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No. NR-T-2.15

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INTEGRATED LIFE CYCLE RISK MANAGEMENT FOR NEW NUCLEAR POWER PLANTS

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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-2.15

INTEGRATED LIFE CYCLE RISK MANAGEMENT FOR NEW NUCLEAR POWER PLANTS

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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. While the guidance provided in IAEA Nuclear Energy Series publications does not constitute Member States' consensus, it has undergone internal peer review and been made available to Member States for comment prior to publication.

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.

The worldwide nuclear industry was strong in the 1970s, when nuclear power plant vendors had many orders, large, experienced engineering organizations and comprehensive in-house capability for design and manufacturing. Organizations maintained robust management systems that helped to ensure the quality of their work and the work of their subcontractors. The licensee was typically responsible for project management and took ownership of safety and quality assurance functions.

Factors that successfully reduce construction risks at nuclear power plants are the licensee's ownership of the project, and the close monitoring and assessment of design manufacturing and construction from the very beginning of the project with a robust management structure. Strong political support from the government and determined building and maintenance of the national nuclear and technological infrastructure also help to ensure the successful implementation of new nuclear power plant projects.

However, the nuclear business environment has changed significantly since the 1970s. While new countries and organizations have joined the industry, more traditional nuclear sector participants and countries have reduced their capacity to start new nuclear construction projects. This loss of experience and capability can create risks for both nuclear construction and operation. Conversely, embarking countries have adopted nuclear power and are expanding their knowledge.

Integrated risk management is designed to apply the risk management process that includes identifying risks, developing strategies to manage risks and implementing those strategies at the early design and construction stage of a facility while considering its entire life cycle. Technical, safety, economic and management considerations are all included in the analysis.

Under this environment, the integrated risk management process provides a tool to monitor quality, cost and scheduling in new nuclear power plant projects. Integrated risk management is an increasingly important activity for safety and non-safety structures, systems and components to deal effectively with uncertainty or potential unexpected events.

Construction risks may cause scheduling delays, cost overruns or quality issues in new nuclear power plant projects. Some risks may cause issues much later in a plant's life cycle. This publication is designed to enhance stakeholders' understanding of the fundamental processes, procedures and methods for integrated risk management, which are mainly applicable in the preparation and construction phases of a nuclear power plant and considering the risks that could realize during the operation decommissioning phases. It also introduces economic evaluation techniques, considering the whole life cycle of a nuclear power plant to understand its economics and risks. Member States considering expanding their existing nuclear power plant fleets can be expected to benefit from this publication, but it will likely be more valuable for Member States embarking on nuclear power programmes.

The IAEA officers responsible for this publication were K. Kang and A. Kawano of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Since the 1980s, the development of advanced nuclear plant designs has increased the interest of power companies in new nuclear power plant (NPP) developments. These standardized NPPs and advances in construction techniques are based on the latest technological innovations and promise short construction periods, low operating costs and more economical decommissioning costs. In addition, new advanced reactor designs have been introduced that are specifically designed for reliable and efficient operation, low cost construction and enhanced safety.

Achieving short and accurately predicted construction durations is critical for any new NPP project's economic and financial success. This is one of the challenges facing the nuclear industry. Construction durations for NPPs, from the first placement of structural concrete to grid connections, have ranged from less than 5 years to more than 12 years. Over the last 40 years, several NPP projects have experienced significant delays and cost overruns. Many reasons are often cited for poor cost control [1], such as:

— Lack of pre-project planning and preparation;
— Changes in the regulatory environment;
— Lack of standardized engineering solutions;
— Loss of competences as a consequence of a long period without new nuclear build projects;
— Overly ambitious cost targets set by project owners and contractors.

When applied to an NPP construction project, the integrated risk management process provides a tool to assess and manage quality, cost and scheduling. Risk analysis and management are an increasingly important project management activity for both safety and non-safety systems, structures and components (SSCs) to deal effectively with uncertainty or potential unexpected events.

The Project Management Institute [2] defines the phases of risk management as follows:

(a) Risk management planning;
(b) Risk identification;
(c) Qualitative risk analysis;
(d) Quantitative risk analysis;
(e) Risk response planning;
(f) Risk implementation;
(g) Risk monitoring and control.

Overall, the nuclear industry has suffered from a negative reputation due to its high capital costs, delays and cost overruns. Although this is not always the case, some nuclear power programmes were completed successfully and on budget. This success is mainly due to two conditions — achieving productivity benefits through completing a series of standard projects and high quality oversight and management of an empowered workforce.

For new NPP projects currently in the conceptual or design phase, the risk allocation techniques that can be embedded in project development structuring will help address the myriad of construction risks faced by NPP new builds, particularly in the areas of risk sharing, interface management and dispute resolution.

Additionally, risk analyses provide a systematic means of categorizing the risks within each schedule. Based on risk rates and sensitivity analyses, the owner/operator and vendor can determine which assumptions and risk factors could have the most significant impact on schedule duration. By focusing on these factors early in the project, the owner/operator and vendor can develop targeted risk reduction strategies to minimize setbacks.

Typically, NPPs are part of a generational fleet belonging to an operating organization. This also often depends on the history of the electricity industry and energy policy decisions. Customers expect a lower cost of electricity over time to promote the economy's competitiveness and a higher standard of living.

Nuclear power plants generally have low operating costs but higher and uncertain construction costs. Therefore, one of the most difficult challenges for an NPP project is financing. The scale and uncertainty of costs and the timeline and complexity of NPP projects make it challenging to attract the necessary capital. Other challenges include the complexity of the vendor–customer relationship, long, international supply chains and the globalization of the nuclear industry.

To compensate for high capital costs, the production of electricity needs to be at competitive prices. To achieve a competitive price, NPPs need to have high capacity factors, competitive operations and maintenance costs, and secure long term fuel supplies. Changing market needs, such as the need to integrate with intermittent renewable power sources, are an emerging trend that leads to new challenges and cost pressures.

Integrated risk management comprises the:

> "processes of conducting risk management planning, identification, analysis, response planning, response implementation, and monitoring risk on a project. The objectives of project risk management are to increase the probability and/or impact of positive risks and to decrease the probability and/or impact of negative risks, in order to optimize the chances of project success" [2].

The financial impact is, in most cases, based on economic analysis for the optimal utilization of financial resources. However, the technical basis for quality control and quality assurance in NPP construction will be increasingly important, especially as NPPs are expected to operate for 60 or 80 years. Thus, it is necessary to consider the integrated approach to minimize negative risk when considering technical requirements and economic assessment.

1.2. OBJECTIVE

The purpose of this publication is to provide practical guidelines on various aspects of integrated risk management for new NPP projects and to share good practices among Member States. This publication highlights the importance of having appropriate risk management policies, especially when considering the various contractual and organizational arrangements in different construction entities, operating organizations and Member States. Tables are provided throughout to indicate causes of risks and their impacts on the applicable NPP or project.

The IAEA has released two publications related to NPP risk management, IAEA-TECDOC-1209, Risk Management: A Tool for Improving Nuclear Power Plant Performance [3], focusing on NPP operational risk and guidelines for integrated risk analysis, and IAEA-TECDOC-994, Guidelines for Integrated Risk Assessment and Management in Large Industrial Areas [4], focusing on health and environmental risk. Guidance and recommendations provided here in relation to identified good practices represent experts' opinions but are not made on the basis of a consensus of all Member States.

1.3. SCOPE

These IAEA publications [3, 4] focus on reducing the radiological, health and environmental risks associated with NPP operation. There is a need for a new publication that provides practical guidelines on implementing a successful risk management strategy in a new build project that considers the entire NPP life cycle. The following issues will be discussed:

(a) Understanding the risk framework, including all relevant types of risk;
(b) Developing meaningful metrics for monitoring the effectiveness of risk management;
(c) Developing strategies and techniques to manage risks, such as risk reduction, mitigation of consequences, risk retention and risk transfer.

This publication mostly focuses on new NPP project risk management in the light of economic considerations from various perspectives. While there are various safety related discussions throughout the text, the risks associated with nuclear and radiation safety and nuclear security are not specifically and comprehensively covered in this publication. The recommendations on risk analysis in the context of nuclear and radiation safety are covered in the IAEA Safety Standards and other supporting publications and are briefly referred to in Section 7.

1.4. STRUCTURE

This publication consists of seven sections. Section 2 describes fundamental theories related to a risk management framework applicable to NPP projects.

Section 3 describes the sources of risks that impact on an NPP, both internal and external. Section 4 provides some theories related to economic risk management, including measuring profitability and evaluating the impact of all risks.

Sections 5–8 provide specifics related to risks in the various phases of an NPP's life cycle; that is, during the project development, construction, operation and decommissioning phases.

The impact of organizational culture from the risk point of view is discussed in Section 9.

1.5. USERS

This publication is intended for the use of NPP owners, operators and other stakeholders who are considering investing, directly or indirectly, in the building of new NPPs. It is especially applicable to newcomers and expanding countries. The following types of organizations are potential consumers of the publication:

(a) Utilities or owner/operators;
(b) Regulatory bodies;
(c) Vendors;
(d) Architect–engineers/contractors;
(e) Consultants;
(f) Subcontractors;
(g) Economic analysts;
(h) Investors;
(i) Academia.

2. STEPS OF RISK MANAGEMENT

This section describes the steps involved in a typical risk management framework and some of the tools available to analyse and address risks.

Risk can be defined as an uncertain event or condition that, if it occurs, has a positive or negative effect on a project objective[2]. Risk management is a continuous process

> "of conducting risk management planning, identification, analysis, response planning, response implementation, and monitoring risk on a project. The objectives of project risk management are to increase the probability and/or impact of positive risks and to decrease the probability and/or impact of negative risks, in order to optimize the chances of project success" [2].

Effective risk management requires early planning for the identification and analysis of risks to allow for contingencies and the implementation of corrective actions in time. It also requires continuous monitoring and reassessment, and communication, documentation and coordination.

A typical risk management framework is described in IAEA-TECDOC-1209 [3]. shows steps to identify risks and techniques or strategies to manage those risks, implement those techniques and monitor their effectiveness.

(a) Risk identification: the purpose is that key stakeholders, including staff and the executives, become aware of potential issues. Identification has to be done early and repeated frequently; a qualitative risk analysis is recommended to prioritize further steps. Such an approach should be included in any strategic planning process. When risk identification and analysis is completed, techniques and strategies to manage risks have to be implemented. Risk management planning includes decisions on reducing risks, retention of risks and transfer of risk when necessary and effective. The risk mitigation planning of strategic risks should be a component of the strategic plan.

(b) Risk management plan implementation: implementation of mitigative actions is allocated to the relevant stakeholders. In principle, the owner of a process owns its risks.

FIG. 1. Risk management framework. Reproduced from Ref. [3].

(c) Monitoring solutions: this is part of the process due to the distribution of responsibilities. Stakeholders are aware and informed of the progress of the action plan. Regular follow-up and analysis of the development of risks and the relevance of implemented mitigating actions contribute to the feedback from the risk owners to the decision makers. Some strategic risks may be confidential so that only a small group of stakeholders have access to such risks and related actions. In this phase, lessons learnt are collected, documented and shared.

International Organization for Standardization (ISO) 31000:2018 [5] provides the principles, a framework and a process for managing risk. The associated International Electrotechnical Commission (IEC) 31010:2018 [6] is a supporting standard for ISO 31000:2018 and guides the selection and application of systematic risk analysis techniques. Major projects and organizations should have defined risk management structures that specify the chain of authority, communication structure and management framework with which risk management and the decision processes will occur.

The Project Management Institute's risk process framework [2, 7] is analogous to those presented above. It adds a step to 'plan risk management', divides the analysis of risks into qualitative and quantitative analysis, and the 'implement risk management strategies' and 'evaluate the effectiveness of solutions' steps are called 'plan risk responses' and 'monitor and control risks', respectively.

For risk management to be effective, it should be an integral part of the applicable management system (e.g. standards, procedures, directives, policies and other management documentation). Such a management system would typically include annual or biannual self-evaluation of the overall risk management process. The evaluations would provide vital feedback to improve the effectiveness of risk management.

2.1. RISK IDENTIFICATION

Risk identification is the first step in any risk management process. A systematic approach is necessary at all levels of an organization to identify risks. This includes low level project and operational risks up to the corporate or executive level. A good practice is to ensure that significant risks are passed upwards to higher levels so that appropriate attention and resources can be applied to managing them.

To manage risk, an organization needs to know what risks it faces and evaluate them. Identifying risks is the first step in building the organization's risk profile. There is no single right way to record an organization's risk profile, but maintaining a record is critical to effective risk management.

Several techniques can be applied to improve the success of risk identification. Some common methods of risk identification are listed in Table 1.

2.2. TECHNIQUES AND STRATEGIES TO MANAGE RISKS

Once risks are identified, organizations need to identify the preferred approach to address each of them. First, the risks need to be analysed and then approaches need to be identified to successfully manage each one. This section covers various techniques and strategies for risk analysis.

2.2.1. Risk registers

The risk register is a document (usually a database) that records, in a systematic way, the key risk of the projects and all the details associated with each risk (e.g. probability, impact, owner, best practices).

In addition to the identification and classification, risk registers include a description of the current status of the risk and means of risk reduction, retention and transfer. A recovery plan should also be added for the case where the risk materializes.

The risk register is a living document that is updated and supplemented regularly during the whole life cycle. When the responsibility for risks has been allocated hierarchically in the organization (and to relevant parties outside the enterprise), the risk register is a management tool to support decision making at all organization levels.

Examples of risk registers are available in Section 2.8 of IAEA Nuclear Energy Series No. NP-T-3.21, Procurement Engineering and Supply Chain Guidelines in Support of Operation and Maintenance of Nuclear Facilities [11], the IAEA's nuclear contracting toolkit, and Appendix I of this publication. The risk register in Appendix I covers risks related to each phase of an NPP's life (preparation, construction, operation, decommissioning). Strategic risks, project planning and management risks, human resource risks and commercial risks have their own categories. The strategic risks cover the whole NPP life

TABLE 1. SELECTED RISK IDENTIFICATION METHODS

Risk identification technique	Description	Reference
Creativity techniques (e.g. brainstorming, buzz groups, bug lists, stepladder technique, synectics)	Methods that encourage creative actions, using techniques for idea generation and divergent thinking, ways of reframing problems, changes in the affective environment and so on. Diversity in the stakeholders' background is a key element for ensuring a wide identification of risk	[8]
Diagramming techniques (e.g. flowchart method, cause and effect diagrams/fishbone diagrams, influence diagrams)	Methods to display information with logical linkages between them. This allows stakeholders to understand the information easily	
Risk workshops	Workshops to identify and prioritize a wide variety of risks concerning organization objectives. They involve both risk owners and experts (professionals and consultants with specific skills and experience but who are not directly responsible for the risk). Diversity in the stakeholders' background is a key element for ensuring a wide identification of risk	
Strengths–weaknesses–opportunities–threat (SWOT) analysis	A framework for assessing an organization's resources and capabilities (strengths and weaknesses) against the external situation (opportunities and threats)	[9]
Experience feedback	Reviews and feedback from construction and operating experience from industry databases, NPP vendors and suppliers, consultants and owner groups Construction and operating experience from water cooled reactors extend for more than 50 years. Safety and knowledge of design basis accidents have improved, as have methods for information exchange	
Project lessons learned	Reports, checklists and feedback from previous similar projects (including previous risk registers) from internal and external sources are essential tools for identifying risks for new projects	
Assumption and constraint analysis	A technique whereby project team members identify and document all of the assumptions being made during the project planning process, and then on a one by one basis identify the risks for the project that exist as a result of each assumption based on the potential inaccuracies or inconsistencies that the assumption may exhibit. There is careful analysis of all the constraints (e.g. site constraints in terms of accessibility) that will arise over the life cycle	[10]

cycle, while other categories are typical for the construction project, the operations period and the decommissioning project.

2.2.2. Qualitative and quantitative risk analysis

Risk analysis is the process of assessing the likelihood of an adverse event in a given context. In the context of this publication, the adverse event is the unsuccessful implementation of the new build NPP project based on economic factors.

Two key features of risks are ‘probability’ (the chance that a risk will materialize) and ‘impact’ (the effect of the risk if it materializes). In this regard, two types of risk analysis can be differentiated: qualitative and quantitative, depending on the way in which the likelihood of the event is estimated (qualitatively or quantitatively).

Qualitative risk analysis is a technique designed to descriptively review risks that have been identified and assign each one a probability and impact or consequences score. In a qualitative context, probability and impact are quantified with likelihood scales. Probability scales with five classes (from 1–5) and the class ‘not applicable’ (n.a.) are popular. The relative impact also has five classes (A–E), from negligible to extreme. Each risk is given a coordinate based on these classes, for example ‘3.C’. The column ‘remarks’ includes a more detailed definition of the risk.

Critically, clear definitions and guidelines are needed for the assessors to reduce the subjectivity in the analysis. For instance, ‘probability 1’ can be defined as ‘a risk that materialized only once or fewer times in previous projects.’ In contrast, ‘probability 5’ can be something like ‘a risk that materializes in the majority of projects’, while ‘impact A’ can be ‘impact up to US $1000’ and ‘impact E’ can be ‘the project will be abandoned’. So, while definitions can change across projects, what is extremely important is that all the organizations involved in the risk analysis of a certain project use the same definitions.

Analysed risks are usually displayed in a risk register or risk matrix (‘heat map’), which provides a good overview of the risks and their relative importance (see Fig. 2). As described above, each risk in the risk register is classified according to two parameters: likelihood (or probability) and consequences. Depending on the application, the scales for likelihood and consequences can be qualitative or quantitative.

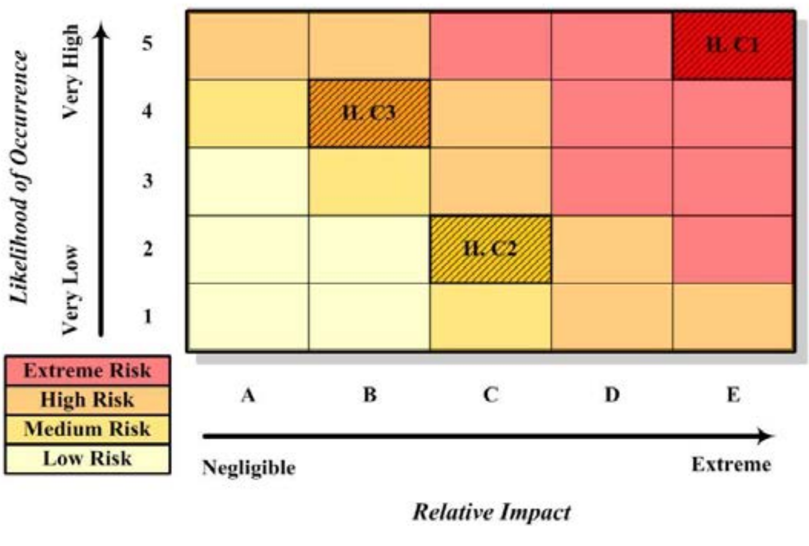

FIG. 2. An example of a risk matrix.

Quantitative risk analysis aims to correctly develop an overall risk model based on a detailed numerical analysis of individual risks. An appropriate base model needs to be selected for analysis. This could include a project's schedule, its cost estimate, a decision tree or the overall life cycle cost of an NPP. High quality data related to the risks are vital for the analysis to be accurate. So much of the effort for these analyses is related to the data gathering exercise.

There are various methods and approaches for quantitative risk analyses that are widely used worldwide for different purposes, mainly aimed at supporting NPP design, operation and maintenance. Such methods include probabilistic performance assessment (PPA), mostly applied for production losses, probabilistic safety assessment (PSA), used in safety assessment (see more details in Section 7.1), among others. PPA is a similar methodology to PSA used in the nuclear safety domain [12, 13]. PPA concentrates on the causes of production losses as an adverse event. A similar but more qualitative methodology, called performance assessment methodology, is presented in European Utility Requirements Volume 2, Chapter 18 [14]. Probabilistic performance assessment predicts the production duration curve of the NPP, considering:

(a) Operating experience from similar plants, systems and components;
(b) All systems that directly or indirectly affect the production of electricity;
(c) Redundancy of systems and components;
(d) Unavailability of systems and components due to preventive and corrective maintenance, failure rates of components, repair times, maintenance intervals and maintenance periods;
(e) Regulatory requirements due to failure in safety related systems and environmental limitations.

Probabilistic performance assessment modelling requires detailed knowledge of plant design and operation. Probabilistic performance assessment methodology can be used for:

— Estimating load factor, production duration curve and annual revenue;
— Optimizing the policy of maintenance outages and refuelling outages;
— Analysing the impact of design modifications, for example optimization of the redundancy of operating systems;
— Prioritizing training processes and optimizing mock-up training;
— Helping to identify risk-significant systems and components;
— Establishing maintenance planning and helping to allocate maintenance resources;
— Making possible operational risk informed maintenance classification of components.

Probabilistic performance assessment estimates the annual loss of production for different years and an average year, also considering random lengthy outages due to various reasons. The results can be used in the net present value (NPV) analysis when estimating the annual revenue. This can be done in many phases of the life cycle, in the early stage of the preparation, during design and construction, during operation and when optimizing the year of decommissioning. A coarse analysis of the units' operating experience from the same supplier may help compare bids.

During the design phase, PPA can demonstrate that the availability performance of the SSCs is sufficient to meet availability targets. It can be used to balance the design availability of the whole plant and to prevent the ineffective overdesign of SSCs. Probabilistic performance assessment can also reveal risks that may be difficult to identify without a systematic approach.

