store and document information over time in each engineering area, as well as providing technical guidance in the preparation of needs and at plant changes, as well as coordination between maintenance strategies and technology development.

III–7.3.4. Decided plans for optimization, maintenance and plant development

Based on the engineering area strategies and the risk assessment, the most optimal plan from, among others, outage planning, resource availability and stakeholder demand is made and executed. The plan needs to be updated each year, and it needs to cover the rest of the life cycle and the resolution needs to be highest for the nearest future.

This structure has helped to create a strong top–down line of sight. It has helped to increase the understanding of how all different decisions affect each other, and it has been clearer that there is a common goal to maximize value from the nuclear asset. It has helped the personnel to realize the importance of prioritizing the projects and problem that provides most beneficial impact on the business total business risk. By also considering the whole remaining lifetime of the plant optimization and the timing for each action, the decision becomes more accurate and it is easier to maximize the value of each investment/modification/maintenance project. An important success factor has been the clear expectations and given strategies from the owners; that is, reach a production cost of approximately €19/MW·h by 2020 and the total production lifetime of each plant needs to be 60 years (for the two units which will continue operation after 2020).

III–7.4. Insights from working with PAS55-1:2008 and ISO 55000:2014

The concept of asset management needs to be seen in its full context. An organization is often well developed in a few areas but less in others. What an organization most lacks, just as Ringhals did, is the close interconnection between different parts of the organization and task carried out. The organization is often good at carrying out each different task; however, the coordination between them is missing and therefore the level of suboptimization is rising. Asset management is all about improving the accuracy of the decisions which need to be made, and by coordinating the activities the information on which decisions are based will improve.

Ringhals has recognized several areas where the standards (i.e. PAS55-1:2008, ISO 55000:2014) and the use of them could be an important piece of the puzzle to make nuclear generation both safer and more competitive. Although this case study focuses on and describes the first steps Ringhals has taken, this does not mean these are the most important ones — they are just one piece of the puzzle. However, for Ringhals these are the areas where the asset management journey according to ISO 55000:2014 started, and the experiences and results so far has been very positive.

Annex IV

UNITED STATES OF AMERICA: CASE STUDY

IV–1. CHALLENGES

Optimizing the financial value of nuclear power plant is one of the key drivers in a plant’s asset management programme. With growing market competition and stringent budgets, the asset management programme has to maximize the financial value of the asset. In recent years, plant owners in the United States of America have closed or announced closure of 14 reactor units at 11 plant sites; 6 nuclear reactors (Crystal River 3 in Florida, San Onofre 2 and 3 in California, Kewaunee in Wisconsin, Vermont Yankee in Vermont, Fort Calhoun in Nebraska) have shut down permanently. The San Onofre Nuclear Generating Station is another example, wherein the operator and the vendor complied with existing regulatory requirements, and engineering risk assessments, and yet were blindsided by the technical challenge, resulting in the plant shutdown. This annex shows what has been done in the United States of America to face this risk.

IV–2. INITIATIVES OF THE ELECTRIC POWER RESEARCH INSTITUTE AND THE NUCLEAR ENERGY INSTITUTE

The NEI nuclear promise initiative has issued a series of bulletins to address ways to increase the economic efficiency at nuclear power plants[1]. EPRI and other stakeholders have developed a risk informed asset management (RIAM) programme.[2] The RIAM programme provides a systematic approach that employs risk management techniques to support long term planning and investment decisions. EPRI reports:

> “The RIAM process…[is] to aid plant decision-makers in determining not only which plant improvement investment options should be implemented, but also how to prioritize plant resources for their implementation based on their predicted levels of profitability. Key decision support indicators include, but are not limited to:
>
> - Net Present Value
> - Projected Earnings (sometimes referred to as ‘profitability’ in RIAM)
> - Projected Costs
> - Nuclear Safety (core damage frequency, etc.)
> - Power Production (availability, capacity factor, etc.)
> - Efficiency (heat rate)
> - Regulatory Compliance”.