Probabilistic performance assessment is typically started before the detailed design phase by performing a historical review and analysis of operating experience. Details surrounding the causes of outages extensions, delays and startup problems are essential inputs to the analyses.

Probabilistic performance assessment requires a complete breakdown of the plant and related performance and maintenance data, especially for systems related to production and those analysed via failure mode and effect analysis tools.

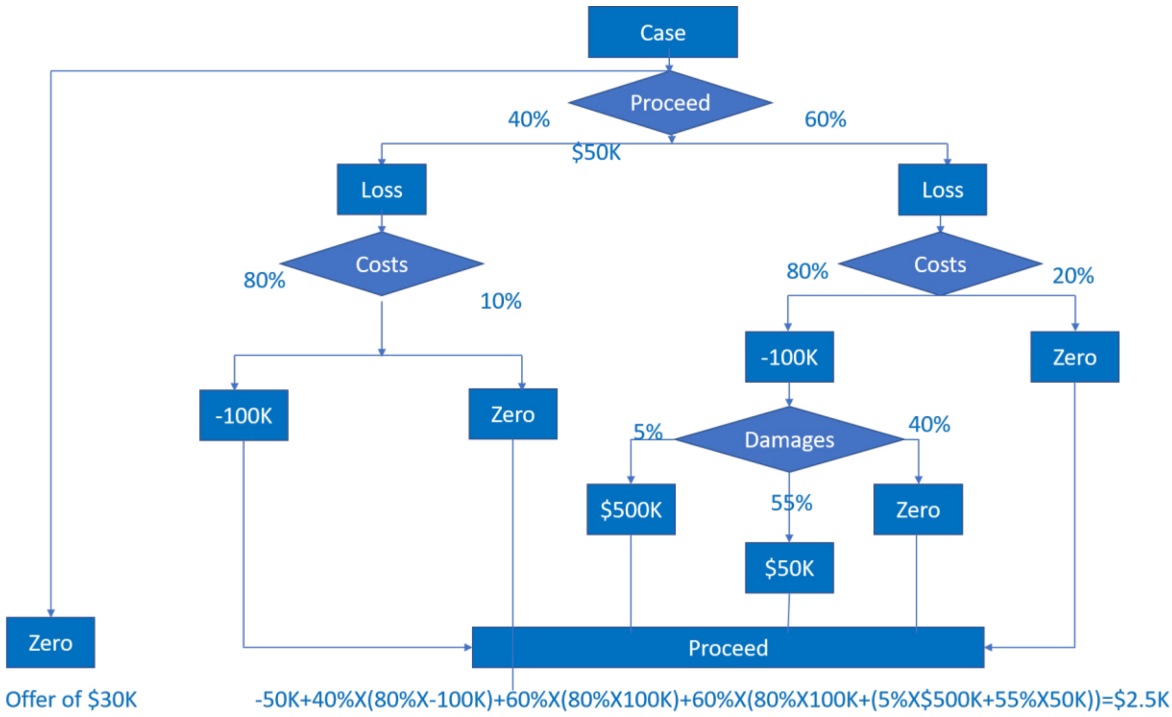

FIG. 3. Decision tree using flowchart symbols. Reproduced from Ref. [15].

After modelling and quantitative analysis, PPA allocates the unavailability of the plant to SSCs. Probabilistic performance assessment results should be used as one input for the maintenance classification of SSCs. Because the results of PPA are probabilistic, they include uncertainties. These uncertainties are part of the annual risk costs in the life cycle cost (LCC).

Another approach for risk analysis is the decision tree approach. The decision tree is a diagram that describes the implications of choosing one decision over one or another of the available alternatives. It incorporates the probabilities and the cost implications of future decisions and helps identify the expected monetary value of different decision paths. A simple decision tree is shown in Fig. 3. In quantitative risk analysis, it is useful to assess how different decisions that might be taken by an organization change the risks in terms of existence, probability and impact.

2.2.3. Risk strategies

Once a risk has been analysed, the risk owner needs to develop a strategy to address the risk. These approaches can be divided into three categories: risk reduction, risk retention or risk transfer. Each of these is discussed in turn below.

2.2.3.1. Risk reduction

Risk reduction involves measures designed to reduce the likelihood of an event occurring or mitigate consequences if the event occurs, or both. Events may include nuclear safety, radiological safety, industrial safety and environmental or economic concerns.

Techniques to reduce an event’s occurrence include engineering measures (e.g. modified designs or processes that eliminate a risk), training of employees, procedure improvements and enforcement of standards. Mitigation of consequences includes measures to avoid events from propagating and measures to reduce the economic impact of severe disruptions. Examples of mitigations might include identifying alternative suppliers in advance or dual sourcing to hedge the risk of a supplier not providing components that are of a sufficient standard. Risk mitigation measures can be pre-emptive, simultaneous-with-event or post-event actions.

Another dimension of understanding the reduction/control tool is to characterize risk management measures according to whether they focus attention on the behaviour of the individuals involved, the functioning of the physical assets (e.g. machinery, control systems), or the environment within which the event would occur.

2.2.3.2. Risk retention

Risk retention is a conscious decision by an organization to retain a risk that cannot be readily reduced or transferred to another party or is not economical or practical to transfer. For example, a large electric utility may choose to be the general contractor for a construction project and retain the risk for overall construction delays, cost overruns and revenue loss related to the project becoming operational. Retention does not mean that the organization does nothing to manage these risks. In the general contractor example, the utility may manage some of the risks of individual parts of the work by transferring them to subcontractors or insurers. However, the overall risk related to the project's in-service date would remain with the utility.

The probability and consequences of such risks should be reviewed, regularly and any new opportunities to reduce the impact should be based on new information. Risk retention often consists of a form of self-insurance, especially if the cost of transferring the risk is greater than the cost of retaining the risk and paying for any potential losses.

2.2.3.3. Risk transfer

Risk transfer implies that the original party exposed to a loss can obtain a substitute party to bear the risk. Insurance or fixed price subcontracting are typical examples of risk transfer. These transfers occur by contract, through the use of financial market instruments or by terms and conditions related to the sale and delivery of products and services.

In some cases, the risk is reduced through a transfer, whereby the risk accepting party can better manage individual risks through a portfolio effect. Insurance contracts, whereby an insurance company or companies can pool their risks and achieve lower overall variability, are an excellent example of such techniques. In other cases, the degree of risk stays the same, but it is transferred to another party (e.g. a subcontractor) who is willing to accept the increased variability of performance for a given price.

Most risk transfer mechanisms are some form of contractual agreement with another party. In contracting, the idea is to transfer the risk to the party that can best control the results, prevent the problem, manage the risk if it happens, or best absorb the impact. The contracting party usually pays a premium for being able to transfer the risk to the other party. Examples of risk transfer mechanisms include hold harmless agreements, incorporation, hedging in financial and commodity markets, operating lease agreements, warranties of quality or performance and insurance contracts.

2.3. IMPLEMENT RISK MANAGEMENT STRATEGIES

Once an organization determines the risk management strategies that it will use, they need to be implemented. Successful implementation usually requires the following:

(a) Assignment of responsibility or ownership for the particular risk;
(b) Commitment of the owner (ideally an organization and a specific person inside that organization) to address the risk;
(c) Resources (funding, personnel or other resources) to implement the strategy;

(d) Authority of the assigned resources to implement the strategy;
(e) Communication of information related to the strategy.

Residual risks that are not being actively managed (risk retained) are generally allocated to contingency management. A contingency is an allowance to manage risk and deal with any consequences during the project. Contingency can be assigned to various project activities or work packages based on the work being performed and assigned at the overall project level. A separate recovery account can be reserved for cases where contingency allowances are later determined to be inadequate.

2.4. MONITOR SOLUTION EFFECTIVENESS

Along the project life cycle, more data and information become available. Moreover, once specific work packages or phases are completed, the relative risk can be eliminated. For instance, at the end of the civil work, all the risks related to civil work can be eliminated, and the relative contingencies released or reallocated at the project level.

Monitoring implementation effectiveness is essential to determine if the chosen strategies are working or if further corrections are necessary. Reviews of project status, risk reduction status, the current status of risks (including identifying and adding new risks), contingency and recovery actions are recommended. A schedule for regular risk reviews at various levels of an organization is typically needed to ensure the completion of these reviews. A process to raise significant risks and issues from the lower levels of an organization to higher levels is also required. Lessons learned at this stage are also essential for the risk management of future projects.

3. SOURCES OF RISKS

Risks for an NPP come from a variety of sources. This section describes the sources of these risks, while later sections provide more details on the causes and impacts of these risks and the mitigating actions possible to deal with them.

The future of nuclear power is developing in a changing environment. This changing environment is characterized by tougher competition between technologies, changes in consumer behaviour, the development of new cultural values and evolving market design to comply with governments' short term imperatives.

IAEA Nuclear Energy Series No. NG-T-1.6, Management of Nuclear Power Plant Projects [15] on nuclear project management describes many influences on nuclear projects (Fig. 4). The influences can be from external stakeholders such as stakeholders, governments, regulators and industry, and internal organizational characteristics such as ownership structures, other projects that are underway, organizational culture, structure, processes, institutional knowledge and communication methods. These influences can generate risks for a nuclear project and should be considered part of a project's risk identification process.

The remainder of this section focuses on some of the risks stemming from these influences. The risks discussed include the following:

(a) External risks:
    (i) Project stakeholder related risks;
    (ii) Risks related to government policy, political climate and energy planning;
    (iii) Commercial and financial risks;
    (iv) Supply chain risks.

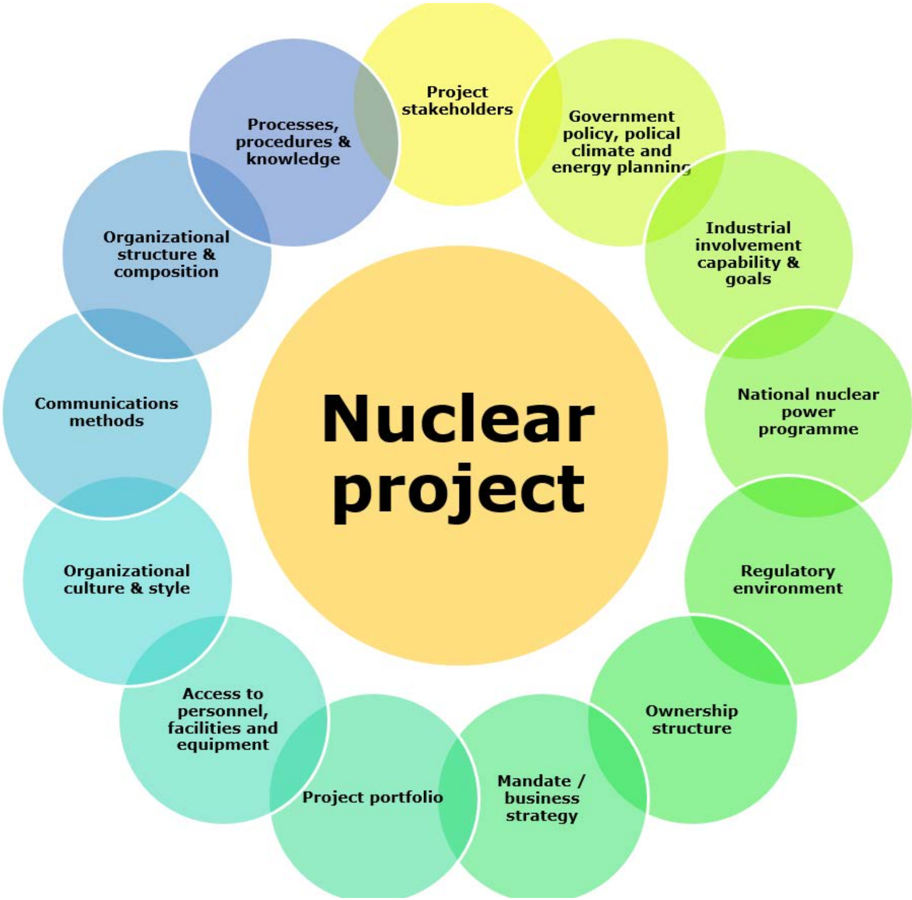

FIG. 4. Nuclear project influences. Reproduced from Ref. [15].

(b) Internal (organizational characteristic) risks:
  (i) Mandate and business strategy;
  (ii) Organizational culture and style;
  (iii) Access to personnel, facilities and equipment;
  (iv) Processes, procedures and knowledge.

Appendix I contains a comprehensive list of risks that may apply to an NPP project, organized into different category areas of strategic risks, preparation risks, construction risk, operational risk, human resources, commercial/financial risk and decommissioning risks.

3.1. EXTERNAL RISKS

External risks stem from outside the boundaries of the corporate and operating organizations, impacting on the project and its organizational culture and performance. The mechanisms by which the organization adapts to these external influences contribute to the organization's culture. In many cases, these influences can be introduced into the organization by its members. External influences can be identified, observed and reacted to but cannot be directly controlled or significantly changed by the organization.

Nevertheless, these factors influence the way an organization meets its objectives. For example, the regulatory body needs to understand and consider the impact of its procedures, programmes, policies and regulations on the licensee’s organizational culture and performance. It can be challenging to assess external influences on the organization, and they are often very country specific.

The following subsections describe some aspects of external risks. IAEA Nuclear Energy Series No. NG-T-1.6 [15] can be referred to for more detail.

3.1.1. Project stakeholder related risks

3.1.1.1. Stakeholders and their goals

Stakeholders can be categorized as internal and external. Internal stakeholders include project and corporate management, employees and other staff. External stakeholders are those whose activities are specific and linked to the company, such as financial and regulatory bodies, decision makers, non-governmental organizations, media, government and, ultimately, public opinion (including that in outside countries). In this section, we deal with external stakeholders.

Risk management needs to consider stakeholders’ concerns and their interactions. Risk management can only be useful if there is good comprehension of this context, and if an appropriate understanding of stakeholders’ expectations is established. If risk management does not consider stakeholders’ concerns, proper and correct answers to the risks might be inconsistent, and reaching the desired level of satisfaction could be impossible or very costly; the outcome of this will be a lack of confidence and poor conditions for the profitability of the industry.

It is essential to define the scope of risk management for each stakeholder and allocate the risks according to the project responsibilities. Certain stakeholders (e.g. regulators, governments) can have prescriptive authority as to whether a project can proceed or not and so need to be managed more carefully.

IAEA Nuclear Energy Series No. NG-T-1.4, Stakeholder Involvement Throughout the Life Cycle of Nuclear Facilities [16] provides details on stakeholder development considerations during a nuclear facility’s life cycle and guidance on implementing stakeholder involvement programmes. A well implemented stakeholder management process is essential to manage project risk.

3.1.1.2. Allocation of risks to stakeholders

All stakeholders having identified risks should manage their own risks. The owner/operator should manage any risks that are common to all stakeholders.

Each organization involved in the NPP project (e.g. the owner/operator and the NPP contractor and subcontractors) should have a risk register that includes the risks contractually allocated to them. A part of the risk register should be defined contractually as the common area, where the risks and their mitigation can be discussed regularly (e.g. through project review meetings). At the same time, each party has its risks that are not discussed with the other party.

3.1.2. Government policy, political climate and energy planning

— The government has a key role in defining energy policy, market designs, pricing models (including carbon pricing), electricity demand models and targets, electricity sector regulations, industrial involvement strategies, environmental regulations and, in some cases, the list of acceptable NPP vendors. Thus any change in government or government policy is a risk for long duration nuclear projects.

— The government’s consistent implementation of the above policies and initiatives and careful support if they change during the construction phase are critical for project success.

— Through its involvement in the energy policy decision making process, the government can give confidence to investors and provide information on the energy policy to the public and all stakeholders. Ultimately, funding for NPP projects should be easier and cheaper as public confidence increases.

Hence, the government may act in aspects of financing such as the discount rate on a regulated market or the design and implementation of a suitable financing framework in an unregulated market.
— Legislative institutions may vote on energy policy and may also provide oversight of its implementation.

3.1.3. Commercial and financial risks

Financial risks are significant for nuclear projects due to the high capital cost and long operating life of NPPs. The risk premium required by the financial sector is thus usually higher than for other electricity generation technologies. The availability of financing is often the factor that decides whether a project will proceed or not. Risks related to the financing of a project include the composition and risk appetite of the investors (governmental and non-governmental), their debt paying and investment ability, the potential for changes in financial markets (e.g. interest rate and exchange rate risks or the broader insurance market) and energy policy changes (e.g. carbon pricing, electricity market design) that may impact on financial viability.

Financing risks are influenced by the potential for project delays and related cost overruns. The direct and indirect costs of delays can lead to protracted lawsuits designed to allocate cost remedies. Construction cost uncertainties can lessen when experience has been gained with the first construction projects and where experience accumulates with each design.

The structure of the electricity market impacts on nuclear financial risk profiles. Regulated markets allow for longer term predictability of electricity prices. In contrast, unregulated markets, especially those that do not capture the value of nuclear advantages such as secure baseload and carbon free power, can be more challenging to navigate. Revenues can become lower than the operating cost over time, and premature shutdowns of operating plants can occur. Policies such as ‘contract for difference’, ‘feed-in tariff’, or ‘regulated asset base’ (RAB) can transfer market risks from the operators to consumers or taxpayers.

For instance, in the United Kingdom RAB is currently considered to be a relevant way to finance new build infrastructure. Critics have raised concerns about RAB, such as whether it transfers risks to the consumers, with risks they cannot control. This concern may be dealt with by implementing effective governance. Another answer could be to substitute the complexities of the RAB with direct government financing. Capital expenditure still involves equity risk that has to be funded. But state funding would bring down the electricity prices needed to service a project’s financing pretty sharply.

Governments should work with owner/operators to develop appropriate solutions. A win–win solution can be designed, addressing the best possible financing for an owner/operator at an agreeable price for its customers. Long term agreements on prices, for instance using a contract for differences, can assist. Critically, the design of an electricity market and how nuclear investment can be included in this market needs to be optimized at a country level according to the specific characteristics of the country. Nevertheless, international experience should be carefully incorporated.

Regardless of how risks are managed and transferred, it is firstly important to identify the key risks, which might include:

— Volatility of prices of resources;
— Volatility of prices of electricity on the market;
— Volatility of exchange rates;
— Volatility of interest rates — when they are high, projects with high capital costs are disadvantaged, and capital costs need to be recovered through a long operating lifetime;
— Risk bearing willingness and capacity of investors (shareholders, financial institutions);
— Insolvency of the main financing bodies/supply chain partners;
— Funding availability at the country level;
— Ability to fulfil contractual obligations (liquidated damages);
— Weighted average cost of capital (WACC) — this is the overall challenge — a higher cost of capital for nuclear projects can lead to a higher cost of electricity than for other generation technologies.

This might not be consistent with energy policy goals unless a single project provides a series benefit effect that achieves energy policy targets in several countries.

Some methods available to manage financial risks:

(a) Lifetime based financial analysis (from preliminary work to decommissioning);
(b) Use of value at risk methodology by energy companies;
(c) Portfolio diversification in response to market pressure;
(d) Calculation of externalities and valuation of impacts (the environment, safety, health).

Economic risk evaluation, including lifetime risk analysis, is discussed further in Section 4.

There are several possibilities to reduce capital costs, including standardizing the series of plant designs, supplying several operators, replicating several reactors of the same design on one site, ensuring that larger capacities lead to economies of scale, and the predictability of the licensing process.

3.1.4. Supply chain risks

Supply chain participants can introduce risk into an NPP in many ways. Suppliers can be late in their delivery (or become unable to deliver at all) or can deliver components with non-conformities. Moreover, substandard, counterfeit or fraudulent parts or services can cause unsafe or uneconomical plant operation, regulatory delays or even lack of public support for the nuclear programme. Material losses during operation or warehousing can impact on overall costs. Suppliers can introduce cybersecurity risks into the NPP or the corporate organization or damage a company's reputation.

The localization of purchases of equipment or services is required by some NPP owners or even by the government for political or commercial reasons. Localization may cause problems if the local subcontractor or manufacturer is not capable of delivering products or services according to codes and standards. The import of components or know-how for particular technologies may also be limited for political or commercial reasons.

Recent IAEA Safety Standards such as IAEA Safety Standards Series No. GSR Part 2, Leadership and Management for Safety [17] define the requirements for managing the supply chain and emphasize the need to ensure that a culture for safety is promoted throughout all supply chain levels. IAEA Nuclear Energy Series No. NP-T-3.21 [11] covers procurement and supply chain issues in detail and includes a section on typical risks and risk management.

Risks, impacts and measures related to procurement and supply chain are discussed in Section 6.3 of this publication.

3.2. INTERNAL RISKS

Internal risks stem from inside the corporate and operating organizations' boundaries, impacting on organizational culture and performance. The organization has more direct control over these influences, but individual divisions within the organization may have limited control over some aspects, and a company's culture evolves and may be difficult to change. The following subsections discuss some aspects of internal risks. IAEA Nuclear Energy Series No. NG-T-1.6 [15] can be referred to for more detail.

3.2.1. Mandate and business strategy

Top level managers set organizational objectives and priorities, allocate resources, promote safety and establish long range planning strategies. Departmental and individual objectives are tied to these goals and strategies. Changes in an organization with respect to these strategies and objectives can have wide ranging implications for risk management of nuclear projects, including changes in budgets, timelines, leadership and contract approaches, and they can even impact on a decision to proceed [18, 19].

3.2.2. Organizational culture and style

Organizational culture refers to the shared assumptions, norms, values, attitudes and perceptions of an organization's members. Every employee enters the organization with values and attitudes concerning different aspects of work.

The organizational culture influences the personal values and attitudes of each employee.

The mission of an organization reflects its organizational culture. It is communicated throughout the organization so that employees should follow the same objectives. The way management promotes safety and how it is prioritized influences all levels of an organization. Official work regulations and work practices, and individual behaviour, contribute to employees' perception of the organization's culture. This perception subtly influences behaviour and contributes to changes in the existing organizational culture.

Organizational culture is not always tangible but influences safety relevant behaviour in everyday situations. It is under continuous change, and management needs to control the direction of the changes. If management does not promote awareness of safety related events, awareness of risks among staff may deteriorate. Non-compliance with rules and procedures may increase, and the risk of deterioration of the organizational culture may increase significantly.

The following methods may be useful for the management in gathering data about risks related to organizational factors:

(a) Behavioural observations: the investigator is present at the site and observes organizational behaviour and work practices through meetings, shift turnovers, and other activities;
(b) Event review: following an event, investigators collect different information about the event to determine the event's contributing and root causes;
(c) Survey, questionnaire: a standardized method for gathering information;
(d) Trend analysis: performance data are gathered over time and analysed to determine trends.

Adverse events may increase when workers have low morale. In this condition, they pay less attention to detail, behaving in less prudent ways, and generally exhibit less responsibility, which can have detrimental effects. To the extent that the organizational culture is supportive, worker morale should be raised, resulting in fewer and less severe negative consequences. Tuler et al. found that organizational culture is an important mediating factor in determining team members' individual risk decisions and the team's overall level of performance. A bibliography of studies on this phenomenon is provided in Ref. [20].

A risk for any organization is self-satisfaction when everything works well and the feeling that nothing is worth improving. To mitigate the risks related to self-satisfaction and blindness to small warning signs, safety critical organizations should develop the organizational learning process to improve future performance continuously. In this process, they identify problems and learn from their experience and the experience of other utilities.

Organizational learning is specifically related to identifying and solving problems, mapping the trends of problems, monitoring these trends and promoting learning. It also should promote a common understanding of roles and responsibilities concerning work practices and processes. Furthermore, it is associated with training, where organizational experience and generic organizational issues can be addressed, and with organizational knowledge, tacit knowledge coming from past experiences that may be transformed.

The organizational learning process should be evaluated regularly using self-evaluation and peer review to improve the process and to decrease risks that make the process ineffective. Such risks can include:

(a) Excessively formal scrutinization of organizational events;

(b) Excessively deterministic and technical approach to events;
(c) Blindness to common root causes of different events;
(d) Unwillingness to see similar causes in their own organization to those from external experience;
(e) Cessation of continuous improvement.

3.2.3. Access to personnel, facilities and equipment

Projects need resources in the form of personnel, facilities and equipment. The extent to which the NPP project has access to these is a key factor for success, and a lack of these comprises a significant risk. Resources may be available within the current organization, they may need to be developed through training, or they may need to be contracted for.

Vendors and contractors may have numerous simultaneous overseas and national projects and may take on more business than may be optimal with their relatively constant level of resources. Overcommitment of such resources may result in project delays or non-optimal scheduling of project preparation activities. At the same time, the owner may have pressure to start the construction as soon as possible (before proper pre-project planning is complete) due to political, public or business issues. These two drivers may cause early project difficulties.

An important feature of a nuclear project that impacts on human resources is the project location. The project location is almost always unique to the project and far away from the project team's home base. The project team thus works in an unfamiliar environment, particularly if it comes from another country. The methods for acquiring project personnel can vary significantly in different parts of the world, and managers of such projects need to be aware of local conditions and customs.

If local staff are not available, and specialists from foreign countries have to be hired to support construction, operations or maintenance, the facility's labour costs may be significantly higher than expected. If maintenance specialist experience is not available during the first few years of operation, delays in maintenance and possible equipment damage may be experienced. Inadequate training, lack of knowledge of the detailed design and poorly developed procedures for maintenance may cause difficulties for the SSCs being maintained. Poor configuration management (CM) and inadequate understanding of the technical requirements may impact on nuclear safety or the capacity factor of the NPP. Recruitment of operation and maintenance and engineering support staff during the construction phase and their involvement in commissioning is recommended.

Developing a human resource plan in which roles, responsibilities, required skills and reporting relationships are identified and documented is a useful asset to mitigate human resource related risks. At construction phases, management should consider the following:

(a) Recruiting the construction team: confirming resource availability and obtaining the team necessary to complete the assignments;
(b) Developing the construction team: improving competences, team interaction and team performance, and familiarizing them with the local culture and rules;
(c) Managing the construction team: tracking team member performance, providing feedback, resolving issues and managing changes to optimize performance.

In the nuclear industry, the facility's industrial life is almost twice the professional life of the employees working there. If there is a lack of domestic professionals, hiring foreign experts/employees is a challenge, with the rising risk of misunderstandings (among different safety and management cultures or languages).

When exporting nuclear technology to another country, the vendor will provide the operator staff training, which could last for several years. Young engineers lack experience and need mentorship and coaching support from senior professionals. This is coupled with a need for an established or lifetime career in the industry. There is an ongoing balancing act between insufficient training and capacity building inside the company and universities to continuously replace needed professionals.

Typical risk sources related to human resources are:

- — Retirement of professional staff;
- — Unfamiliarity with a culture or rules in a country;
- — Limited supply of nuclear experts and suppliers with numerous simultaneous projects all around the world;
- — Dissatisfaction of foreign workers due to inadequate social and religious services on site;
- — Labour mobility and hiring restrictions;
- — Labour disputes;
- — Abrupt changes in labour laws;
- — Lack of training;
- — Specific industrial characteristics within the region;
- — Lack of safety culture and quality culture;
- — Lack of mentorship.

IAEA Nuclear Energy Series No. NG-G-2.1, Managing Human Resources in the Field of Nuclear Energy [21] and IAEA Nuclear Energy Series No. NG-T-2.2, Commissioning of Nuclear Power Plants: Training and Human Resource Considerations [22] provide information on managing human resources in the nuclear energy field in general and during commissioning specifically.

3.2.4. Processes, procedures and knowledge

3.2.4.1. Processes and procedures

The process of the identification, development, verification and implementation of rules, procedures and methods is based on standards for work activities and often on an analysis of function and tasks. The word proceduralization is a neologism created to emphasize the process involved in developing and maintaining internal standards for work activities. Proceduralization is not only limited to control room procedures but also includes formalization and standardization of all work activities on all organizational levels (e.g. quality assurance standards). The concept of proceduralization includes identifying the functions and tasks in work processes, developing rules and procedures, verifying and implementing them, and finally evaluating and modifying them, if necessary. The proceduralization process incorporates learning from past experiences and ensures the participation of end users and human factor specialists, and appropriate inclusion in training programmes. This factor is linked to the coordination of work, communication, and training factors.

Procedures can reduce the risk of performance errors by ensuring that the steps followed have been reviewed for correctness and that the procedure contains the sum of the organization’s collective knowledge regarding how to perform an activity efficiently and safely. The Institute of Nuclear Power Operations (INPO) identifies procedure use and adherence as one of its good practices [23].

The following steps are seen as useful in the development of good procedures:

(a) Standardize and formalize recurring and critical work activities, taking into consideration personnel experience and knowledge;
(b) Provide clear information within procedures on the potential risks of activities and critical steps;
(c) Incorporate human factors, ergonomic principles and experience into the procedures;
(d) Ensure that the workers who will use the procedure participate in its development, design and modification;
(e) Strike a balance between the strict proceduralization and standardization of work activities and the skills and experience of the personnel;
(f) Include quality management steps within the procedures.

Work methods are a part of an organization's processes and procedures. It is imperative to develop a process for planning, scheduling, integrating, allocating and implementing resources and establishing responsibilities for coordinated work activities. The 'co-ordination of work' factor defines how work is to be carried out in a formal way, taking the allocation of technical, financial and time resources into consideration. It sets out the framework for the assignment of personnel to required tasks and the interactions between different positions. It defines the interdependences of work activities and, consequently, their interfaces, and makes the interrelations of all the work activities transparent and traceable. This results in a common understanding of how things are done and how they relate — that is, organizational knowledge.

3.2.4.2. Organizational knowledge

Organizational knowledge is the understanding personnel have regarding the organization's formal and informal processes, procedures and practices, and how work is accomplished. Organizational knowledge is of two types. The first type encompasses the members of the organization's views on work reality — that is, how the organization functions — which is gained by being part of the everyday working environment.

This includes their risk related knowledge of:

— The mission of the organization;
— How budgets, time and technologies are distributed;
— The way work activities should be carried out formally;
— Attitudes toward procedure adherence;
— How the work practices are accomplished (which may be formal or informal).

The second understanding of organizational knowledge may be characterized as 'hidden knowledge' present in employees' memories, which is not captured unless it is made explicit and documented adequately. Employees accumulate experiences and become more expert in their fields by doing their job day to day, and this expert knowledge is only available to them because it is their stored knowledge. Organizational knowledge or 'corporate memory' often plays a more crucial role than documented procedures in official work practices.

The main risk related to organizational knowledge is the loss of retained knowledge. Individuals may retire or otherwise leave an organization, or key roles may be outsourced and leave gaps in skills or knowledge. Lessons learned may end up being learned all over again, with negative consequences. Knowledge retention and human resource strategies can be formulated to help reduce this risk, and the IAEA has issued numerous publications in this area, including Refs [24–27].

4. ECONOMIC RISK EVALUATION

Making an investment decision to proceed with a new nuclear project requires, among other things, an economic evaluation to determine whether the financial outcomes of the project meet owner requirements for financial return while delivering electricity to the grid and end customers at a competitive price. A robust economic evaluation will account for the risks that can impact on the infrastructure over its lifetime. Evaluating such risks, including their probability and potential consequences, and then developing mitigation plans, on both an individual and an integrated basis, helps organizations make strategic and operational decisions.

Evaluating risk using technical and economic indicators is important to quantify each risk's impact and establish the basis for its management. Section 2 identified methods of assessing, quantifying and

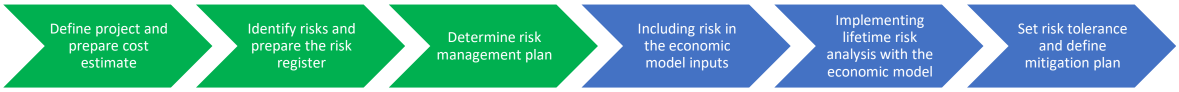

FIG. 5. Project analysis flow diagram.

managing risk, while Section 3 set out the sources of risks that might impact on a nuclear power project throughout its lifetime. A critical step is to build a risk register that identifies the risks, ranks them, sets out mitigation plans, including costs, and identifies an owner for each risk. Only once this risk register has been completed should the project proponent move on to this step, incorporating risk into the economic model.

The process flow outlined in Fig. 5 will begin once the risk register is complete, and the last three steps are discussed in Sections 4.4 and 4.5 below. First, a brief introduction to the approach to economic modelling of a project will be described, including how to ensure that risks are considered appropriately to determine project viability. Risks can ultimately become a cost that impacts on the project economics, either initially as funds are included in the project cost to accommodate risks, or during implementation when risks come to pass, and the project is affected with increased costs. A distinction should be made at this stage between 'downside risk' (threats) and 'upside risk' (opportunities[1]). Investors usually look at both and adjust their expectations in terms of returns accordingly. A robust economic model aims to support decisions on how best to manage risks and then provide a realistic and reliable prediction of the project's financial outcome. Once the project is underway, this analysis should be kept up to date, but it should always be acknowledged that there is no substitution for good project management to keep a project on track and ensure that it meets its intended outcome.

From the methodology point of view, probabilistic approaches enable variation and uncertainty to be quantified, mainly by using probability distributions instead of fixed values in risk analysis. A probability distribution describes the range of possible values (e.g. for cost overrun) and shows which values are most likely within the range. The result of a probabilistic risk analysis is shown as a distribution, showing the range of impacts that are possible and which impacts within that range are most likely. A quantitative and probabilistic approach also makes it possible to have a unique, shared and transparent metric, allowing for an objective evaluation of different risks and mitigation strategies for other processes during different parts of the NPP's life.

4.1. MODELLING NUCLEAR PROJECT ECONOMICS

Determining a project's value requires assessment of the cash flows, both in and out, over its lifetime. A commonly used approach to determine financial viability is to calculate the NPV. The net present value considers how cash outflows from capital and operating expenditures (CAPEX and OPEX) — and cash inflows from revenues from the sale of electricity — are distributed over the economic life of a power generation project (including decommissioning). The net present value is calculated by discounting the expected cash flows (CFs) of the project starting from (see Fig. 6.) the project development phase (negative CFs), through the engineering, procurement and construction phases (negative CFs), the operational phase (positive CFs) and the decommissioning phase (negative CFs). Discounting is a financial valuation technique primarily used to value a stream of future cash flows. Discounting is based on the notion of the *time value of money*: a dollar is worth more today than it would be worth tomorrow.

[1] An example of upside risk is a situation where the government chooses to tax carbon emissions heavily, which would provide nuclear (and clean energy sources) with a competitive advantage.

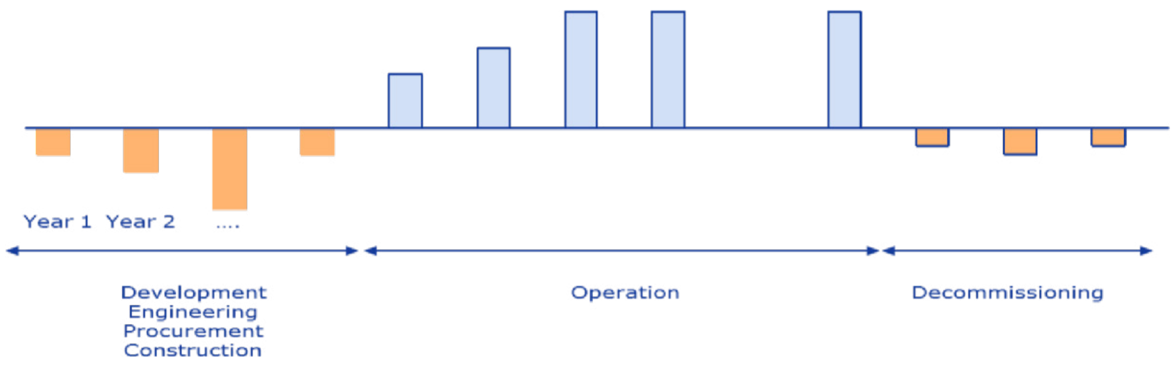

FIG. 6. Typical cash flow distribution for a project.

The net present value is the difference between the present value of cash inflows and cash outflows. Equation (1) is used to calculate NPV:

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \tag{1}$$

where C_t is net cash inflow during the period t (paid at the end of each period), r is the discount rate and T is the number of equal periods (usually years).

By definition, a discount rate is a measure of risk, and choosing the appropriate discount rate is essential for the analysis. For government projects, the discount rate may be the cost of funds to the government or a social cost of capital (defined as a reflection of a society's relative valuation of today's well-being versus well-being in the future). For projects undertaken in a regulated electricity market, the discount rate is generally set to the weighted average cost of capital (WACC) of the organization undertaking the project [28]. The WACC is a calculation of a firm's cost of capital in per cent. Each category of capital is proportionately weighted, or, in other words, is the cost to the firm of raising funds to undertake its activities. All capital sources, including common stock, preferred stock, bonds and any other long term debt, are included in a WACC calculation. A firm's WACC increases as the volatility of the price of an asset of the firm compared to the volatility of market prices in general, such as a stock index, increases, and the rate of return on equity increases. An increase in WACC denotes a decrease in valuation and an increase in risk. To calculate WACC, multiply the cost of each capital component by its proportional weight and take the sum of the results. The method for calculating WACC can be expressed in Eq. (2):

$$\mathrm{WACC}\ [\%] = \frac{E}{D+E} R_{\mathrm{e}} + \frac{D}{D+E} R_{\mathrm{d}} (1 - T_{\mathrm{c}}) \tag{2}$$

where R_e is the cost of equity, R_d is the cost of debt, E is the market value of the firm's equity, D is the market value of the firm's debt, $E/(D+E)$ is the percentage of financing that is equity, $D/(D+E)$ is the percentage of financing that is debt and T_c is a corporate tax rate.

Three parameters can be used to assess the project outcome using discounted cash flow analysis — NPV, discount rate and electricity price. Fixing two of these parameters and calculating the third provides different but equivalent approaches to financial assessment.

First, the discount rate and price of electricity can be the input, and NPV is the output. A positive NPV indicates that a project's projected earnings (in present money) will exceed the anticipated costs (also in current money). A project with a positive NPV is viable, as it is expected to exceed the rate of return required by the project's shareholders. If the NPV is negative, the project is not feasible, as shareholders will not meet their required return; that is, the rate of return will be less than the WACC.

Alternatively, the analysis can calculate the internal rate of return (IRR), which is defined as the discount rate at which the NPV of a project's cashflows becomes equal to zero. IRR calculations rely on the same formula as the NPV. Once the IRR is determined, it is then compared to the WACC to determine if the desired rate of return will be achieved.

Finally, an approach can be used where the WACC (discount rate) is fixed, and the price of electricity is calculated to provide a result for the analysis of an NPV equal to zero. This is often simplified to calculate a 'levelized cost of electricity' (LCOE), that is, the fixed cost of electricity (same cost each year over the project operating life) at which discounted costs equal discounted revenues. The levelized cost of electricity compares different projects (often different technologies of power plants) and ranks their competitiveness. However, for a specific project, and to assess project viability, the actual cost of electricity should be modelled year by year (e.g. to include escalation).

The inputs required to create a cash flow model are listed below.

4.1.1. Cost assumptions

(a) The capital cost to design, license and construct the plant. This will include all costs from site acquisition, securing regulatory approvals to build and operate the plant, to the actual costs to build the plant, including all materials and labour until the unit is declared to be in service and is ready to provide electricity to the grid.
(b) Operating costs consisting primarily of the labour costs to operate the plant (both the owner and the contractors), fuel, materials (spare parts and consumables) and financial costs, such as insurance.
(c) Capital improvements during operations. Modern nuclear plants are expected to operate for a long time, from 40–80 or more years. During this time, the plant will require capital improvements to replace critical components or facilitate upgrades or investment to enable long term operation.
(d) The cost of end-of-life liabilities. This includes an allowance to ensure that all wastes can be safely stored and disposed of at the end of plant life and that the plant can be decommissioned once it is out of service. These costs are usually estimated, with the estimates updated periodically over the plant life, and with funds collected from the electricity customer as an annuity spread over the plant's operating life. This ensures a fully funded account to ensure that these activities can be carried out once the plant is out of service, and there are no longer revenues from selling electricity.

4.1.2. Schedule assumptions

(a) The construction period, including both the time to develop the project and secure approvals and the time to physically construct the plant. It is important to capture when money starts to be expended (cash outflow) until the plant is in service and produces revenues (cash inflow).
(b) The operating period — how many years the plant is to be operated.
(c) The decommissioning approach — will the plant use prompt or delayed decommissioning, meaning will the plant be disassembled soon after the end of life, or will it be placed in a safe storage state for some time before final disassembly?

4.1.3. Economic and financial assumptions

(a) The discount rate — usually defined as the WACC (although this may differ for some government led projects that may use a social discount rate).
(b) The optimal approach to modelling would include the financing plan's details, including debt/equity ratio, the cost and tenor of debt and the required equity return of the investors. This allows for any of these parameters to be evaluated further in a sensitivity analysis.
(c) The escalation rate or the expected rate of inflation in the local economy.
(d) Exchange rates for equipment and services procured in foreign currency.
(e) Tax rates and any special tax incentives or deferrals.

4.1.4. Revenue assumptions

(a) Usually, revenue is driven by two parameters: the price of electricity and the amount of electricity generated. Other revenue sources (e.g. cogeneration, desalinization) may also be relevant.
(b) The price can be set out as described above or can be calculated as the model output. The electricity price assumption will depend upon the project model (e.g. regulated, merchant plant, PPA).
(c) Electricity generated is based on two parameters, the planned outage rate (the amount of time spent for scheduled outages for plant maintenance, improvements and refuelling) and the forced outage rate (the rate of unplanned outages to correct unanticipated plant issues that force the unit not to operate). This is all predicated on market demand for selling all the electricity generated by the plant. Variations in this assumption would be addressed as a risk.

4.2. DRIVERS OF LIFETIME ECONOMICS OF NPPS

Using a model, as outlined in Section 4.1 above, the next step is to understand the parameters that have the largest impact on the project's economics. The LCOE can describe the economics of power generation by an NPP. NPPs are generally characterized as having relatively high capital costs with long project schedules, followed by an operating period with low and stable operating costs. As a result, the most impactful economic parameters for the project are the discount rate (or WACC) and the capital cost. This can be seen in the tornado diagram in Fig. 7, where the impact of each of the parameters on the LCOE is calculated by varying each parameter up and down by 50%.

The largest sensitivity is to discount rate, followed by capital cost (or overnight cost). The discount rate is important because of the relatively long project schedules for nuclear projects that incur high financing costs before the start of operating revenues. Capital costs represent the largest economic input and thus impact on the output relative to its share of lifetime costs, with all of that coming early in the project life cycle, and so having the least amount of discount compared to future revenues that are discounted from further ahead.