With regard to economics and decision making for asset management for long term operation, the levelized cost of electricity calculations for existing plants are based on a levelized average lifetime cost approach for the residual lifetime and future expenses (excluding past expenses or investment), using the discounted cash flow method and residual planned investment.

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[1] See www.nei.org/resources/delivering-the-nuclear-promise

[2] ELECTRIC POWER RESEARCH INSTITUTE, Risk-informed Asset Management (RIAM): Method, Process, and Business Requirements, Rep. 1009632, EPRI, Palo Alto, CA (2005).

The ‘cash’ costs correspond to the cost of future investments (recorded in fixed assets and subject to accounting depreciation), to the operating expenses (expenses of personnel and intermediate consumptions, including fuel, taxes, refurbishment) and ultimately to the costs associated with shutdown and dismantling. The cash cost methodology has to be retained to decide whether to continue the operation of existing nuclear power plants. The cash costs of existing plants are not much subject to rise, as they are not very sensitive to the evolution of uranium prices.

Dismantling costs and waste costs are for most of them covered by provisions or dedicated assets. An increase of these costs would have a limited influence. The cost of fuel, which includes the cost of uranium, represents a relatively small share of the production cost of existing plants. For dismantling, the inventory of dismantling costs is set up at the beginning of operations, and presents only a very small change along time in production.

The costs of the back end management of radioactive waste include mainly the operational cost of spent fuel management and future cost of waste management (including interim storage and final disposal). For future long term costs, waste owning producers have also included provisions covered by dedicated funds or equivalent. New provisions are made each year in relation to the additional production of waste.

Decommissioning costs are largely fixed and are independent of the duration of operation. The longer the plant operates, the more the relative weight of these costs decreases, which reinforces the interest of continued operation. The costs of existing nuclear power plants are therefore known and globally stable, notwithstanding the need for anticipation with regard to possible refurbishment or additional safety issues as part of sound asset management.

Annex V

ASSET MANAGEMENT BENEFITS FOR THE UN SUSTAINABLE DEVELOPMENT GOALS

This annex explains how an effective asset management programme can provide benefits both to the owner/operator and to society, as articulated through the UN Sustainable Development Goals (SDGs).[1]

V–1. AFFORDABLE AND CLEAN ENERGY (SDG No. 7)

Safe and reliable electricity production is essential for the welfare of humanity and key to a robust, sustainable power generation system capable of: delivering a clean, reliable and continuous supply of power; baseload generation; and flexibility in adapting to changing demand while meeting safety and security needs. Nuclear power can also be used for delivering clean water and sanitation while avoiding carbon emissions, which is also part of SDG No. 6 (clean water and sanitation).

The cost of electricity from a nuclear plant is affordable and stable, for which asset management plays an important role in providing a platform for economic growth and value for the consumer in terms of:

(a) Fuel cost: Stable and predictable fuel costs due to the high energy content of uranium, which can be easily stored. Uranium features stable prices with little volatility, uncertainty or risk of interruption, making it a valuable part of a portfolio. In fact, the fuel cost represents a small part of the overall production cost.
(b) Current operation and maintenance costs: Mostly predictable and are in line with large generation capacity.
(c) Long lived assets: Capable of operating beyond 40 years, even up to 80 years, with implementation of ageing management programmes, refurbishment of large components and additional upgrading investment, as needed.

V–2. DECENT WORK AND ECONOMIC GROWTH (SDG No. 8)

Asset management programmes for nuclear power plants can provide a major impetus for sustainable growth at the country level as follows:

— Contributes to country energy independence;
— Reduces trade balance due to a reduction in fossil fuel imports;
— Develops a high skilled and qualified workforce and advanced technology;
— Contributes to regional economies and the development of local industrial activities and resources for plant operation to fulfil safety conditions and to maintain operating capacities at an adequate level.

[1] GENERAL ASSEMBLY, Transforming our world: The 2030 Agenda for Sustainable Development, A/RES/70/1, UN, New York (2015).

V–3. INDUSTRY, INNOVATION AND INFRASTRUCTURE (SDG No. 9)

Asset management provides a platform for sustainable nuclear power generation and also an opportunity for industrial and technological innovation which is used in nuclear power plant operation. These innovations include: development of advanced physical modelling and calculation codes; industrial standards; non-destructive monitoring technology; instrumentation and control; robotics; and remote operation.

V–4. RESPONSIBLE CONSUMPTION AND PRODUCTION (SDG No. 12)

Asset management for nuclear power is part of a responsible consumption and production technology, which:

- Contributes to the generation of low carbon electricity;
- Contributes to a reduction in fossil fuel consumption and resulting impacts on the climate;
- Includes a responsible policy for safety and minimizes any impacts of radioactive releases;
- Offers solutions and resources for spent fuel and waste management and avoids a burden on future generations.

V–5. CLIMATE ACTION (SDG No. 13)

There is an understanding that nuclear power supports efficient and reliable electricity power generation that does not produce carbon dioxide and other greenhouse gases. However, the safety, security and affordability of the technology require constant optimization to ensure that it remains part of an energy mix for a given country. It is also a major asset for environmental policy goals and low carbon baseload generation, a unique combination of large capacity, dispatchable and flexible generation, and clean air generation without pollutants such as carbon, sulfuric or nitrous oxides. Asset management is key to driving affordable power generation. As such, it contributes to the development of sustainable cities and communities (SDG No. 11).

Annex VI

ASSET MANAGEMENT FOR NUCLEAR NEW BUILD PROJECTS

A nuclear new build project may be implemented in many ways depending on the commissioning agent (the owner). The different scenarios are as follows:

- Does the owner have an existing nuclear fleet?
- Will the utility have to be built at the same time as the nuclear power plant?
- Is this new build one of several?
- Will the operating organization be the owning organization?
- Is there an existing organization providing management and engineering services?
- What is the nature of the contracts for engineering, procurement and construction (EPC)?
- What will be the influence of the government, regulations and finance?

In all of these scenarios, the focus for the new build project needs to be on ensuring that asset management is considered from the start, which includes the initial definition of requirements of the facility. This annex describes a set of overarching principles to guide the development of the asset management environment for operations to continue during the EPC phase of a nuclear new build project.

Current asset management standards focus on the optimization of operational facilities but recognize that the principles are appropriate throughout the life cycle. However, the opportunity to enact asset management principles during the EPC phase is rare. Typically, the nuclear design (engineering) process is very good at identifying risk and designing out or managing the risk of failures that may impact safety. However, operational impacts (operability) are not always considered as thoroughly. The need to design for operability is not always at the forefront of the EPC organization's thinking. The goal is to design and build a safe plant to time, cost and quality, and not primarily to design a plant that operates effectively. This is especially true if the EPC organization has no role in the operation of the plant and there is a disconnect between the two organizations (e.g. in a turnkey contract). However, processes need to be established to ensure that the future requirements of operational asset management are considered and delivered as part of the EPC contracts. For instance, in the collection and validation of information (data) throughout the build process which will support future asset management needs.

In addition to the physical build of the station, the following steps are needed to build an asset management capability in a nuclear new build scenario. This needs to be done in parallel with the physical build process and needs to be considered as soon as possible in the process:

(a) Build the processes: Identify and develop the operational processes such that they facilitate asset management. They also need to support the business case of the new station being built (safety, 60+ years commercial operation, capacity factor >90%, minimal outage, low maintenance costs, etc.).

(b) Identify and build the information systems (applications): If they are not already in place, select, procure and configure an integrated set of systems (applications) that will support the processes being developed to meet the business case of the station.

(c) Specify the data requirements and build them into contracts: The EPC contracts needs to be structured to enable the continual capture of data to facilitate safe, efficient and effective operation of the site from the first day. The information needs to be appropriate for the proposed operational processes (including Refs [VI–1 to VI–3], statutory and regulatory requirements). Information includes 3-D models, drawings and documents, and 1-D data, including the master equipment list and all associated attributes and relationships between objects.