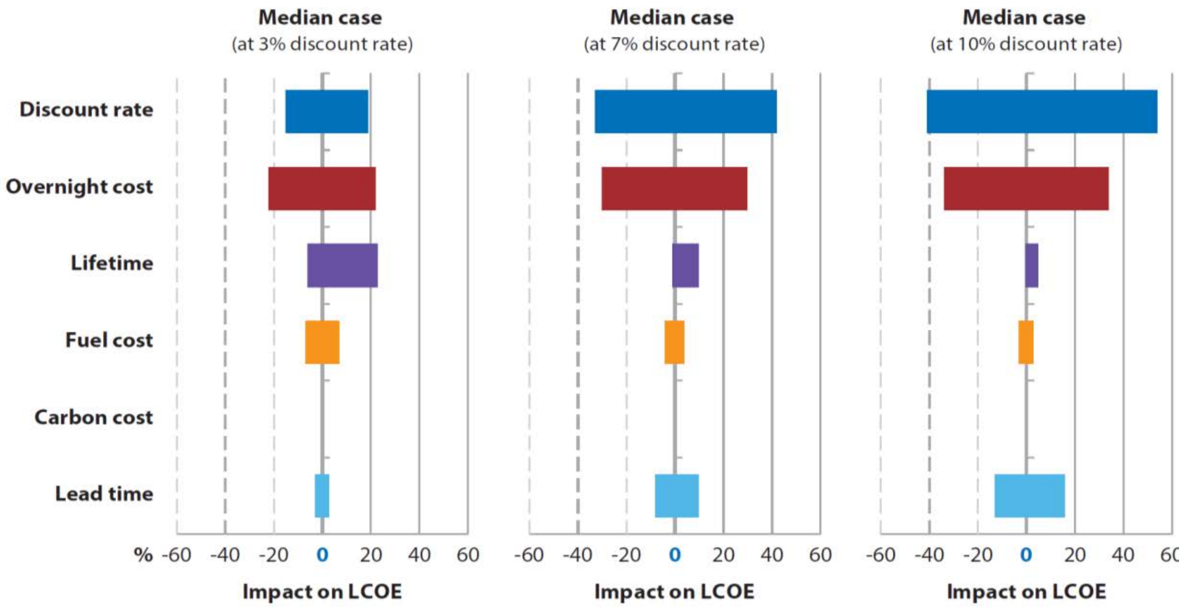

FIG. 7. Tornado chart — nuclear. Reproduced with permission from Ref. [29].

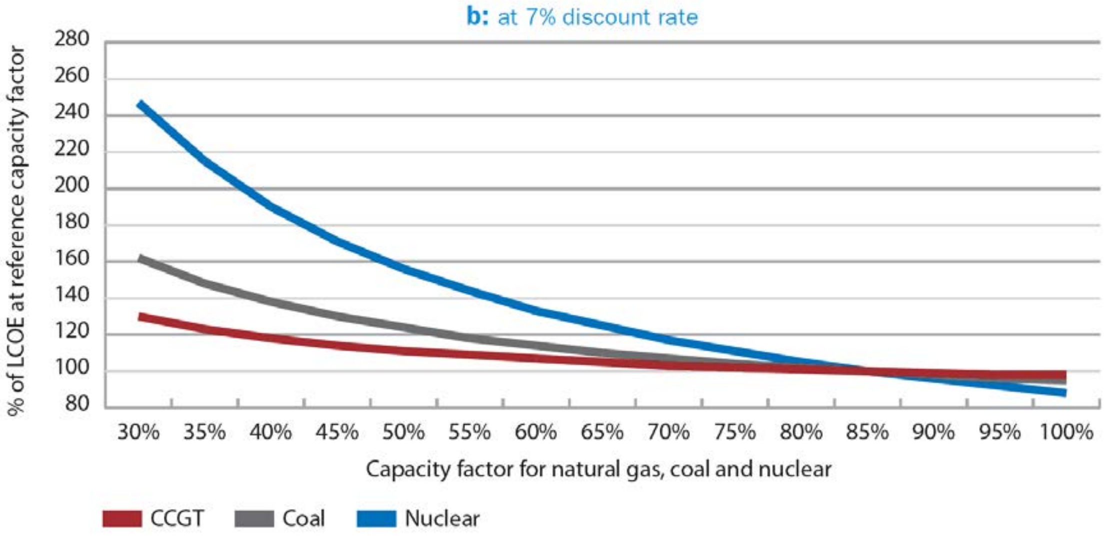

FIG. 8. LCOE as a function of capacity factor. Adapted from Ref. [29].

Once the unit is in operation, the sensitivity is to generation. In Fig. 8, this sensitivity is expressed as a capacity factor, which is the actual generation relative to the total possible generation if the unit is operating at 100% output for the entire year. This, again, is clear, as revenues are a simple function of the price of electricity times generation. Since most costs are fixed and not a function of generation, this explains the large impact of reduced generation. Of course, the operating and maintenance costs are also important and should also be managed.

While the risks associated with all of the inputs described in Section 4.1 need to be assessed, priority should be given to those risks that impact on the three most sensitive parameters: discount rate, capital cost and generation revenues.

4.3. OPTIONS FOR MANAGING RISK

Once all the risks are collected and assessed in a risk register, as described in Section 4.2, the next step is to evaluate how they can be managed and included in the economic assessment.

Section 2.2.3 lists three risk strategies: risk reduction (i.e. mitigation), retention and transfer. Risk retention can be managed by adding a cost to cover the retained risk. Risk transfer can be managed with two strategies, by transferring risk through contracting and by passing the risk onto a third party. The resulting four approaches to managing risks are shown in Fig. 9.

4.3.1. Transferring/contracting out of risk

When structuring a project (which is the approach to contracting and arriving at an agreed sharing of risks among project stakeholders), the risks can be allocated to different project participants. The type of contract structure is selected to address risk ownership; for instance, some risks will be carried by contractors and subcontractors as they accept a fixed price for their product or service. At the other end of the spectrum, the customer may accept a large amount of risk in a regulated market where most costs are passed through to the customer, or their risk may be limited in the case where the owner accepts a power purchase agreement with a pre-agreed price for electricity that may only be adjusted for a minimal set of unexpected events. Addressing risk sharing in contractual relationships is a complicated task. When undertaking this, it also has to be remembered that risk sharing or transferring is a technique to manage

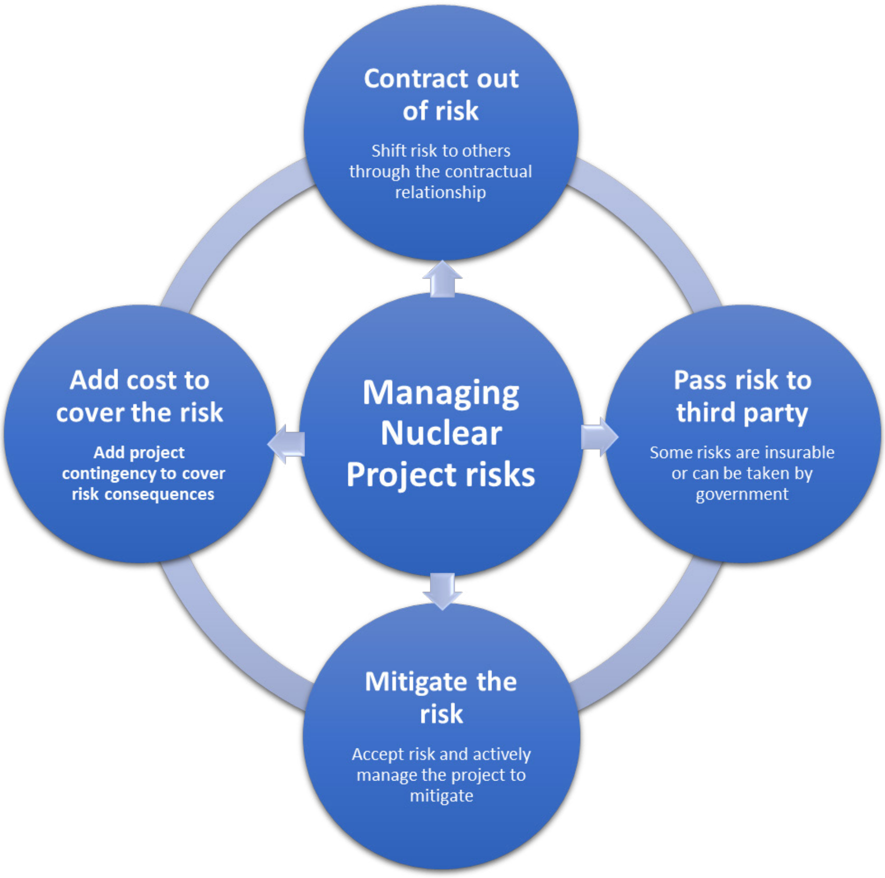

FIG. 9. Approaches to risk management

risk, not remove it. After all, there is no scenario where a contractor or subcontractor fails and the project succeeds. It is important not to try and push risks onto a party that cannot manage that risk and understand there is always a price for taking on risk; any party accepting a risk will include an allowance for it in their price [30].

4.3.2. Pass risk to third party

Some risks are outside of the control of the project stakeholders and can be covered by insurance. One example is construction all risk insurance that protects from accidents or extreme weather events. Insurance can be costly and coverage is generally limited to an identified set of events. However, very often projects carry insurance to address these low probability unexpected events that sometimes have large consequences. Given the nature of the nuclear industry, some risks are best taken on by governments, such as nuclear liability (the consequences of a nuclear accident) and the long term liabilities of nuclear waste management and project decommissioning, as these are so far into the future that the continuity of the project organization cannot be assured (e.g. another party may not be able to cover the risk financially or may even no longer exist).

4.3.3. Mitigate the risk

This is the broadest category. The best approach to addressing risks is to manage them actively. As discussed in Section 2, there is no replacement for identifying and assessing risks early and then taking swift action to mitigate them, reducing them to an acceptable level. They then have to be actively managed to ensure that the mitigation plan is ready to minimize the consequences if they occur.

4.3.4. Add cost contingency to cover the risk

When all has been done to manage and control risks, there will remain the likelihood that some of these risks will come to pass and will impact on the project. In this case, the project has to include a project contingency, in terms of both time (for schedule delay risk) and costs, to accommodate the consequences within the project budget. How this can be calculated will be discussed further below. Nuclear projects have to be competitive with alternative forms of generation. Therefore, the objective is to add sufficient contingencies to cover risks and provide an opportunity for the investors to earn their desired return while ensuring that the cost of electricity to the customer remains competitive. Not managing project risks through other means adequately and adding too much contingency to compensate will have a negative impact on the project economics and viability.

4.4. ACCOUNTING FOR RISK IN THE ECONOMIC MODEL

The economic model described in Section 4.1 should address risk at two different levels. First, the main parameters should incorporate risk into their base case input assumptions (Section 4.4.1). The base case of economic analysis can then be developed. This would be followed by lifetime risk analysis (Section 4.4.2) by considering scenarios to consider those risks not fully covered by the base case's model inputs.

4.4.1. Including risk in the economic model inputs

The risks are included as inputs to the model through two main parameters, discount rate and project contingency.

Discount rate, by definition, is a measure of risk. In financial theory, a riskier project will require a higher rate, while a lower risk project will attract a lower rate. Contingencies are then attributed to the project, as allowances in the inputs in both time (schedule) and cost to accommodate the impact of risk. In this section, we will discuss how each of these is determined.

4.4.1.1. Setting the cost of capital (WACC)

As shown above, the cost of capital or discount rate is the most sensitive parameter in evaluating project viability. As also discussed in Section 3.1.3, the structure of the electricity market impacts on nuclear financial risk profiles. In the early days of electricity generation, most projects were regulated by a government entity that determined what costs were prudent. All prudently incurred costs would be passed on to the customer at a rate set by the electricity regulator. Starting in the 1990s, there was a trend in some regulated jurisdictions to deregulate electricity generation, putting more of the risk back onto the generator (or owner/operator of the generating plant). This was effective for gas fired projects, as their relatively low capital cost suited this model. Most of their electricity cost is a result of fuel costs, and in most cases the cost of fuel is passed on directly to the customer. However, NPPs, with their relatively high fixed costs and low variable costs, struggled to operate under this model.

In the UK, for example, the Hinkley Point C project was implemented on a model known as 'contract for difference' (CfD), under which a price of electricity is agreed upfront and the difference between that price and the market price is either paid to the owner or paid back by the owner, as the case may be. In this model, the generator agrees (for a fixed number of years) to a price for energy at the start of the project and then accepts the risk that it will be sufficient to cover its costs in the future. Given the long project schedules and the very long operating lives of nuclear plants, this model builds

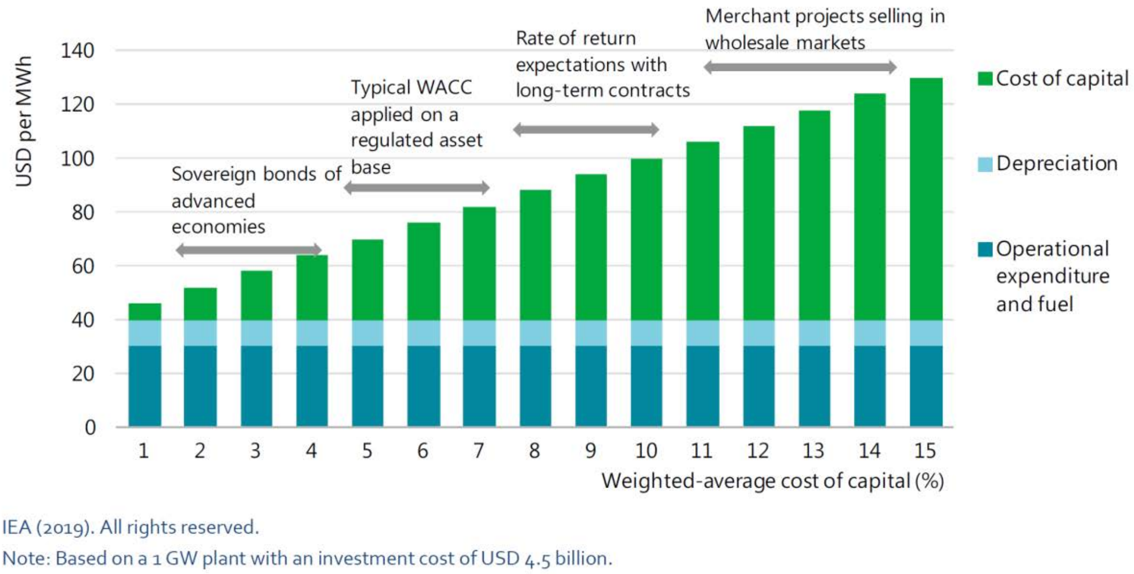

FIG. 10. Illustrative LCOE for a new NPP project according to the cost of capital. Reproduced with permission from Ref. [31].

in significant risks through relatively high discount rates. It is challenging to take on all future risks over such a protracted time frame.

In the CfD model, the ‘market risk’ (i.e. the electricity price) is allocated to the consumers because the difference in the CfD will be in their electricity bill. The investment and technology risk is on the owner, with the owner paying any extra costs in construction and operations. If the NPP’s capacity factor is lower than expected, the risk is, again, on the owner. Hence, it is in the owner’s best interest to build a reliable plant because they will not get paid if they do not produce electricity.

Figure 10, from the IEA report, Nuclear Power in a Clean Energy System [31], shows the extreme sensitivity of electricity cost to the cost of capital and the potential to reduce electricity costs with different risk sharing models.

It is now evident that the structuring of a project is essential, as different risk sharing models can result in a variation of more than double the cost of electricity from the plant [32]. This is the driver for the UK now investigating a RAB type of model, where more risk is shared with the Government and the customer to keep the cost of capital and hence the cost of electricity low. It is beyond this publication’s scope to discuss these options in detail, nor is it intended to make recommendations on a given project model. For this publication, the cost of moving risk from one party to another has to be evaluated. The project stakeholders can then determine if the price paid to transfer risk is good value for money.

4.4.1.2. Adding in project contingencies to the cost and schedule of a project

Once the project structure is agreed upon, and the cost of capital is known, the next step is to set the project’s primary economic inputs, the capital cost and the associated cash flow (project schedule). Many of the related risks are discussed in detail in Section 6.

There are many ways to determine the appropriate contingencies to add to project costs and schedules. A simple deterministic assessment can be used (evaluating risks one by one and assigning a contingency value to cover the risk), but this often results in relatively high contingencies, as each risk’s costs are stacked one on top of the other. For projects that are repeated frequently, a simple allowance based on experience can be sufficient. An example may be a company that installs piping who, after making an estimate based on the volume of pipe to be installed, usually adds a constant allowance that experience has shown to be sufficient to cover uncertainties in most of its projects. Of course, it is always important to review the project and ensure there are no risks that differ significantly from those in past projects, and if there are, adjust the allowance accordingly.

The most common current approach to risk analysis is calculating the reasonable cost and schedule contingencies using a probabilistic risk model. A probabilistic approach will review each cost element and determine a range of possible cost and schedule outcomes around the base estimate (which should be the most likely outcome from the estimator's perspective, not the best case scenario). Discrete risks will also be assessed with a range of impacts on time and cost, along with a probability distribution. The ranges are determined through interviews with those who prepared each element of the estimate and understood the scope of work and associated risks best. The importance of developing this part of the risk analysis input cannot be overstated.

While simple probability approaches can be used, such as a triangular distribution, many tools are available, such as @Risk[2] or Crystal Ball[3], that enable a more detailed assessment using a Monte Carlo analysis to provide an expected outcome at different confidence levels. Once the risks are input into the model, a probability distribution of the outcomes will be produced for both cost and schedule (see Figs 11 and 12). Based on the project proponent's risk tolerance, a confidence level will be selected. The cost and schedule outcome at that level (e.g. at 90% confidence) will be compared to the base estimate and schedule. The difference will be added to the base estimate to form the project cost and schedule contingencies.

This analysis is primarily used for the economic model inputs to set the capital cost and project schedule. Other assumptions, such as the operating costs and generation, will have inputs that may benefit from this type of analysis. Due to the long term of these projected costs and the extensive data available, a deterministic approach will set the base case value more often.

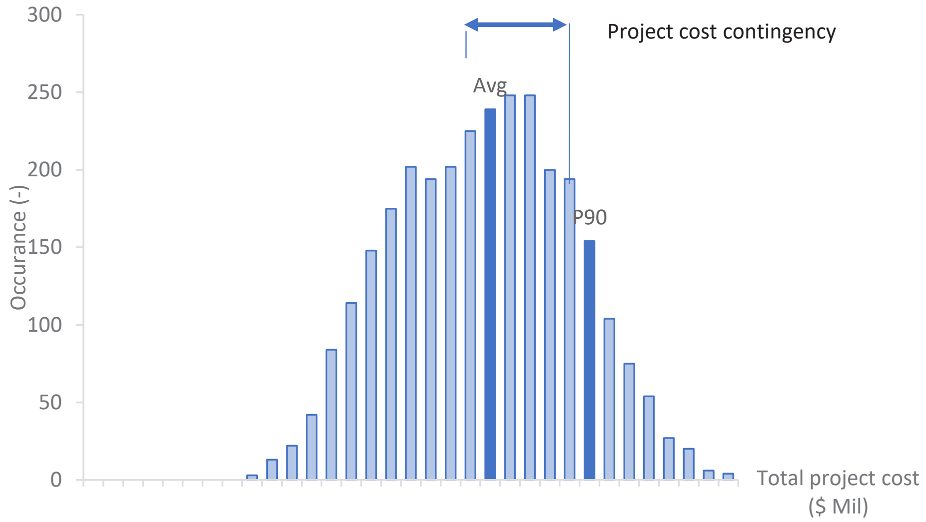

FIG. 11. Distribution of total project cost due to risk.

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[2] See: https://www.palisade.com/risk/

[3] See: https://www.oracle.com/applications/crystalball/

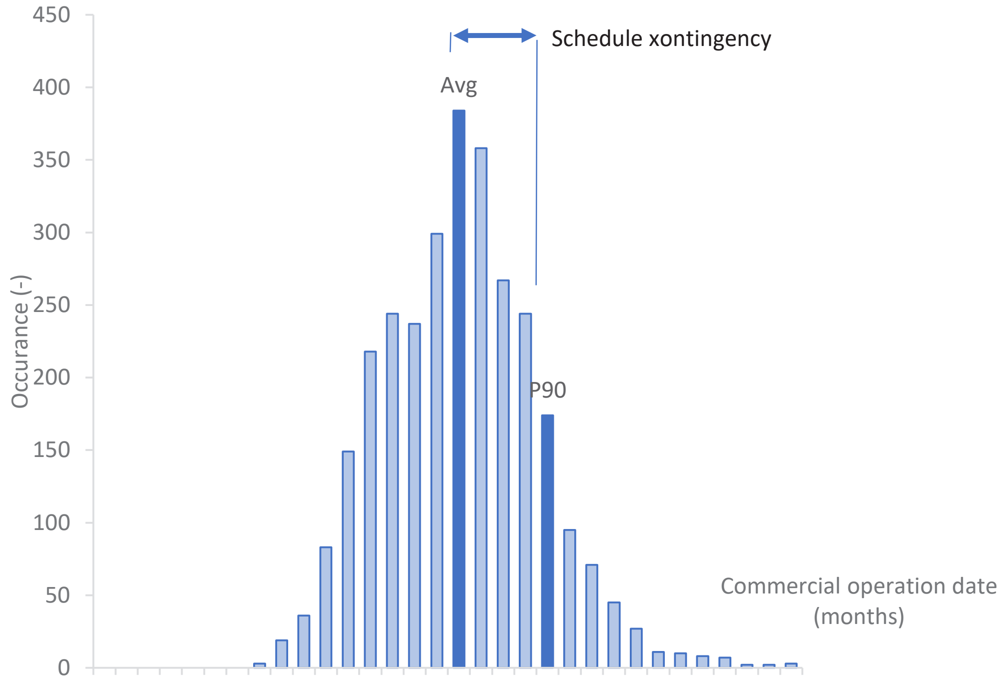

FIG. 12. Distribution of commercial operation date due to risk.