(d) Build the operational technology (OT) and information technology (IT) infrastructure: Build a flexible OT/IT environment capable of taking advantage of future innovation in technology, such as augmented reality, mobile and wearable devices, autonomous vehicles and robotics.
(e) Manage the information handover: Manage the handover of information (including 3-D models, drawings, documents, data) from the EPC phase to the operational station and utility.
(f) Explore innovation: Explore how innovation ideas from the Electric Power Research Institute, IAEA, partner organizations, vendors, universities, other industries can be adapted to help the utility meet its operational ambitions.
(g) Build the asset management organization: Develop the processes, organization, training and technology to support the ongoing asset management needs of the operational utility and station.

A nuclear new build project may provide an opportunity to build an asset management and supporting information management infrastructure from scratch in a green field environment. This is an enormous opportunity, but it is not easy. Several principles need to be explored.

VI–1. PRINCIPLE 1: BUILD ASSET MANAGEMENT FOR THE FUTURE

Do not recreate what was appropriate 20 years ago. A new nuclear build project needs to have very ambitious operating goals to meet its business case: minimal outage time, high capacity factor, minimal outage duration, minimal unplanned losses. To meet these principles, the asset management environment has to be ambitious and reflect where the asset management industry is heading in ten years. Rather than recreating systems used in existing nuclear generating companies, the IT architecture has to enable agile and comprehensive integration between the major systems groups with asset data at the core and 3-D visualization used extensively to improve productivity (see Fig. VI–1).

VI–2. PRINCIPLE 2: OPERATING SYSTEMS WILL USE AS-BUILT 3-D MODEL VISUALIZATION FOR THE HUMAN–MACHINE INTERFACE

Operations require as-built 3-D models as well as as-designed 3-D models. The 3-D model produced during the design has to be updated during the build process to reflect the as-built situation. Design changes over a certain tolerance have to be updated to the 3-D model during construction. Changes in this tolerance could be generated using as-built laser scans, which can be layered onto design models during construction. Walled-in equipment, embedding and penetrations also need to be scanned.

VI–3. PRINCIPLE 3: DATA CENTRIC CONFIGURATION MANAGEMENT

The objective of the information gathering process for the operational nuclear plant follows the principles of configuration management to ensure that accurate information consistent with the physical and operational characteristics of the power plant is available in a timely manner for making safe, knowledgeable and cost effective decisions (see Fig. VI–2).

Obviously, during the design and build process, the three elements of the configuration management triangle will be out of step until the commissioning of the plant and supporting documentation and data are declared ‘as-built’. However, the ‘gap’ needs to be known and continually managed throughout the process to ensure that all elements are correctly designed and documented in an as-built fashion.

Traditionally, information has been exchanged between EPC organizations and the owner/operator organization using PDF documents. While this information can be correct, it is more difficult to find or to prove it is correct and complete than information held within structured electronic databases.

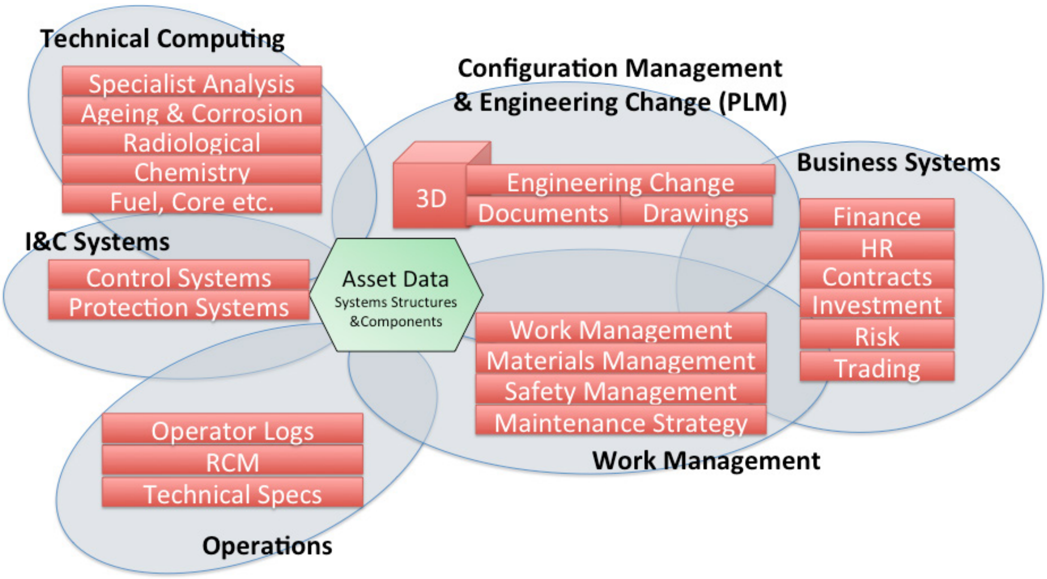

FIG. VI–1. Agile and comprehensive integrated information management architecture [VI–4].

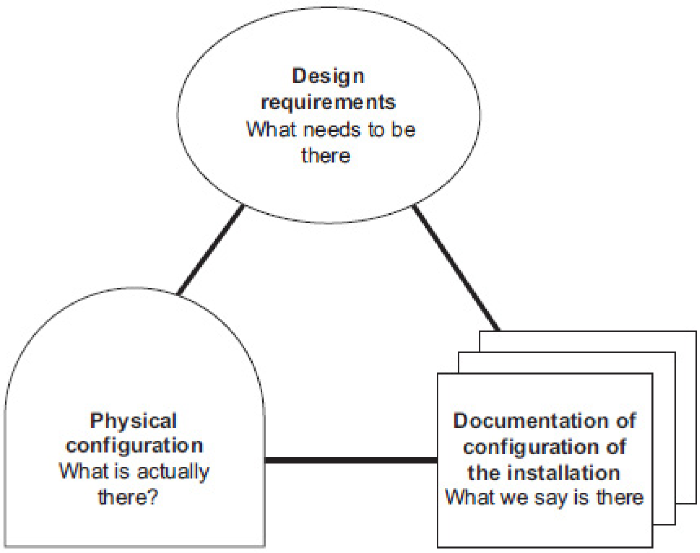

FIG. VI–2. Consistency model for configuration management [VI–5].

IV–4. PRINCIPLE 4. THE OWNER/OPERATOR HAS TO SPECIFY THE INFORMATION (DATA) REQUIRED FROM THE EPC ORGANIZATION

Around 70% of the information that will be generated for the lifetime of the plant can be collected and validated during the EPC phase. The following data collection principles need to be observed:

— Include 3-D models, drawings, documents and data.
— Relationship data have to be comprehensively populated.

— Aim to produce a data rich IT environment where all information about an asset can be obtained at the push of a button.
— Ensure that all documentation, work history, 3-D models, design requirements, pre-job briefs, and maintenance videos are available to the user.
— Provide the operational station with pre-operational asset data to know about the complete life cycle of critical structures and components.
— Collect and hand over to the operational site all design decisions, non-conformances, concessions, design changes, manufacturer data sheets, manufacturer inspection records, construction quality records, and pre-operational maintenance history.
— Collect and validate data throughout the build process. This will ensure there is no delay to the station startup while establishing the configuration management equilibrium.

REFERENCES TO ANNEX VI

[VI–1] INSTITUTE FOR NUCLEAR POWER OPERATIONS, Equipment Reliability Process Description, INPO AP-913, Rev. 2, INPO, Atlanta, GA (2007).

[VI–2] INSTITUTE FOR NUCLEAR POWER OPERATIONS, Work Management Process Description, INPO AP-928, Rev. 1, INPO, Atlanta, GA (2003).

[VI–3] BRITISH STANDARDS INSTITUTION, Specification for the Optimized Management of Physical Assets, PAS55-1:2008, BSI, London (2008).

[VI–4] WAKEMAN, M., Enterprise Asset Management (EAM) for Beginners: Nuclear Information Management, Createspace Publishing, Scotts Valley, CA (2018).

[VI–5] INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Nuclear Installations, IAEA Safety Standards Series No. GS-G-3.5, IAEA, Vienna (2009).