4.4.2. Implementing lifetime risk analysis with the economic model (scenario analysis)

At this stage of project development, the project structure has been determined, and the base case inputs to the economic model have been set. This model includes an allowance for risk in both the capital cost and the project schedule. The next step is to run the base case and determine the project outcome. If the NPV is positive, the base case of the project analysis demonstrates project viability.

While this base case analysis will have addressed most of the risks identified in later sections of this publication, there is still a need to look at scenarios where risks that might not be fully covered but are in the risk register can be addressed. These will be more associated with more considerable unexpected risks that may cause delays and the longer term risks associated with the project's operation phase. Scenarios can be set by varying individual risks or looking at combinations. This is where using a Monte Carlo approach to the economic model will provide the most insights. Examples of the risks that may be assessed at this level include:

- Project delays as a result of unexpected events (such as a pandemic);
- Construction and commissioning cost overruns due to project management and execution failures;
- Changes in economic assumptions, such as escalation of interest rates over the life of the project;
- Changes in the electricity generated due to extended outages for plant repairs;
- Price changes due to market evolution or the inability of the market to accept all the energy;
- Operating and maintenance cost risks due to salaries rising more than planned or new benefits to employees not previously considered;
- Any other risk that may impact on the economic outcome of the project.

It should be noted that the risk of changes in the costs of the end-of-life liabilities has to be assessed but generally does not have a material impact on the project. It is customary for the estimates to account for these liabilities be reviewed periodically during the plant life. Any changes would be accommodated by an increase in the amount charged to the customer to ensure funding adequacy. Once a plant is operating,

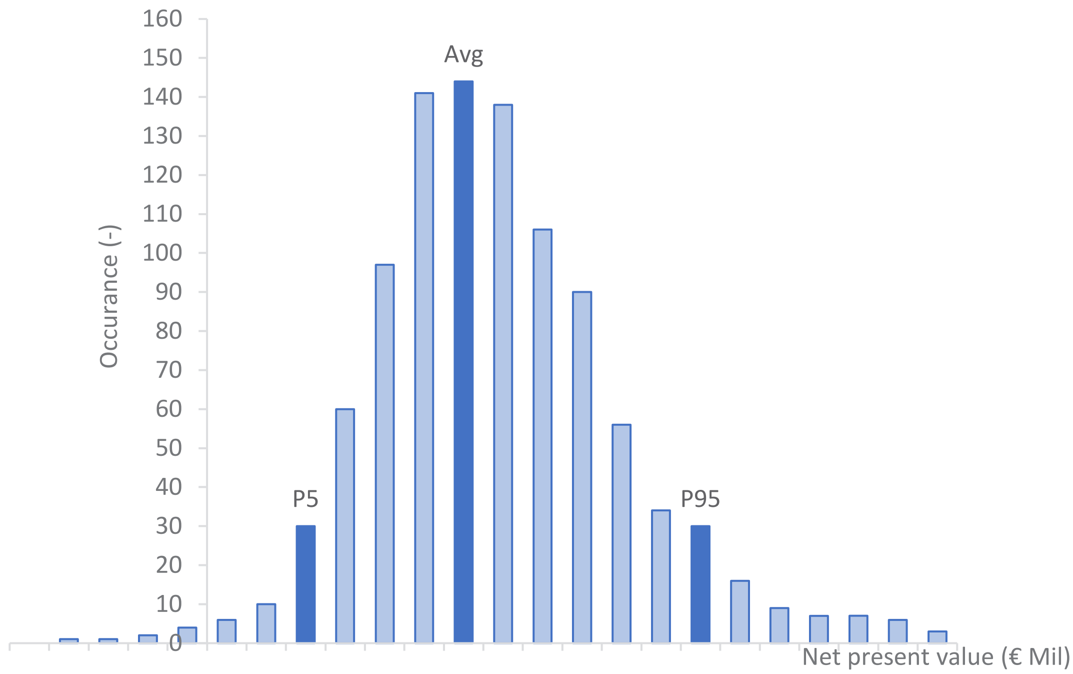

FIG. 13. Distribution of NPV due to risk.

even though increases in these costs may impact on the project economics (they remain a very small part of the cost of electricity), they will have to be accommodated as the wastes will have been generated. The plant will need to be decommissioned.

As with assessing the project contingencies, probability distributions describe uncertainty in the relevant variables. These will show up in a range of NPVs (refer to Fig. 13).

4.5. SETTING RISK TOLERANCE AND DEFINING A MITIGATION PLAN

The process of defining a mitigation plan is an important and crucial step in risk management. Each potential step of mitigation has to be evaluated in quantitative and probabilistic terms describing the new profile of the related post-mitigation risk. For each mitigated risk, the severity of the possible adverse consequence(s) and the probability of occurrence of each consequence will need to be re-evaluated, taking into account the expected positive outcomes of the mitigation as well as the costs of the mitigation itself. In this way, it is possible to have a risk based analysis of costs and benefits. The Monte Carlo simulation is then rerun considering the effects of the mitigation, and the new probability distribution curves are calculated, including the new probability distribution curve of the NPV due to the mitigated specific risk. The new marginal impact of the mitigated specific risk on the NPV is the mitigated specific risk's economic value. This becomes a tool for setting the mitigation plans by having quantitative analysis showing the cost of accepting the risk versus mitigating it.

There are several mitigations for a specific risk in many cases: repeating the approach explained above for each mitigation makes it possible to rank the mitigations according to their economic efficiency. As a further step, it is possible to run the Monte Carlo simulation for different sets of mitigations of a specific risk and make the best choice, also choosing the optimal combination of mitigations for the specific risk. In this way, the entire process is always developed using a risk based cost–benefit approach.

The same approach is then reiterated for all the most relevant risks and related mitigations until a final set of mitigations is defined for all the risks. Once the optimal risk mitigation plan and related costs have been defined, the final step consists of recalculating the post-mitigation NPV.

The utilization of quantitative and probabilistic risk management approaches makes it possible to compare the economic effects of both 'internal' and 'external' mitigations. A typical example is whether it is preferable to buy strategic spare parts to reduce the duration of an outage in the case of machinery breakdown (e.g. a transformer failure) versus buying business interruption insurance coverage. The same applies to evaluating the purchase of any insurance coverage and the definition of its features and related costs.

In this section, an approach to modelling the project life cycle, including assessing its inherent risks, is presented. A robust model provides useful information to enable risks to be analysed quantitatively and mitigation plans to be put in place. Specific risks that may impact on different parts of a project throughout its life are discussed in the following sections. A discussion of how to manage financial risks is found in IAEA Nuclear Energy Series No. NG-T-4.6, Managing the Financial Risk Associated with the Financing of New Nuclear Power Plant Projects [28].

Of most importance, these tools and approaches help to manage risk. Managing risk is an active process that begins when considering a new project and does not end until the project has reached its end of life.

5. PROJECT DEVELOPMENT PHASE RISK MANAGEMENT

The project phase includes all activities from the development phase of a project to commercial operation. Pre-feasibility and feasibility studies precede the project phase. Project risks can materialize between the pre-feasibility of the project and the end of the project. Still, their sources can be from decisions made before the start of the formal project, and their consequences can impact on the cost during the operation and decommissioning phases of the NPP. Materialized project risks may have consequences for cost, schedule or quality. These all have an impact on the life cycle cost of the NPP. This section provides guidance on risk management during the development phase of a project.

5.1. IAEA MILESTONES APPROACH

The IAEA has developed numerous publications to support Member States during NPP project development. The key process is described in IAEA Nuclear Energy Series NG-G-3.1 (Rev. 1), Milestones in the Development of a National Infrastructure for Nuclear Power [33]. Following a structured process in developing a country's national infrastructure is an integral part of identifying and mitigating risks associated with planned NPP projects.

An overview of the NPP project phases and milestones structure is provided in Fig. 14.

Knoiwn as 'the Milestones publication', Ref. [33] describes

> "19 infrastructure issues that need to be considered for each milestone. The order does not indicate relative importance. Each issue is important and requires careful consideration. Different organizations will need to consider which issues relate most to them and to plan their work and resources accordingly. The three key organizations — that is, the government, the owner/operator and the regulatory body — need to ensure awareness of all issues."

The 19 infrastructure issues are as listed below:

— National position;
— Nuclear safety;
— Management;
— Funding and financing;
— Legal framework;
— Safeguards;
— Regulatory framework;
— Radiation protection;
— Electrical grid;
— Human resource development;
— Stakeholder involvement;
— Site and supporting facilities;
— Environmental protection;
— Emergency planning;
— Nuclear security;
— Nuclear fuel cycle;
— Radioactive waste management;
— Industrial involvement;
— Procurement.

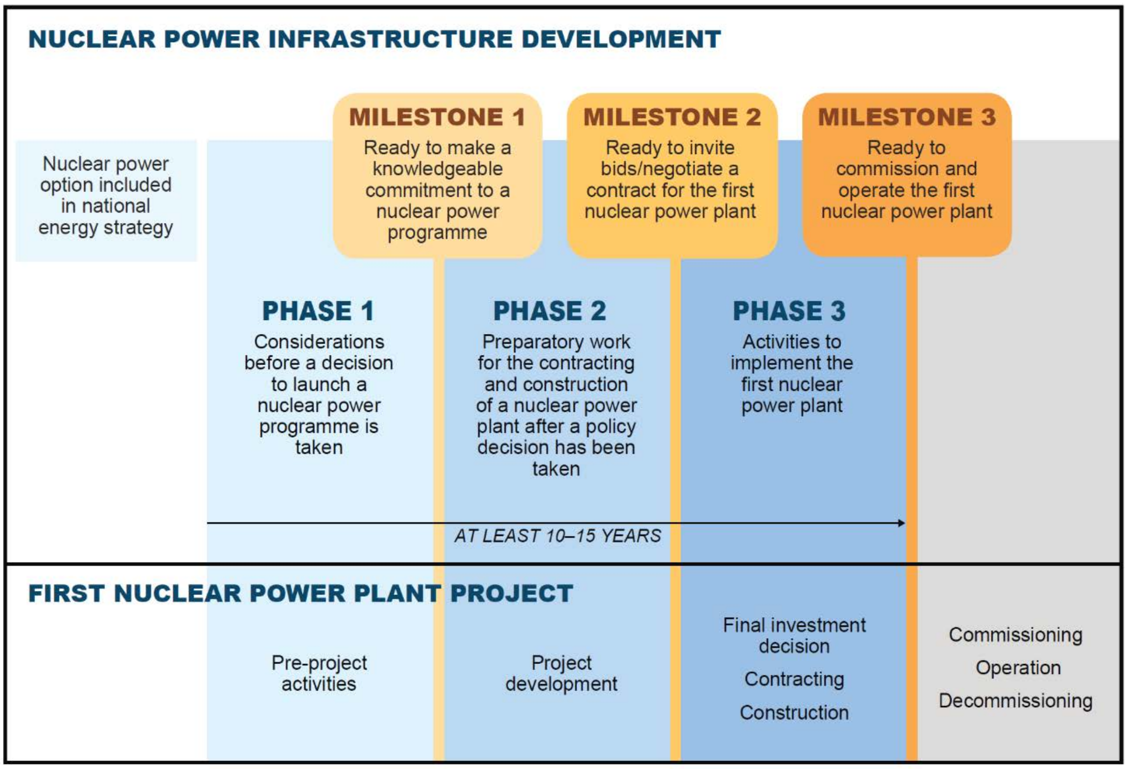

FIG. 14. Schematic representation of NPP project phases and milestones. Reproduced from Ref. [33]

A nuclear infrastructure bibliography[4] is available that provides references to IAEA publications related to each infrastructure area. Appendix II provides a selected list of such references at the time of issuance of this publication and the risk messages contained therein. Many of the infrastructure issues have associated e-learning module[5] that further expand on the printed publications' topics. Two other online resources are available: a nuclear contracting toolkit[6] and a communicator's toolbox[7]. The contracting toolkit provides processes, templates and guides that allow procurement professionals to concentrate on the high value and risk areas in which extra attention is required to achieve optimal results. The communicator's toolbox offers tools to support effective communication on the benefits and risks associated with the use of nuclear technologies.

5.2. WORLD NUCLEAR ASSOCIATION ANALYSIS

The World Nuclear Association (WNA) regularly reports on nuclear power economics and provides recommendations on planning and delivering NPPs and managing their life cycle. A recent report [34] detailed the key risks for NPPs during project phases (Table 2) and methods to help control and monitor those risks (Table 3). The phases are similar to those described in the IAEA approach. Organizations need to consider all of the NPP life cycle risks during project development, since many actions can help reduce the facility's overall risk profile throughout its life.

5.3. PRE-PROJECT PLANNING

Project planning is difficult if the definition of objectives is not clear because of a poorly defined scope, inadequate project member competences and undefined project managers' responsibilities.

The Construction Industry Institute defines pre-project planning as "the process of developing enough strategic information to allow owners to address risk and decide to commit resources that will maximize the chance for a successful project" [35]. Pre-project planning has many names, such as front end loading, front end planning, feasibility analysis, programming, conceptual planning, among others. Previous Construction Industry Institute research, and several other references, have documented that project success is greater when an increased pre-project planning level is achieved.

The Construction Industry Institute's analysis [36] looks at whether the project team has developed the project to the extent that it fully understands the basis for the project decision (e.g. the project's objectives, scope, technology to be used, value proposition), the basis for design (e.g. site conditions, infrastructure requirements, process, equipment, civil/structural, instrumentation and control (I&C) and electrical requirements) and the execution approach (e.g. procurement strategy, deliverables, project controls, project execution plans). Each of these elements applies to nuclear projects.

During the early phases of nuclear projects special attention needs to be paid to licence applications, project financing, design, long lead equipment procurement, construction contracts, site work and nuclear island excavation.

Inadequate preparation of design is a considerable risk for an NPP project. Design technology management, schedule risk and constructability should be considered during design. The design schedule has to match and be consistent with the equipment procurement, construction and erection schedules.

Furthermore, project schedules have to be reasonable and practical. Full investigation and absorption of practical experience in both domestic and in foreign countries are required. Further, national conditions

[4] See: https://www.iaea.org/topics/infrastructure-development/bibliography#section-4.

[5] See: https://www.iaea.org/topics/infrastructure-development/e-learning-for-nuclear-newcomers.

[6] See: https://www-legacy.iaea.org/NuclearPower/Infrastructure/NuclearContractingToolkit/index.html.

[7] See: https://www.iaea.org/resources/nuclear-communicators-toolbox.

need to be evaluated, including engineering management methods, technical capacity and equipment availability, among others. Every section of the schedule needs to be analysed in detail and adjusted if necessary. Scheduling is discussed more fully later in Section 6.1.4.

Some risks and impacts related to pre-project planning are listed in Table 4.

Some methods to help reduce risks related to the pre-project planning process include:

— Engage in a detailed, structured pre-project planning process that gathers information from all project participants and experience from similar projects to ensure that the project team is aligned around the project decision, the basis for the design and the basis for execution.
— Use the above information to develop an achievable project schedule that takes the status of any preparatory work, national conditions, requirements and capabilities into account.
— Ensure that sufficient pre-project planning is complete before the start of construction activities.

TABLE 2. RISKS DURING NPP PROJECT PHASES (ADAPTED FROM REF. [34])

Type	Development	Construction	Operation	Decommissioning
Technical	— Regulatory assessment — Site suitability — Environmental impact — Planning approvals	— Safety — Design completion/ changes — Regulatory assessment/ approvals — Vendor and contractor performance — Equipment supply chain — Skilled and experienced workforce — Construction quality — Transport routes to site — Industrial relations	— Safety — Plant performance — Skilled and experienced workforce — Nuclear event elsewhere — Nuclear event — Beyond design basis events — Fuel supply chain	— Safety — Design completion/ changes — Regulatory assessment/ approvals — Contractor performance — Equipment supply chain — Skilled and experienced workforce — Transport routes to/from site — Availability of waste management routes and disposal
Business case	— Economics — Demand forecast — Used fuel and radioactive waste disposal	— Design changes — Delay	— Electricity markets — Trading and price — Capacity factor — Carbon price — Fuel costs — Capital additions — Early closure — Cost of waste and used fuel disposal	— Decommissioning fund cost escalation — Decommissioning fund performance
Social and political	— General public support and local approval — Policy supporting the need for nuclear power — Decommissioning and waste management policies and implementation — Carbon pricing mechanism — Environmental policy			

5.4. MANAGEMENT SYSTEMS

A well developed and followed management system is a crucial risk reduction tool. It helps maintain alignment between participants and clarifies roles and responsibilities, reducing the risk of inefficiencies, errors, schedule delays and cost overruns.

Such a management system should be established, implemented, assessed and continually improved. It should be aligned with the goals of the organization and contribute to the achievements of the project. A management system has to integrate all management elements so that safety requirements are established and applied coherently along with other requirements. The management system's main goal should be to achieve and enhance safety by bringing together all requirements for managing the organization in a coherent manner.

The management system should include processes for risk management. Risk management from the project phases should be transferred to the operational organization. The operational risks identified

TABLE 3. RISK CONTROL AND MONITORING FOR NPP PROJECTS (ADAPTED FROM REF. [34])

Type	Development	Construction	Operation	Decommissioning
Technical	— Internationally accepted designs — Building on existing nuclear sites	— Develop sound contractual arrangements for involved parties — Invest in supply chain infrastructure — Good training programmes — Invest in transport infrastructure — Previous construction experience — Strong project management	— Involvement in organizations such as the World Association of Nuclear Operators — Good training programmes — Invest in new nuclear fuel facilities — 'Fleet' approach to reactor management — Invest continuously in plant maintenance and improvement	— Decide on decommissioning strategy as early as possible — Invest in workforce training
Business case	— Seek investment from major power users — Build business case on various demand scenarios — Investigate opportunities for revenue stabilization	— Stick to standardized designs — Use an appropriate mix of permanent and contract staff	— Develop sound long term power contracts or otherwise develop revenue stabilization options (e.g. capacity markets) — Develop a balanced portfolio of fuel contracts in line with utility risk management policies — Nuclear knowledge management	— Contribute to well defined fund as required
Social and political	— Public debates and hearings — Regular opinion polling — Gain cross-party political support — Emphasize environmental advantages of nuclear — Develop waste management policy with government			

TABLE 4. PRE-PROJECT PLANNING RISKS AND IMPACTS

Cause	Risk	Impact
— Project objectives and scope not fully defined — Basis for design not fully defined — Execution approach not fully defined	— Additional scope needs to be added to the project at a late stage — Incomplete designs; unanticipated design or regulatory issues arise late in the project. Design or construction rework needed. Loss of configuration control — Coordination or logistical issues. Unattainable schedule — Delays in receipt of required materials or resources — Project starts construction before sufficient preparation is made	— Unanticipated costs — An excess number of design changes during construction or commissioning — Delayed start of construction or operation — Delays during construction or commissioning

in the project phase should be regularly (e.g. annually) updated during the operation phase, and the prevention and mitigation plans and the possible losses should be included in the annual business plan. The categorization of risks in the operation phase may be different from those in the project phase. One possibility is to categorize risks according to strategic goals. Then it is easy to find the owner of each risk.

The IAEA has published numerous safety standards related to management systems, including IAEA Safety Standards Series No. GS-G-3.1, Application of the Management System for Facilities and Activities [37] and IAEA Safety Standards Series No. GS-G-3.5, The Management System for Nuclear Installations [38].

5.5. REGULATORY AND LICENSING MANAGEMENT

There is a need in every country for an independent nuclear safety authority in charge of oversight of nuclear related activities, including delivering the licence to construct and operate NPPs. The nuclear safety authority has full authority to inspect and, if necessary, to shut down the facility. The operator has to comply with safety requirements according to the safety authority's competences and is fully responsible for compliance with the safety requirements. It is essential that the regulations are stable and consistent with the requirements for good health and respect for the environment, without any over-demand, and that they, at the same time, integrate lessons learned. Construction and operating costs could increase sharply without good comprehension of safety requirements and the sharing of safety culture among actors. For the NPP owner/operators, lessons learned from peer reviews may be of benefit, for instance, by exchanging feedback and experience through the World Association of Nuclear Operators (WANO), INPO or owner groups.

Effective communication between the owner/engineering, procurement and construction contractor and the nuclear safety authority during the early stages of a project (i.e. the project development phase) is extremely important. The parties need to have a clear understanding of the project's nuclear safety requirements and how the requirements will be met during design, construction, and operation. All participants in the design and construction phase, including vendors, owner/operators and subcontractors, should be familiar with these safety requirements to incorporate a high nuclear safety culture within their organizations.

If the key stakeholders do not have a clear understanding of the licensing process, there is a significant risk for an NPP project. For instance, if the national regulator has not accepted the NPP design, there is a risk that crucial design assumptions may not be accepted, licensing requirements may be misunderstood, and expensive rework, project delays and cost increases may be encountered.

TABLE 5. LICENSING RISKS AND IMPACTS

Cause	Risk	Impact
— Technical issues not understood or dispositioned to the regulatory body's satisfaction — Changes in design or regulations necessitating rework or repeated performance of licensing steps — External events causing changes in national regulations — Regulatory body has insufficient trained staff to progress licensing on the desired schedule — Public not convinced regulatory body is independently assessing NPP safety	— Delays in licensing — Loss of public support for the project	— Delayed start of construction or operation

Changes in regulatory requirements arising from external events are an ongoing risk to the owner/operator. A national regulator may require additional safety requirements following rare events or nuclear accidents. The risk of events that have not yet occurred can be estimated using probabilistic safety assessment (PSA) techniques. Preparedness for rare events is possible in the design phase based on a site- and plant unit-specific PSA that incorporates a local set of hazards.