Annex VII

ASSET MANAGEMENT FOR DECOMMISSIONING

Decommissioning is a unique stage in the lifetime of a nuclear power plant that needs to be considered from the initial plant design and throughout its life. However, the existing fleet of nuclear power plants around the world have varying levels of focus on decommissioning due to regulations at the time of construction, closure and the prevailing economic and political conditions. Decommissioning falls into two main categories: decommissioning of an existing plant and no new build; and new build application to support decommissioning.

A project based approach is normally adopted for both categories. On this basis, asset management needs to be considered during the definition of the project, which includes the initial definition of the requirements of the facility. When considering decommissioning of an existing plant, the following asset management elements need to be considered:

— Resource and staff transition;
— Infrastructure required;
— Competence;
— Regulatory licence requirements;
— Operational model through transition to decommissioning;
— Decommission strategy and its impact on costs.[1]

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Nuclear Power Plants, Research Reactors and Other Nuclear Fuel Cycle Facilities, IAEA Safety Standards Series No. SSG-47, IAEA, Vienna (2018).

DEFINITIONS

The following definitions have been taken from the IAEA Safety Glossary[1] and ISO 55000:2014[2].

ageing. General process in which the characteristics of a structure, system or component gradually change with time or use.

ageing management. Engineering, operations and maintenance actions to control within acceptable limits the ageing degradation of structures, systems and components.

asset. An item, thing or entity that has potential or actual value to an organization. Value can be tangible or intangible, financial or non-financial, and includes consideration of risks and liabilities. It can be positive or negative at different stages of the asset life. Physical assets usually refer to equipment, inventory and properties owned by the organization. Physical assets are the opposite of intangible assets, which are non-physical assets such as leases, brands, digital assets, use rights, licences, intellectual property rights, reputation or agreements. A grouping of assets referred to as an asset system could also be considered as an asset.

asset life. Period from asset creation to asset end of life.

asset management. Coordinated activity of an organization to realize value from assets. Realization of value will normally involve a balancing of costs, risks, opportunities and performance benefits.

asset management plan. Documented information that specifies the activities, resources and timescales required for an individual asset, or a grouping of assets, to achieve the organization's asset management objectives. The grouping of assets may be by asset type, asset class, asset system or asset portfolio. An asset management plan is derived from the strategic asset management plan. An asset management plan may be contained in, or may be a subsidiary plan of, the strategic asset management plan.

asset portfolio. Assets that are within the scope of the asset management system. A portfolio is typically established and assigned for managerial control purposes. Portfolios for physical hardware might be defined by category (e.g. plant, equipment, tools, land). Software portfolios might be defined by software publisher, or by platform (e.g. PC, server, mainframe). An asset management system can encompass multiple asset portfolios. Where multiple asset portfolios and asset management systems are employed, asset management activities should be coordinated between the portfolios and systems.

asset system. Set of assets that interact or are interrelated.

audit. Systematic, independent and documented process for obtaining audit evidence and evaluating it objectively to determine the extent to which the audit criteria are fulfilled.

commissioning. The process by means of which systems and components of facilities and activities, having been constructed, are made operational and verified to be in accordance with the design and

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[1] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection, 2018 Edition, IAEA, Vienna (2019).

[2] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Asset Management: Overview, Principles and Terminology, ISO 55000:2014, ISO, Geneva (2014).

to have met the required performance criteria. Commissioning may include both non-nuclear and/or non-radioactive and nuclear and/or radioactive testing.

cost–benefit analysis. A systematic technical and economic evaluation of the positive effects (benefits) and negative effects (disbenefits, including monetary costs) of undertaking an action.

critical asset. Asset having potential to significantly impact on the achievement of the organization's objectives. Assets can be safety-critical, environment-critical or performance-critical and can relate to legal, regulatory or statutory requirements. Critical assets can refer to those assets necessary to provide services to critical customers. Asset systems can be distinguished as being critical in a similar manner to individual assets.

decommissioning. Administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility.

dismantling. The taking apart, disassembling and tearing down of the structures, systems and components of a facility for the purposes of decommissioning.

inspection. An examination, observation, surveillance, measurement or test undertaken to assess structures, systems and components and materials, as well as operational activities, technical processes, organizational processes, procedures and personnel competence.

licence. A legal document issued by the regulatory body granting authorization to perform specified activities relating to a facility or activity.

life cycle. Stages involved in the management of an asset. The naming and number of the stages and the activities under each stage usually vary in different industry sectors and are determined by the organization.

maintenance. The organized activity, both administrative and technical, of keeping structures, systems and components in good operating condition, including both preventive and corrective (or repair) aspects.

objective. Result to be achieved. An objective can be strategic, tactical or operational. Objectives can relate to different disciplines (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization wide, project, product, process). An objective can be expressed in other ways, e.g. as an intended outcome, a purpose, an operational criterion, an asset management objective or by the use of other words with similar meaning (e.g. aim, goal, or target). In the context of asset management, asset management objectives are set by the organization, consistent with the organizational objectives and asset management policy, to achieve specific measurable results.

occupational exposure. Exposure of workers incurred in the course of their work.

operating lifetime, operating life. The period during which an authorized facility is used for its intended purpose, until decommissioning or closure.

operation. All activities performed to achieve the purpose for which an authorized facility was constructed. For a nuclear power plant, this includes maintenance, refuelling, in-service inspection and other associated activities.

operational limits and conditions. A set of rules setting forth parameter limits, the functional capability and the performance levels of equipment and personnel approved by the regulatory body for safe operation of an authorized facility.

operator (operating organization). Any person or organization applying for authorization or authorized and/or responsible for safety when undertaking activities or in relation to any nuclear facilities or sources of ionizing radiation.

optimization (of protection and safety). The process of determining what level of protection and safety would result in the magnitude of individual doses, the number of individuals (workers and members of the public) subject to exposure and the likelihood of exposure being as low as reasonably achievable, economic and social factors being taken into account (ALARA).

organization. Person or group of people that has its own functions with responsibilities, authorities and relationships to achieve its objectives. The concept of organization includes, but is not limited to, sole-trader, company, corporation, firm, enterprise, authority, partnership, charity or institution, or part or combination thereof, whether incorporated or not, public or private.

organizational objective. Overarching objective that sets the context and direction for an organization's activities. Organizational objectives are established through the strategic level planning activities of the organization.

organizational plan. Documented information that specifies the programmes to achieve the organizational objectives.

policy. Intentions and direction of an organization as formally expressed by its top management.

regulatory body. An authority or a system of authorities designated by the government of a State as having legal authority for conducting the regulatory process, including issuing authorizations, and thereby regulating the nuclear, radiation, radioactive waste and transport safety.

repair. An action on a non-conforming product to make it acceptable for its intended use.

requirement. Need or expectation that is stated, generally implied or obligatory. 'Generally implied' means that it is custom or common practice for the organization and stakeholders that the need or expectation under consideration is implied. A specified requirement is one that is stated, for example in documented information.

stakeholder (interested party). A person, company, etc., with a concern or interest in the activities and performance of an organization, business, system, etc.

strategic asset management plan (SAMP). Documented information that specifies how organizational objectives are to be converted into asset management objectives, the approach for developing asset management plans, and the role of the asset management system in supporting achievement of the asset management objectives. A strategic asset management plan is derived from the organizational plan. A strategic asset management plan may be contained in, or may be a subsidiary plan of, the organizational plan.

structures, systems and components. A general term encompassing all of the elements (items) of a facility or activity that contribute to protection and safety, except human factors.

ABBREVIATIONS

CMMS	computerized maintenance management system
EDF	Électricité de France
EPC	engineering, procurement and construction
EPRI	Electric Power Research Institute
FMECA	failure mode, effects and criticality analysis
IPOP	investments portfolio optimal planning
ISO	International Organization for Standardization
LCOE	levelized cost of electricity
LTO	long term operation
NEI	Nuclear Energy Institute
NPV	net present value
OLCs	operational limits and conditions
O&M	operation and maintenance
PPM	project portfolio management
PSA	probabilistic safety assessment
RBI	risk based inspection
RCM	reliability centred maintenance
RI–ISI	risk informed in-service inspection
RIAM	risk informed asset management
SSCs	structures, systems and components