Some risks and impacts related to regulatory issues and licensing management are listed in Table 5.

Some methods to help reduce risks related to the licensing process include:

— Pre-licensing review of new designs by the regulatory body;
— Early engagement by prospective vendors with the national regulatory body to understand national positions, regulations and safety requirements;
— Establishing national licensing requirements at an early stage aligned with internationally recognized (IAEA or vendor country) safety standards;
— Establishing a comprehensive licensing plan for the project that is agreed to by the regulatory body;
— Assuring investors regarding the minimization of changes to licensing requirements over the project life cycle;
— Allocating sufficient schedule time and budget to account for licensing activities;
— Encouraging open and effective communication with the regulatory body and the licensee;
— Training regulatory staff and licensee staff, especially for new regulatory bodies and licensees, in NPP design concepts and licensing details;
— Obtaining assistance from owner/operator and regulatory staff from jurisdictions that utilize similar designs.

A typical process to perform licensing management is described in Section 2.5 of IAEA Nuclear Energy Series No. NP-T-2.7, Project Management in Nuclear Power Plant Construction: Guidelines and Experience [39].

5.6. SITING AND LAND ACQUISITION

5.6.1. Land acquisition

Land acquisition and relocation should be managed to reduce or mitigate the risk to the project's preparatory work. Land acquisition can be a significant risk in countries where private land ownership right is strong, and expropriation is expensive and time consuming or impossible.

Land acquisition and relocation requires well prepared plans, and a demolition organization is recommended if there are installations to dismantle. The required tasks are as follows, although their order and importance depend on local legislation:

(a) Physical investigation;
(b) Cost estimation;
(c) Detailed programme development and approval;
(d) Funds;
(e) Land acquisition contract signing;
(f) Land requisition approval;
(g) Land requisition;
(h) Agreement with relocation households, enterprises, schools, etc.;
(i) Implementation of relocation.

If the land has previously been used, demolition work may be necessary for site preparation, which is the key risk for the scheduled start of NPP site preparatory work. Demolition work has a number of characteristics, such as:

— Government relocation policy;
— Timeliness;
— Size of the area;
— Characteristics of the land;
— Amount and scope of displacements;
— Width of working range;
— Multi-company task;
— Long lasting and complicated task.

The risks and impacts related to land acquisition are listed in Table 6.

TABLE 6. LAND ACQUISITION RISKS AND IMPACTS

Cause	Risk	Impact
— Lack of government support — Strong private land ownership — Lack of funds — Time consuming demolition work	— Land not available for preparatory work as planned	— Delays in the scheduled start of site preparatory work with impacts on subsequent activities

Some measures to reduce or mitigate the risks include the following:

— Performing detailed estimates for the cost of land requisition and ensuring that sufficient funds are in place;
— Analysing and estimating the quantity of demolition work and preparing a detailed schedule for demolition activities;

— Building on an existing nuclear licensed site, if possible;
— Seeking local government support, if needed;
— Implementing a land acquisition process in agreement with the local community/land affected persons in a timely manner.

IAEA Safety Standards Series No. SSR-1, Site Evaluation for Nuclear Installations [40] and IAEA Safety Standards Series No. SSG-35, Site Survey and Site Selection for Nuclear Installations [41] and IAEA Nuclear Energy Series No. NG-T-3.7, Managing Siting Activities for Nuclear Power Plants [42] discuss siting activities for nuclear installations.

5.6.2. Site preparation

Before the first concreting date (FCD), site preparation work includes construction planning, general layout, infrastructure development (water supply, electricity supply, roads), building of temporary construction facilities, construction material procurement, materials testing and personnel training. These should all be well planned, implemented, available and functioning to support FCD and subsequent construction.

The risks associated with site preparation are listed in Table 7.

TABLE 7. RISKS AND IMPACTS RELATED TO SITE PREPARATION

Cause	Risk	Impact
— Unreasonable general site layout — Delay of water supply, electricity supply and temporary facilities — Lack of research and experimental verification of main building materials — Shortage of qualified managers, technical staff and workers	— Reworking of pipe gallery or roads, increases of additional transportation load — Some site preparation phase work activities cannot start — Shortage of main building materials supply — Increase of occurrences of human error	— Difficulties of site management, increasing cost and security risk — Difficulties with schedule management and increasing cost — Some construction activities cannot start or may be suspended

Suggested measures to reduce or mitigate the risks include the following:

— Risk identification and analysis should be performed, and countermeasures should be incorporated into construction planning. This planning should include evaluating risks associated with different construction sequences for units on the same site.
— Experienced experts should be recruited to evaluate construction plans.
— General site layout arrangement is a dynamic process and should be well planned based on site terrain, permanent/temporary facilities, roads (including heavy component roads), tower crane location and construction sequence, as well as health, safety and environment (HSE) and security requirements.
— The provision of water supply, power supply and access roads, including bridges or tunnels, should be ensured. These will involve local governments, regional grid operators and other outside organizations. Contracts or agreements will need to be signed, and this should be well planned and coordinated and implemented in an organized fashion to ensure that they can be available and functioning to support site preparation phase work.
— Construction of temporary facilities, including concrete mixing stations, civil engineering laboratories, steel structure workshops and steel processing workshops, should also be well planned and implemented to be available and functioning before FCD.

— The supply chain for civil and erection materials has to be investigated and evaluated carefully. Moreover, some critical raw materials, such as cement, steel, stone and welding rods, need to be tested and inspected before use.
— Before the start of construction, the involved personnel should be trained, assessed and qualified; only then can they commence work after approval.
— The living accommodation for site staff and workers should be put in place in advance.
— Necessary conditions to maximize the outcomes from the labour force, including fair wages, a proper labour camp with hygienic conditions, safety appliances, and safe and healthy working conditions should be secured as appropriate in the contract.

Example

There are six units planned for the Fuqing site in China. When preparatory work for the first unit (unit 1) was started, the schedule was very tight. The risks related to starting construction of the units on the site had not been fully evaluated. It was decided to place unit 1 on the distal end of the peninsula because a smaller quantity of earthwork was required for that location. However, a horizontal trench connecting unit 1 was located above a vertical trench that connects to subsequent units. The vertical trenches needed to be built under the existing horizontal trench, which was already in service. This sequence increased the complexity of the construction of the vertical trenches and added to the cost. The first unit should have been located considering the work needed for subsequent units, and a comprehensive analysis of advantages and disadvantages should have been conducted before proceeding. The site layout for the Fuqing units is shown in Fig.15.

Example

In the case of pressurized water reactor (PWR) NPPs in China, the completion of the access road is planned appropriately six months before FCD, the water supply should be in use 10 months before the FCD, and the electricity supply 11 months before the FCD. The completion of the concrete mixing station is appropriate seven months before FCD. The civil engineering laboratory, steel structure processing workshop and steel processing workshop should be completed six months before FCD. Failing to adhere

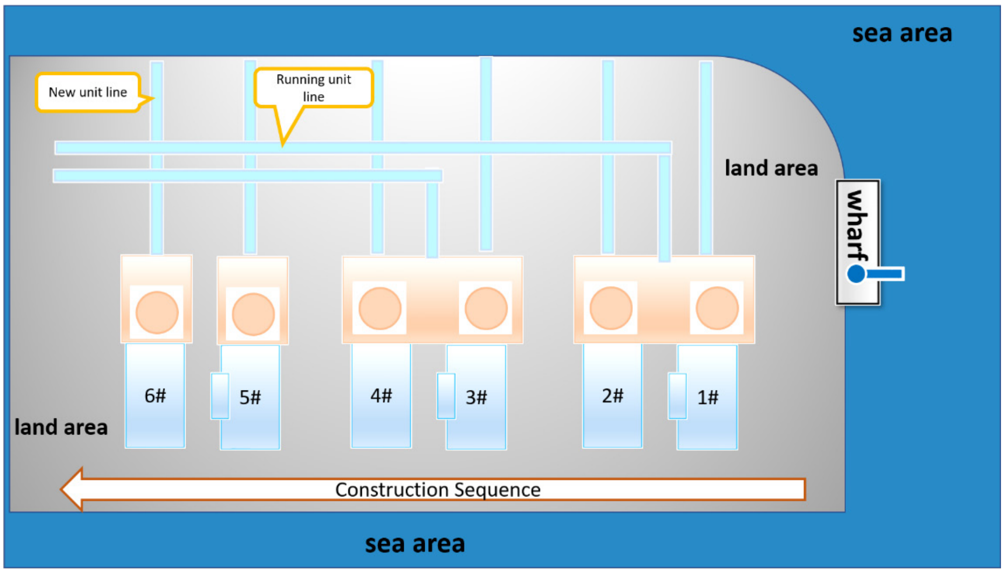

FIG. 15. Site layout for Fuqing units.

to these guidelines risks delays in the project, as the necessary work that requires such infrastructure cannot be executed as planned.

6. CONSTRUCTION PHASE RISK MANAGEMENT

The NPP construction process poses many risks. Some of these risks impact on the viability of the NPP project itself, such as the risk of budget or schedule overruns, which can lead to loss of stakeholder support. Others can impact on the NPP later in its lifetime, such as undetected quality issues that might cause equipment failure or nuclear safety issues in the future.

Experience has shown that a critical risk for NPP projects, or any large capital project, is to start significant field activities before the project is sufficiently ready to proceed. The IAEA has developed a Construction Readiness Review (CORR) service [43] that can be used as a risk analysis and reduction tool. The CORR guidelines recommend that construction project readiness be assessed in the following thematic areas, with specific guidance available for each:

(a) Project management;
(b) Engineering readiness;
(c) Procurement/material/supply chain readiness;
(d) Construction readiness;
(e) Construction completion assurance/system turnover process;
(f) Quality management and records;
(g) Human resources and training;
(h) Targeted area reviews;
(i) Technical visits.

Each of these areas, except for (h) and (i), which are specific to a given review mission, are discussed below in the context of risk management.

6.1. PROJECT MANAGEMENT

IAEA Nuclear Energy Series No. NP-T-2.7 [39] discusses project management in NPP construction and NP-T-1.6 [15] describes project management in general, and risk management in particular, in a nuclear context. Securing project insurance is a risk mitigation tool that is discussed in IAEA Nuclear Energy Series No. NG-T-4.1 [44]. References [7, 45–54] also deal with project risk.

The CORR guidelines [43] refer to the following areas as being of special importance concerning project management within nuclear construction. Each will be discussed in the context of risk management:

(a) Scope control;
(b) Front end planning;
(c) Project estimating;
(d) Project scheduling;
(e) Project metrics;
(f) Stakeholder alignment;
(g) Maintenance of community engagement and support;
(h) Roles and responsibilities;
(i) Project oversight;
(j) Risk management;

(k) Project contract and procurement strategies;
(l) Project change control;
(m) Project delay/suspension provisions.

6.1.1. Scope control

Projects risk going off schedule or having cost overruns in the absence of proper scope control. An accumulation of seemingly small changes made at the lower levels of an organization can add up to major problems. The time and money needed to address a series of relatively small changes can impact on the overall project schedule and cost. Often referred to as 'scope creep', such small changes may move slowly and unofficially without corresponding changes to a project's formal milestone dates or budgets.

A key contributor to good scope control is the establishment of clear project requirements at the outset. If poor or incomplete requirements are documented, there will be a greater desire for project scope changes to meet stakeholder needs.

Scope control also contributes to a project's perceived success, stakeholder perceptions regarding a project manager's effectiveness and project team morale [55].

Thus, rigorous processes need to be in place to identify the baseline project scope and control any later changes in that scope. A 'change control board' or similar organization that is tasked with approving any changes is one method that is employed within many organizations. Lack of good scope control can lead to major cost overruns on a project.

Some measures that contribute to good scope control are discussed in Sections 6.1.12 (project change control) and 6.2.4 (design change process).

6.1.2. Front end planning

Section 5.3 discusses pre-project planning or front end planning during the preparation phase. This process should be continued into the start of the construction phase to help identify areas where more definition or work may be needed before proceeding to construction.

6.1.3. Project estimating

Project cost estimation is an important part of an NPP project. Accurate cost estimation will help establish a proper expectation of the project's return on investment and will reduce the probability of overspending. Overly optimistic estimation, usually on the low side, can lead to difficulties during project execution. In the beginning, a low estimate may attract investment. However, this will lead to unrealistically high expectations for the project's return on investment. When the project eventually overspends, refinancing will be a challenge. This can lead to financial strain, which can lead to project suspension or cancellation.

The accuracy of project cost estimation is related to the following factors:

— Maturity of the technology (first-of-a-kind (FOAK) versus established design);
— Level of design completeness at the time the estimating is done;
— Accuracy of price data when estimating;
— Cost of equipment, material and labour supply over time (addressing risks related to inflation, currency changes and shortages);
— Experience of the project team members (leadership, designers, construction trades) on similar projects and working together;
— Experience of the cost estimation organization and the methods used to allocate project contingency to address risks.

Poor estimation of costs, resources and time is a traditional risk for project planning. Some causes can include a lack of project management skills, complex activities, lack of time for preparation and planning, estimation without experience or knowledge, overestimation, ignoring historical data of other projects, and improper estimation methodology [56].

6.1.3.1. Estimation methodologies

IAEA Nuclear Energy Series No. NG-T-1.6 [15] provides resources related to project estimation, including the methods recommended by various organizations. A complete cost estimate is critical for a project's success, as it serves to manage expectations among the project's funders and other stakeholders. Of particular importance is the communication of an estimate's quality or uncertainty range. Early in a project, when a clear project definition is not present, a single value estimate for the total project cost will have, by necessity, a wide accuracy range. Later on, when firm price commitments for various aspects of the project have been obtained, the accuracy range can be much tighter. Stakeholders can often focus on a single project cost number rather than on the underlying risks and assumptions behind that value. Many nuclear projects have suffered from poor communication of the inherent risk of a project's budgeted cost increasing as more information is obtained.

Incorporating project contingency, based on estimate uncertainty, is a tool that is used in many projects. Although work can be done to reduce, mitigate and transfer known risks, it is impossible to eliminate all project risks or account for all potential events. Therefore, some contingency is necessary for all major projects, including NPP projects. Some contingency can be available to the project manager to deal with known risks, while other contingency may be held at a higher level of the organization to deal with events that are unanticipated or of a corporate nature.

Table 8 details some risks and impacts associated with project estimates.

TABLE 8. RISKS AND IMPACTS RELATED TO PROJECT ESTIMATION

Cause	Risk	Impact
— Incomplete analysis of the complete scope of the project — Inadequate benchmarking of similar projects — Poor communication of estimate quality to project stakeholders — Low level of design completion leading to high levels of assumptions embedded in the estimate — Inexperienced staff involved in estimation	— Poor quality estimate of budget and schedule — Project decisions are not based on an appreciation of underlying risks	— Unanticipated cost increases or schedule delays — Perception of cost overruns where none may have occurred — Poor project approval decisions — Unrealistic expectations from stakeholders or investors

Some measures to reduce or mitigate the risks related to project estimating include:

- Follow a structured process for project estimation;
- Document the assumed scope of the estimate (what is included and what is not);
- Benchmark similar domestic and international projects, both nuclear and large industrial non-nuclear projects;
- Document assumptions and risks associated with project estimates;
- Communicate assumptions, risks and estimate quality consistently when providing estimates to project decisions makers;

— Collect historical and current price data for equipment, material and human resources, and analyse and predict their variation trends;
— Provide training to project decision makers as necessary regarding estimation processes and estimate quality ranges;
— Use a completed design as much as possible.

6.1.3.2. *Work breakdown structures*

A work breakdown structure (WBS) is a tool used for project planning and estimation. As described in IAEA Nuclear Energy Series No. NG-T-1.6 [15], it is a deliverable oriented decomposition of a project into smaller components, sometimes called work packages. A fully developed WBS based on the project's complete approved scope is useful to ensure that the scope and responsibilities are defined for all aspects of the project and that the interfaces between the owner/operator, suppliers and subcontractors are clear. It also provides the necessary framework for detailed cost estimation and control, and guides schedule development and control.

Having an inadequate WBS can hinder determination of the detailed industrial content of each component of the project, management of the interfaces of components and control of progress. This can hinder cost planning and scheduling and the development of project teams.

Table 9 details some risks and impacts associated with WBSs.

TABLE 9. RISKS AND IMPACTS RELATED TO WORK BREAKDOWN STRUCTURES

Cause	Risk	Impact
— Incomplete WBS — Lack of a well designed WBS	— Some activities may be missed or overlapped — Increased risk of contract claims	— Unanticipated cost increases, costs or schedule delays — Rework and increased difficulties with scope management

Some measures to reduce or mitigate the risks related to WBSs include:

— Set the WBS structure to match how the project will be managed (different contract approaches lend themselves to different WBS structures);
— Develop a standard WBS coding structure (five or six levels is typical for an NPP project);
— Focus on objectives and deliverables at different levels of the WBS;
— Identify support activities within the WBS;
— Ensure a process is undertaken to confirm that all the deliverables and activities are included within the WBS;
— Verify the purpose or need of each major deliverable within the WBS;
— Ensure that a process is available to adjust the WBS as needed.

6.1.3.3. *Risk of quantity*

The risk of quantity refers to the risk that the quantity of items needed for the NPP project (physical items such as numbers of valves, metres of pipe or cable, number of person-hours for engineering or construction, or other items that can be quantified) can change. In the case of proven NPP constructions, the risk of quantity usually only has a minor impact on project cost risk. Most often, the cause of the risk of quantity is design improvements, design changes or mistakes leading to costly rework. However, their impacts are typically insignificant when compared to the entire cost of an NPP.

Particularly in the case of a FOAK NPP, the risk of quantity may have a significant impact on project cost risk. The risk of quantity depends on how proven and detailed the design is. As for project cost in the feasibility and preliminary design stage, more contingencies should be considered in cost estimates, including the estimated cost based on the quantity offered by design. Therefore, the quantity risk in FOAK should be updated carefully by using the information in various design phases and the data from three dimensional CAD or building information modelling models. Meanwhile, the changes in quantity need to be monitored at various stages and guarantee that the risk of quantity is under control. There should also be adequate contingency to address any potential surprises.

Table 10 details some risks and impacts associated with quantity estimation.

TABLE 10. RISKS AND IMPACTS RELATED TO QUANTITY ESTIMATION

Cause	Risk	Impact
— Low level of design completion — Design tools not available to measure bulk material quantities accurately — Loss, damage or theft of material — Lack of experienced cost estimation staff and improper application of methodology	— Overly optimistic or pessimistic estimates — Need to reorder material during construction	— Unanticipated cost increases, cost or schedule delays

Some measures to reduce or mitigate the risks related to quantity include those identified in Section 6.1.3.1.

Example

In Fuqing units 1 and 2, the shortage of bulk material, including piping, fittings, fasteners and galvanized sheet metal, was serious and had a negative impact on piping and support prefabrication. The main cause of the bulk material shortage was that the bulk material list was prepared with input at a lower level of design completion and did not fully reflect the category and quantity actually needed. A tight preparatory work schedule caused a lower level of design completion. The incomplete bulk material list resulted in additional procurements, which were time consuming, and the required material was delivered late. More than eight additional procurements were conducted for nuclear class 2 and 3 carbon steel seamless tubes, each of which required permission from the regulatory body before the vendors started manufacture. High levels of design completion are an important prerequisite for the preparation of a complete bulk material list.

6.1.3.4. Risk of market price

The risk of market price reflects the risk of equipment, labour, material, rent and exchange rates of foreign currencies for the total project cost. Overall, the risk of increasing market price is inevitable, and labour costs will escalate over time. The cost of equipment, material and rent may be waived over the construction period, but they will eventually rise. Furthermore, the exchange rates for foreign currency will fluctuate, sometimes substantially. The exchange rate risk for foreign currency may increase or decrease the total cost of the NPP significantly.

Some measures to reduce or mitigate the risks related to quantity include those identified in Section 6.1.3.1. Additionally, special attention should be paid to contract language for price escalation provisions, and financial currency hedging mechanisms should be considered.

Table 11 details some risks and impacts associated with market prices.

TABLE 11. RISKS AND IMPACTS RELATED TO MARKET PRICES

Cause	Risk	Impact
— Foreign currency fluctuations — Inadequate contracts or hedging mechanisms to protect against fluctuations — Delays in design, procurement or construction leading to different market conditions — Force majeure affecting bulk material pricing — Local or regional labour conditions (e.g. other projects, labour shortages)	— Overly optimistic or pessimistic estimates — Unplanned cost increases	— Unanticipated cost increases

6.1.4. Project scheduling

Controlling a project's schedule is one of the main determinants of its economic success. Consequently, managing project schedule risk to minimize delays and related cost overruns is critical.

A project schedule should be both reasonable and practical. Experience from previous and active foreign and domestic projects should be sought and incorporated and adapted for local conditions such as regulations, transportation logistics, technical capacity, availability of labour and material and other factors.

The more uncertainty a project has, the more schedule contingency should be allocated. As discussed in Section 6.1.3, a structured method to allocate project contingency is recommended.

NPP project schedules usually have two major stages: the preparatory work before the first concreting date (FCD) and the project construction schedule from the FCD to the end of performance test.

Figure 16 shows an example of a general project schedule. Feasibility studies are followed by design; usually, five or six years before the construction is launched. Design, licensing and procurement activities need to start very early to reduce project risk. The preparation of the preliminary safety analysis review (PSAR) starts 42 months before construction. The main equipment procurement starts at least two years before FCD.

Whether or not the design, licensing and procurement activities can start early depends on many factors, such as the selection of the reactor type, the site, the main supplier, the contract strategy, funding requirements and the requirements of the regulatory body.

Table 12 details some risks and impacts related to project scheduling.

TABLE 12. RISKS AND IMPACTS RELATED TO SCHEDULING

Cause	Risk	Impact
— Lack of comprehensive project risk analysis before schedule preparation — Lack of well prepared schedule baseline for the project	— Schedule baseline does not reflect the actual situation of the project — Countermeasures are not put in place for anticipated risks	— Inefficient allocation of resources — A large number of schedule changes, increasing the possibility of project delays and cost overruns

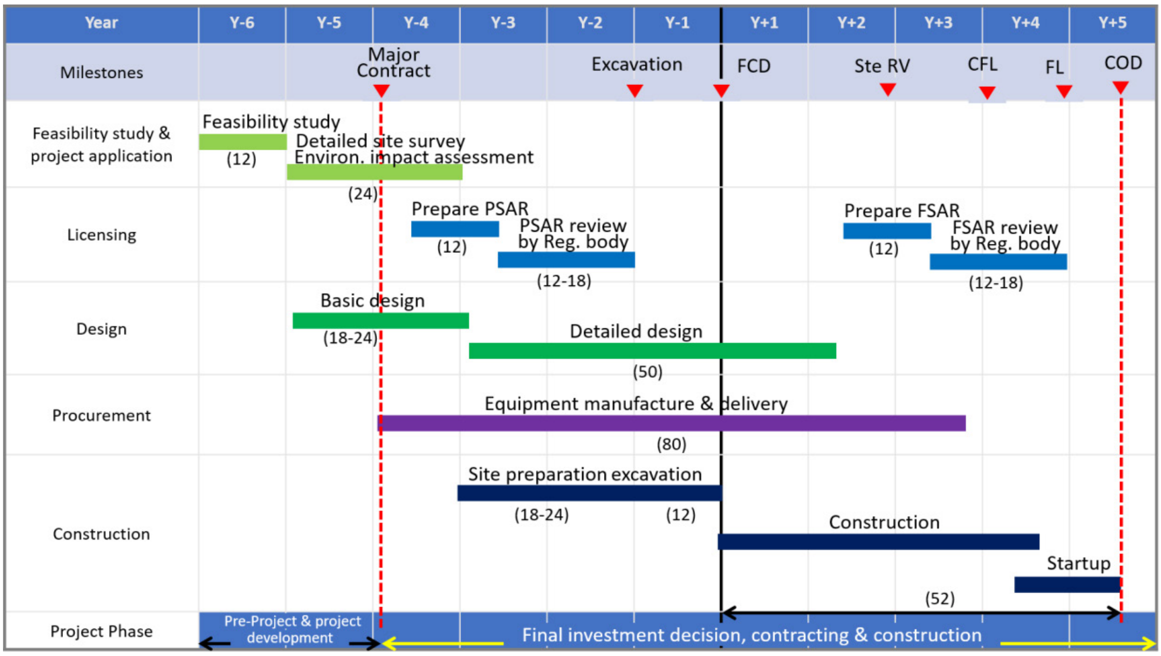

FIG. 16. Typical NPP project general schedule.

Some measures to reduce or mitigate the risks related to project scheduling include:

— Perform schedule risk analysis, including analysing the availability of resources, before starting construction schedule development to incorporate countermeasures into the schedule.
— Involve the key participants in preparing the schedule. Thus, the participants can share their knowledge and experience and develop a more rational and achievable schedule.
— For the critical path method (CPM) (see Section 6.1.4.1), estimate the duration of activities through feedback from the reference power plant or experience with the actual condition of the project.
— Perform a qualitative risk analysis (a 'deterministic' technique) to support the estimation of durations. Note that the CPM cannot reflect the impact of risk on the schedule, so further risk analysis is recommended.
— For quantitative risk analysis, create risk models within the scheduling risk analysis programme before the project starts. Risk analysis is run, and results are interpreted to populate a risk register and a mitigation plan.
— After the project starts, regularly update the project schedule's risk model and repeat the risk analysis to determine the predicated project duration and the driving risk factors. The driving risk factors provide the basis for adjusting the schedule and further actions to be taken.
— Benchmark the schedule against national and international experience.
— Include schedule contingency or margin, as appropriate, into the baseline schedule. The more uncertain the project is, the more margin should be allocated.

Example

Fuqing unit 5 is the first unit to follow the Hualong 1 design. Before starting the project, the quantitative risk analysis method was used to estimate its total duration. The steps were as follows:

(a) Identify the risks and perform qualitative analysis. Evaluate the impacts of each risk.

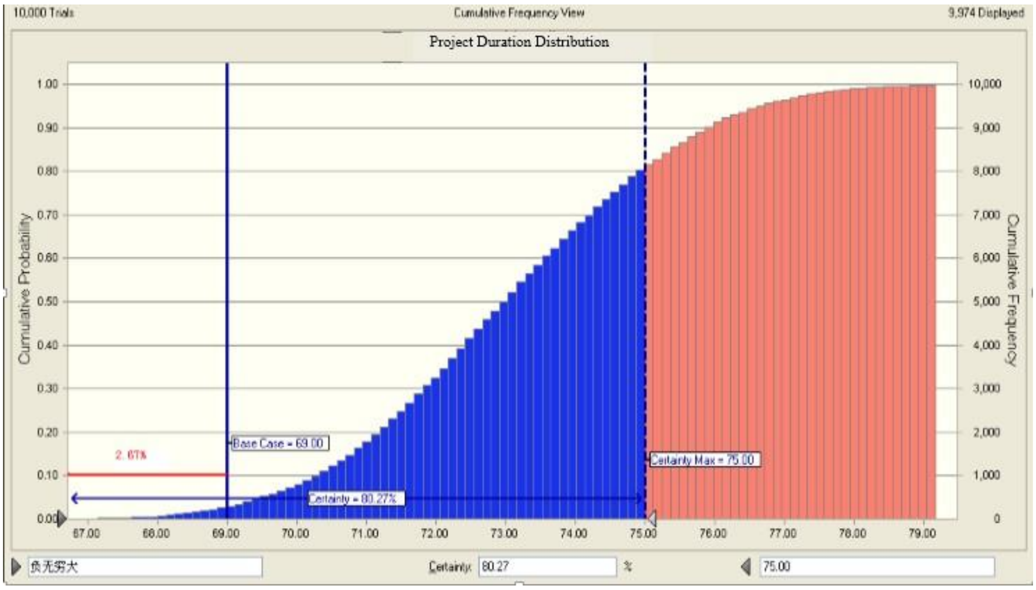

FIG. 17. Example of project duration distribution

(b) Establish the schedule risk model and main activities. Add logic to define the relationships of the tasks.

(c) Collect risk data. Estimate risk quantitative indices and probabilities based on the qualitative analysis of the logic.

(d) Assess risk impact and select programme. Through Monte Carlo, run risk analysis and obtain the probability distribution and risk factors driving the project.

Figure 17 displays the duration of a 78 month engineer, procure and construct (EPC) project contract, with a reference period of 62 months, a risk period of 10 months and a grace period of 6 months. The simulation results show that the probability of the total duration being less than 69 months is <3%, and the probability of it being less than 75 months is 80%. The probability of the duration being more than 78 months is 2%.

Example

By March 2014, work at Fuqing unit 3 had continued for 38.2 months from FCD, which is the peak period for equipment construction. The team could estimate the construction project's duration using quantitative risk analysis methods, considering that several equipment items had been seriously delayed. The steps to address this were as follows:

(a) Revise the schedule risk model according to the critical path progress, key risks and resources;

(b) Re-evaluate risk data, such as the risk quantification index and its probability;

(c) Assess risk impact and select programme. Through the Monte Carlo method, obtain the probability distribution and risk factors driving the project;

(d) Revise the schedule based on the result of probability distribution and risk factors driving the project.

Figure 18 displays a project duration distribution map. The probability of the total duration being less than 61.64 months is 6.8%. The probability of the total duration being less than 62.5 months is 80%. Based on the analysis, the probable duration is 62.5 months. Risk factors driving the project are shown in Fig. 19, with the installation of the 26 t main steam valve being the most significant. This enabled the

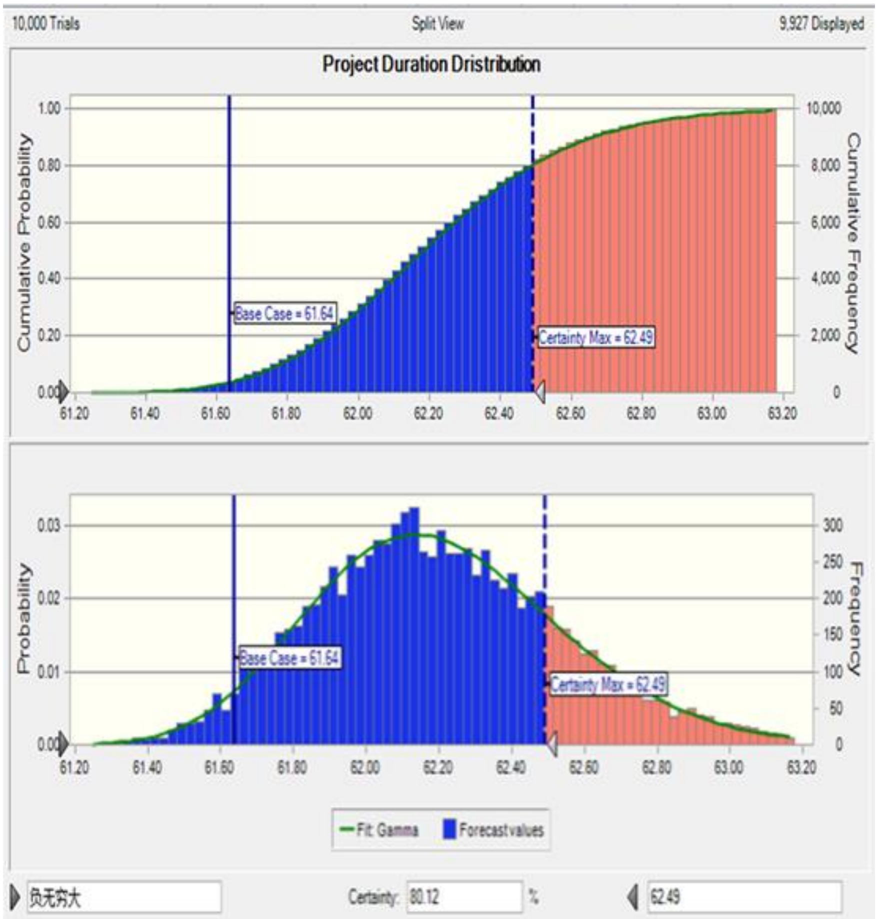

FIG. 18. Example of project duration distribution map.

project team to take mitigative actions for the risks associated with the valve installation (e.g. ensuring a proper quality plan, all valve accessories and supporting facilities available, prerequisites completed, using experienced workers).

6.1.4.1. Scheduling methods

Critical path method is a step by step project management technique to establish the project's duration and the schedule for each task and identify tasks on the critical path. It is an approach to project scheduling that breaks the project into multiple tasks, displays them in a network diagram, and then calculates the project duration based on estimated durations for each task. It identifies tasks that are critical, timewise, in completing the project. The duration of the activities can be estimated through feedback from a reference power plant or experience. The finish time for milestones and the total duration of the project can then be determined. In its standard formulation, it is a deterministic technique. There is only one option for time evaluation, which is the characteristic of CPM, as well as a deficiency. For any given project, the schedule logic and the duration between activities could be variable. The CPM method cannot reflect the impact of risk on the schedule.

A quantitative method for risk analysis of project duration risk that is based on CPM, the programme evaluation and review technique (PERT) or graphical evaluation and review technique (GERT), uses the Monte Carlo method to run risk analysis to obtain predicted durations. The algorithm is included in some scheduling programs, such as Primavera, MS Project and @Risk. Before the project starts, risk models

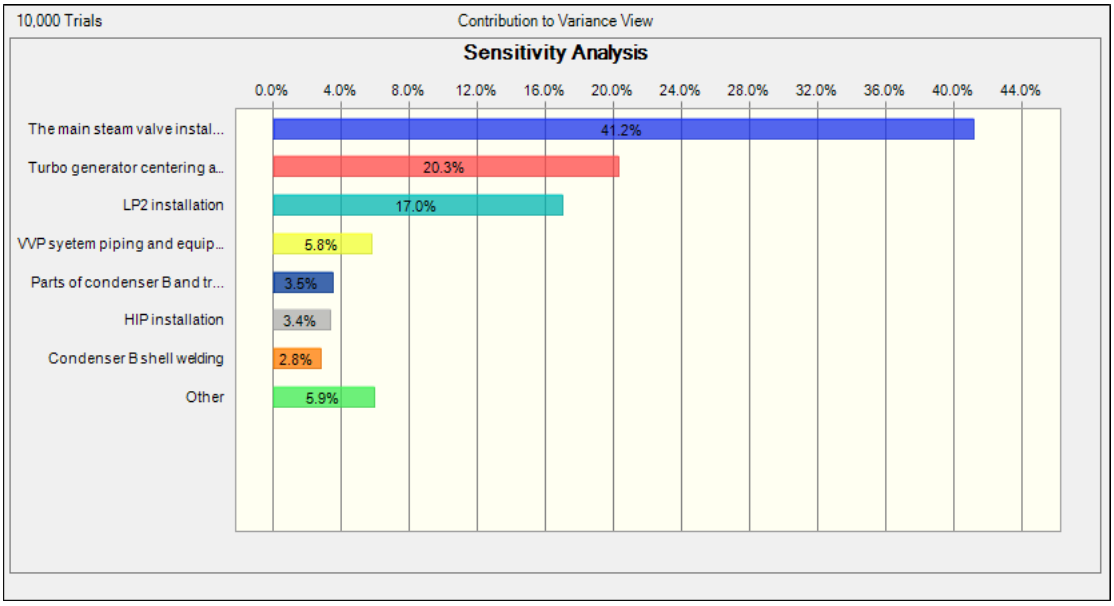

FIG. 19. Example of project duration sensitivity analysis.

are created within the scheduling risk analysis programme. Risk analysis is run, and results are interpreted to populate a risk register and a mitigation plan. After the project starts, the project schedule's risk model is regularly updated, and the risk analysis is repeated to obtain the predicted project duration and the driving risk factors. The driving risk factors provide the basis for the adjustment of the schedule.

In the quantitative risk analysis, the risk and opportunity for each task are identified. In schedule risk analysis, the minimum and maximum duration for each task are identified in addition to the expected value of the duration. The distribution is based on the minimum, maximum and average values instead of the traditional deterministic value. A simulation is run to obtain a distribution for the duration of the entire project. The sensitivity of the project duration to each task is then estimated.

6.1.4.2. Scheduling and project management tools

Project management tools are a software class that enables work items to be analysed and the people, products, processes and projects to be managed per the intended cost, schedule and quality. An information management system (IMS), including design management, procurement management, schedule management and risk management functions, is a common project management tool and has been widely used during NPP construction.

Applying an IMS can contribute to accurate, timely and comprehensive project information supporting risk management. The software can help predict the best outcome from various proposals using existing data, which provides a scientific and objective basis for formulating risk measures.

The application of an IMS influences the management of the construction of an NPP project. Therefore, selecting the proper IMS for an NPP project is a key decision. Some risks associated with project management and IMS tools are listed in Table 13.

Some measures to reduce or mitigate these risks include the following:

- — Select an established, reliable IMS. Secondary development of IMS may be necessary to make the IMS reflect specific business processes and ensure that data interfaces are established between different areas (design, procurement, construction, commissioning).
- — Train personnel about project management tools and techniques and in the use of the IMS.

— A knowledge management system is helpful for construction, operation and decommissioning. The knowledge management system may use valuable information generated from the IMS. Such interfaces should be considered and allocated during the secondary development of the IMS.
— An integrated project management system with a clear division of responsibility and a straightforward management process is one of the prerequisites for the IMS's secondary development.
— Input of data should fully reflect actual project status and should be consistent and up to date.
— The form in which the information is presented has to be unified and standardized.
— A configuration management system should be in place to ensure that existing versions are kept up to date and approved and are relevant.
— Ensure that information is only accessible to authorized parties.
— IT engineers should be used to keep the IMS performing smoothly.

6.1.5. Project metrics

Performance indicators (PIs) provide evidence to site management and stakeholders concerning the progress of a project. The use of PIs allows site personnel and stakeholders to understand the project's progress and its related issues. A broad range of performance indicators is needed; otherwise, aspects of the project may suffer. For example, safety and schedule may suffer if PIs only address financial aspects.

To evaluate each risk's economic value potentially affecting a project, organizations need to define the metrics to measure the economics (including profitability) of their projects, find the drivers that affect profitability and evaluate the impact of each risk on the drivers.

Earned value management system (EVMS) is a project management technique for measuring actual cost and time performance against forecasts (the baseline). EVMS refers to risk management implementation based on a breakdown of planned work. Earned value is measured by monitoring the amount of work performed per unit cost. Typical metrics used by an EVMS include planned value, earned value, actual cost, variances and performance indicators (Fig. 20).

Note:

— Planned value (PV) — the authorized budget assigned to the work breakdown structure component;
— Earned value (EV) — the value of work performed expressed in terms of the budget assigned to the WBS component;
— Actual cost (AC) — the value of the cost of work performed, spending for the actual work;
— Cost variance (CV) — a measure of cost performance on a project, CV = EV – AC;
— Cost performance index (CPI) — a measure of cost efficiency on a project, CPI = EV / AC;
— Schedule variance (SV) — a measure of schedule performance on a project, SV = EV – PV;
— Schedule performance index (SPI) — a measure of schedule efficiency on a project, SPI = EV / PV;
— Estimate to complete (ETC) — the expected cost needed to complete all the remaining work;
— Estimate at completion (EAC) — the expected total cost of a scheduled activity, EAC = AC + ET;

TABLE 13. RISKS AND IMPACTS RELATED TO IMS TOOLS

Cause	Risk	Impact
— Data input is incorrect, out of date or does not fully reflect the actual project status — Inconsistent data input — Data not updated when needed — Poor reliability of IMS	— The information is incorrect, ambiguous or incomplete — The information is incompatible with necessarily related items — IMS cannot provide a stable service	— Difficulty in evaluating the actual progress of the project and making correct decisions — Poor configuration management, which has a negative impact on operation — Information is not available for some time

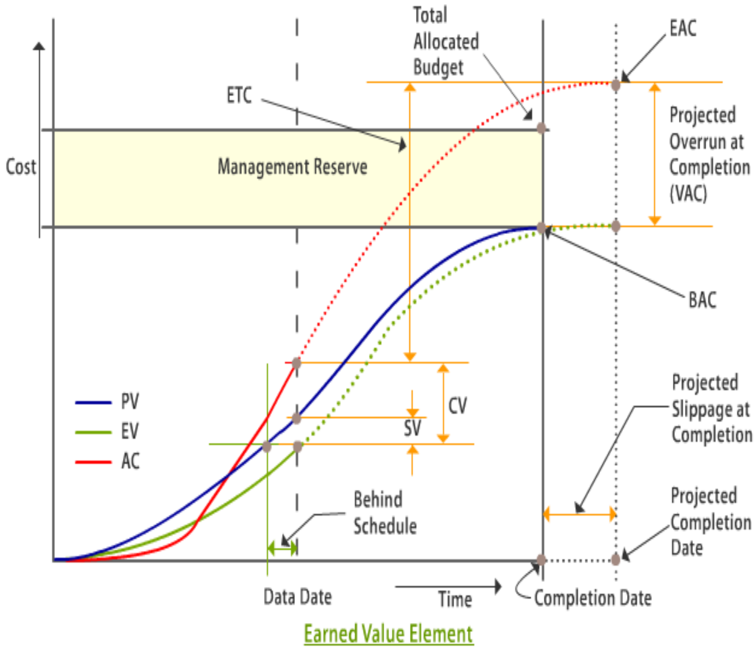

FIG. 20. Overview of earned value management.

— Budget at completion (BAC) — the total budget for the completion of work, BAC = Σ PV;
— Variance at completion (VAC) — the expected cost of the final budget variance, VAC = BAC – EAC.

Figure 21 shows an example of the use of an earned value metric in practice. The civil work contract for the Fuqing unit 5 project was a unit price contract. At one point in the project, the earned value tracking chart showed that the estimate at completion (EAC) of the project would be above the planned value (cost baseline). Through analysis, the cause of the overspending was determined to be that the cost of reinforcement was underestimated in the project plan. As a FOAK project, it was difficult to estimate the exact amount of civil work, so that a unit price contract was adopted. However, using the earned value method, the China Nuclear Power Engineering Co. (CNPE) could forecast the overspend during construction and identify the risk causes. This allowed sufficient time to take measures to address the issue.

The steps used to perform the EV analysis for Fuqing were:

(a) The complete project WBS based on the project's complete approved scope was developed. The WBS clearly defined the work scope and interfaces between the civil contractor and erection contractor for the nuclear island (NI)/conventional island (CI).
(b) The schedule prepared based on the WBS was rational and practical to reflect each activity's duration and logic.
(c) The costs of the contract were broken down (into operation units) and allocated to each activity/task in the level 3 schedule (contract schedule), and then discussed and agreed upon by contractors.
(d) Budget value curves for civil work and erection work for the NI and CI were established.
(e) The prerequisites for each payment were established, depending on the completed quantity and quality performance for related tasks. The quality performance could be judged by the quality control point in the quality plan for the specific activity, which would be checked and approved, if qualified, by a supervising engineer coming from the supervision company.
(f) The completed quantity and quality performance for related tasks would be evaluated; if the results were satisfactory, the earned value would be calculated, and then the progress payment would be calculated accordingly.