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Technical Committee Meeting

Vienna, Austria: 9–11 October 2018

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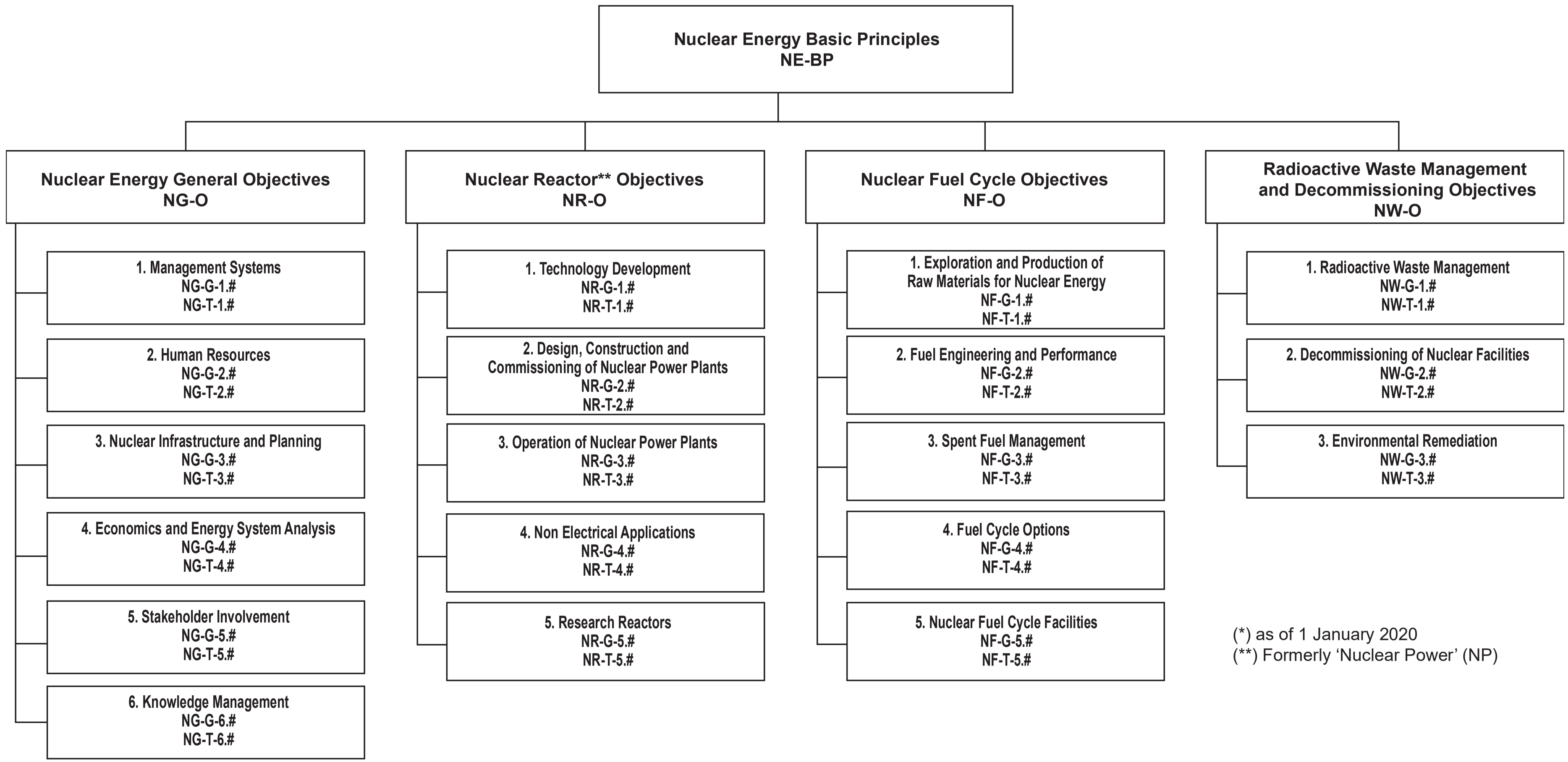

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