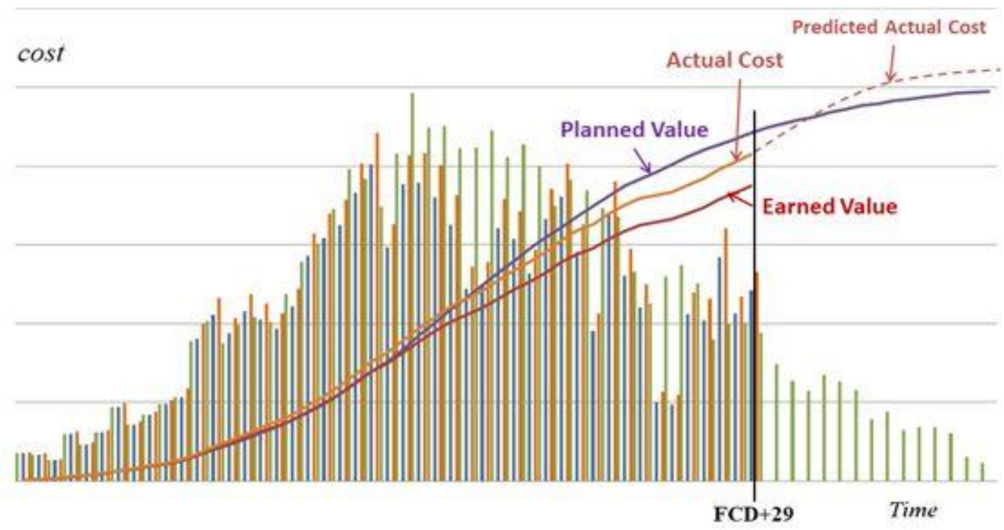

FIG. 21. Earned value use during an NPP project. Reproduced courtesy of CNPE.

Previously, contract payments were integrated with the schedule plan and quality plan. Subcontractors were usually paid based on the completed quantity of work or a milestone. However, there were more disputes between China Nuclear Power Engineering Co. (CNPE) and subcontractors related to the completed quantity or quality, which resulted in payment delays. Payment delays led to cash flow shortages for subcontractors and had a negative impact on the implementation of the project. By comparison, the earned value payment proved to result in fewer disputes, providing smoother cash flow for subcontractors and smooth project implementation.

The earned value payment approach has also been applied to subsequent projects: units 5 and 6 of the Tianwan NPP project and units 1 and 2 of the Zhangzhou NPP project.

Some risks associated with having poor project metrics are detailed in Table 14.

TABLE 14. RISKS AND IMPACTS RELATED TO PROJECT METRICS

Cause	Risk	Impact
— Inadequate project metrics defined	— Project status is not accurately known — Underlying issues and problems do not surface or are not addressed — Project participants work to incorrect or conflicting priorities or have incorrect incentives	— Project affected in the areas of cost, scheduling or quality

6.1.6. Stakeholder alignment

Stakeholders can make or break a project, and poor alignment can risk project cancellations, suspensions or early decommissioning. Stakeholders can be from inside or outside of the country that the NPP project is being built in and may include “government leaders, suppliers, the news media, medical and health professionals, special and public interest groups, consumer groups, other non-governmental organizations, individual citizens and informal opinion makers who may significantly affect the opinion of the community” [15].

Project funders and governments need to maintain alignment in support of the NPP, understand its inherent risks and contingencies, and influence public opinion to maintain project support over its life cycle. The project execution organization and the owner/operator need to engage proactively and openly with these key stakeholders through multiple channels and attempt to influence public policy in support of the facility.

Table 15 lists some risks and impacts related to stakeholder alignment.

TABLE 15. RISKS AND IMPACTS RELATED TO STAKEHOLDER ALIGNMENT

Cause	Risk	Impact
— Resources not applied to progress project when needed — Certain stakeholders not working in the best interests of the project — Project leadership not paying attention to stakeholder alignment	— Unclear direction for project team members — Inefficient execution or duplication of work	— Project delays or cost overruns — Cancellation of projects — Early closure of NPP facilities

Various IAEA publications discuss stakeholder involvement and alignment throughout the lifetime of a nuclear facility, including Refs [16, 57–59]. Community engagement and support are discussed more thoroughly in the next section. Figure 22 shows some stakeholder relationships for a typical NPP project.

The owner, Fuqing Nuclear Power Company, communicated with stakeholders at an early stage of the project. Stakeholders included the regulatory body, local government, investors, the China National

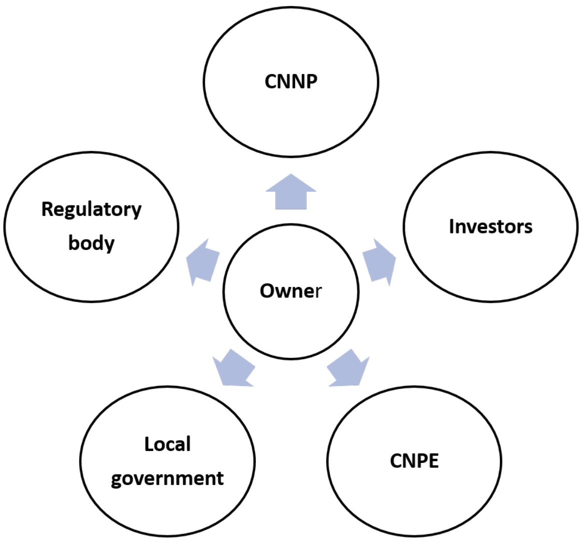

FIG. 22. Fuqing Nuclear Power Company interfaces with stakeholders.

Nuclear Power Co. Ltd (CNNP; the parent company) and CNPE (the general contractor). The objectives of communication with stakeholders were:

(a) To reach a consensus on how to manage the risks and how to obtain funds to control the risks if needed;
(b) To get related stakeholders involved in risk identification and make them take corresponding responsibility for risk management;
(c) To share risk information during construction;
(d) To establish common ground on how to manage the risks.

Such communication and consultation with stakeholders on risk management continued throughout the project.

6.1.7. Maintenance of community engagement and support

Nuclear operating organizations have learned the importance of maintaining ongoing support from and engagement with their host communities. Construction of a nuclear facility inevitably brings significant changes, both positive and negative, to the area around the chosen site. The IAEA's stakeholder involvement publications [16, 57] and the nuclear communicator's toolbox[8] emphasize the importance of paying attention to this area, and communications efforts need to start before and during facility construction. At the start of construction, the community may have little knowledge of the science and impacts of the facility. It may harbour fears that need to be addressed openly and transparently, and may not be fully aware of the ongoing benefit derived from the facility in terms of jobs and economic activity.

Some areas where ongoing attention is needed include (from the nuclear communicator's toolbox):

— Supporting informed choices;
— Setting goals and professionalizing outreach functions;
— Explaining a complex industry;
— Earning credibility;
— Recognizing the science of communication;
— Communicating with stakeholder groups;
— Engaging diverse audiences.

Table 16 lists some risks and impacts related to community engagement.

TABLE 16. RISKS AND IMPACTS RELATED TO COMMUNITY ENGAGEMENT

Cause	Risk	Impact
— Lack of knowledge of the risks and benefits of operating the facility — Fear of radiation risks	— Community becomes hostile to licensing of the facility and engages politicians or regulators with concerns	— Delays to or refusal to grant the operating facility licence — Cancellation of projects — Early closure of NPP facilities

Some measures to reduce or mitigate these risks include the following:

— Establish public outreach and education initiatives in the local and regional communities at an early stage;

[8] See: https://www.iaea.org/resources/nuclear-communicators-toolbox.

— Encourage and include independent organizations (e.g. regulators, academia) in communications initiatives to provide unbiased information;
— Establish a reputation for the company as a positive force in the community, funding charitable and other initiatives supporting the local community;
— Promote open, honest communication with local government authorities and the public at large.

6.1.8. Roles and responsibilities

The roles and responsibilities in a project need to be clear. Unclear roles and responsibilities can cause inefficient interactions between departments or contractors, leading to inefficient project execution, schedule delays and cost overruns. Well run projects have a clear project organization, a defined project execution plan, and clearly defined and assigned project roles. Clear and sensible organizational change control processes should be in place, and project communications protocols should be defined.

Table 17 lists some risks and impacts related to project roles and responsibilities.

TABLE 17. RISKS AND IMPACTS RELATED TO PROJECT ROLES AND RESPONSIBILITIES

Cause	Risk	Impact
— Lack of clarity regarding project roles and responsibilities	— Critical activities are not performed or effort is duplicated — Parts of the organization working at cross-purposes — Disputes over the division of responsibility between different departments or contractors. Work repetition — Contract claims	— Delays or inefficiencies in project execution — Cost increases

Some measures to reduce or mitigate these risks include the following:

— Define the roles and responsibilities of all project participants clearly in a project execution plan;
— Ensure participants understand their defined roles through face to face reviews of the project execution plan;
— Use a well developed work breakdown structure that covers all activities and the complete scope of the project;
— Define the specific roles and responsibilities of different contractors clearly in their written contracts;
— Continually reinforce responsibilities and a culture of cooperation through senior management.

6.1.9. Independent project oversight

Project oversight includes methods organizations use to provide independent assessments and reviews of the progress of the project. For large projects such as NPPs such oversight can assure the owner/operator, project financers, regulators and other bodies that the project is proceeding safely and according to plan.

Oversight typically follows a layered approach, with various organizations providing their insights into the project. These can be representatives of the Board of Directors, senior management, governments, insurers, regulators, external quality management experts and others, each performing reviews or audits and reporting out to oversight bodies. A separate risk management organization (described in Section 6.1.10) can be tasked with identifying and collating overall project risks.

Table 18 lists some risks and impacts related to project oversight.

TABLE 18. RISKS AND IMPACTS RELATED TO PROJECT OVERSIGHT

Cause	Risk	Impact
— Lack of external project oversight or ineffective oversight	— Project issues are not identified or addressed on time	— Delays in addressing key project issues relating to cost, schedule or quality impacts

6.1.10. Internal project risk management

Because of the quality and safety requirements for NPP construction projects, the NPP project management organization and its management systems need to be as sound as possible. The establishment of a risk management system does not necessarily require the inclusion of additional governance in the management system, but rather incorporation of the concept and methods of risk management. Each project team member's risk management responsibilities should be clear, and everyone in the project needs to be involved in risk management.

Project stakeholders can help to develop unified project goals in the early stages of the project. A risk management committee is often set up as a high level decision making organization to help manage overall risk during construction.

Some typical internal management functions that can be put in place include:

— Definition and establishment of project goals and standards;
— Collection, tracking, trending and analysis of safety and other performance information;
— Promotion of an organizational learning process to identify problems and to learn from past experiences and improve performance;
— Detection and management of possible internal conflicts between safety and economic benefits;
— Management of technical and organizational change;
— Establishment of an effective communication process with stakeholders, including the regulatory body, contractors, the local public, media and trade unions;
— Establishment and monitoring of good working practices and processes (enforced by walkarounds, housekeeping standards, material condition standards).

Table 19 lists some risks and impacts related to internal project risk management.

TABLE 19. PROJECT RISK MANAGEMENT RISKS AND IMPACTS

Cause	Risk	Impact
— Lack of well designed project management organization and integrated management systems — Lack of a risk management culture	— The division of responsibility for risk management not clear — Ineffective and inefficient risk management	— Significant negative impact on the execution of the project, resulting in project delays and cost overruns

Some measures to reduce or mitigate these risks include the following:

— Develop a project risk management strategy in consultation with stakeholders;
— Ensure that the division of responsibility concerning risk management is clear for each participant;
— Incorporate risk management into the project management system. The basic principle of risk management is that the project manager is the leader of the risk management of the project; similarly, the manager of each department or section is the leader of risk management for his/her scope.

— Ensure that one department or section (e.g. project control department or section) is assigned leadership to organize risk management for the whole project, including procedure preparation, data collection, trend analysis and reporting;
— Ensure that each project team member and everyone involved in the project is involved in risk management;
— Train personnel to understand the key elements of risk management;
— Establish and update the risk management culture inside the participant's organization, including the owner, general contractor, subcontractors and vendors.

Example

CNPE established a risk management organization for Fuqing units 5 and 6 as follows (the owner/operator project management structure is shown in Fig. 23):

— A project risk management committee was established at an early stage of the project;
— Unified risk management objectives for the project were clarified;
— The project manager ensured that risk management resources could be deployed in time;
— Information communication and reporting mechanisms for risk management were established;
— A periodic senior management meeting was held that dealt with risk management issues.

The Joint Decision-Making Group comprised the senior management from the owner, CNPE, main vendors, main constructors, design institutes, supervision company. A monthly meeting was held to review progress, evaluate the risks and allocate the resources needed to reduce or mitigate the risks. The owner

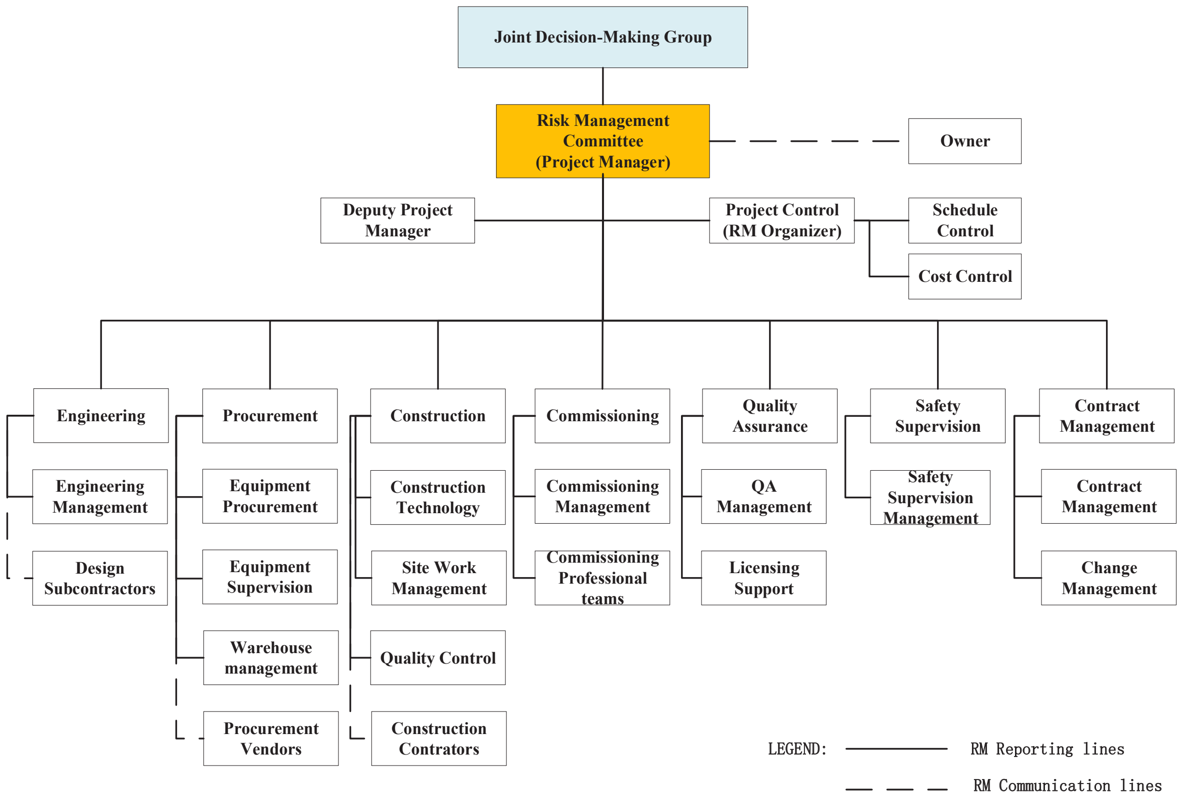

FIG. 23. Fuqing units 5 and 6 risk management committee.

and CNPE chaired the meeting alternately. The project manager was responsible for the implementation of post-meeting actions.

A project risk management committee was established at an early stage of the project. The project manager was the committee leader and was responsible for the resources needed for risk management. The manager of each department was the leader for the risk management of its activities. For example, the design manager was responsible for design risk management. The project control section was the leader for the risk management for the whole project. Information communication and reporting mechanisms were established. Periodic meetings (daily, weekly or monthly) were held to deal with risk management issues at different levels.

6.1.11. Project contract and procurement strategies

Contract management starts from the stage of preparing a request for tender to contract closeout. A well prepared contract, including a clear scope and clear interfaces, is necessary for a smooth project and helps avoid and mitigate the construction risks proactively.

A poorly designed or managed contract, a poorly performing vendor, or a lack of owner/operator oversight can lead to unexpected cost increases or delays during construction, or even project cancellation. Contractual arrangements between the owner/operator, nuclear steam supply system (NSSS) vendors and architect–engineers (AEs) can affect many of the project's activities, durations and logistics.

The IAEA nuclear contracting toolkit[9] provides advice on managing contracts for NPP projects.

Three main types of project execution and contractual approach have been applied to industrial projects, including NPP projects:

(a) Engineering, procurement and construction contract, or turnkey approach;
(b) Split package (island) approach;
(c) Multiple package approach.

A summary of the risks and impacts for each contracting type is provided in Table 20, and some generic risks related to contracting are provided in Table 21.

Some measures to reduce or mitigate contract risks include the following:

- Perform a make or buy analysis before making decisions on project execution approach and contract types.
- Establish clear responsibilities and scope for supply for all project participants, including subcontractors.
- Select an appropriate contract approach (turnkey, split package or multiple package) based on the capacity of the owner/operator and the vendor.
- Allocate project risks to the organizations that are most capable of controlling them. Project risks cannot be pushed entirely to vendors, and quoted prices might not be reasonable if the vendor is assigned risks that it cannot control.
- Establish a robust contract management oversight organization within the owner/operator organization.
- Reduce controllable risks as much as possible before issuing the project request for proposal (RFP) to the potential bidders. This includes finalizing national laws and regulations related to the project and choosing a site.
- Avoid FOAK or mitigate FOAK risks through the use of cost and schedule contingency.
- Complete the basic design before finalizing the project's scope. If this is not possible, consider a flexible pricing method with stage gates.
- Establish a clear, collaborative, mutually supportive working culture between the parties.

[9] See https://www-legacy.iaea.org/NuclearPower/Infrastructure/NuclearContractingToolkit/index.html.

— Select a contractor with demonstrated good performance (reduces incentives for extras and interparty litigation).
— For EPC contracts, ensure that the contractor maintains consistency between the general contract and the subcontracts. Some risks, allocated to the general contract by the owner, may be transferred to those subcontractors who can manage them.

TABLE 20. RISKS AND IMPACTS RELATED TO CONTRACT TYPES

Type	Cause	Risk	Impact
— EPC contract or turnkey contract	— Contracted with only one entity — Loss of control due to risk transfer — Potentially a higher contract price (if the owner lacks pricing knowledge) — Limited resources within the qualified vendor — EPC/turnkey contract price is based on a project estimate that was not well designed and prepared	— Limited involvement in project management, design and construction — Limited technical transfer and localization (except as negotiated) — Delay of supply of main components (due to longer negotiation time for the entire contract) — Limited vendor capability — Gap between EPC/turnkey contract price and the actual cost is large	— Failure of the project if the vendor has insufficient capabilities — Cost overruns — Schedule delay
— Split package (island) approach	— Maximum responsibility assigned to the owner due to interfaces and compatibility	— Increased interface problems	— Loss of control of the project — Failure of project
— Multiple package approach	— Maximum responsibility assigned to the owner due to interfaces and compatibility of systems and technologies	— Increased interface problems — Increased possibility of incompatibility of systems and technologies within the NI or CI	— Loss of control of the project — Failure of project

TABLE 21. GENERIC CONTRACT MANAGEMENT RISKS AND IMPACTS

Causes	Risks	Impacts
— A poorly designed or managed contract — Inappropriate risk sharing mechanisms between contract participants — A poorly performing vendor — Lack of oversight by owner/operator and/or general contractor — Lack of an effective contract change management system	— Scope and interface among contracts not clear — Risks that are assumed to be managed are not actually managed — Contract changes — Rework — Quality issues — Contract disputes and time consuming contract changes	— Unplanned cost increases or delays during construction and potential project delays and cost overruns

— Ensure that the owner's scope of risk events and the force majeure terms are clearly defined.
— For split package and multiple package approaches, ensure that responsibilities and costs are specified in the contract between the subcontractors and the owner. Ensure that contracts specify how to compensate for the losses related to other contractors' performance due to improper coordination.
— Incorporate appropriate incentives to help maintain high levels of performance.
— Ensure that an effective change management mechanism is prepared and accepted by all parties before contract signing.

A typical process for main contract management is described in Section 2.4 of IAEA Nuclear Energy Series NP-T-2.7 [39]. The publication describes typical contract types, aspects to consider when selecting a contract type, and a typical contract's structure and content. IAEA Nuclear Energy Series NP-T-3.21[11] on procurement covers other aspects of the contracting process and items to consider for inclusion in contracts for new build projects.

Example

An EPC approach was adopted for the construction of Fuqing unit 5, a Hualong 1 design FOAK project. When the general contract was negotiated, it was challenging to set the EPC contract's price because of lower level design completion and there being no constructed reference plant. An alternative pricing method was discussed and agreed to, which set the price in two stages. In the first stage, the design fee, management fee and commissioning cost were considered. The EPC contract price was set (fixed price), and meanwhile the construction cost and procurement cost were set as a temporary price, which could be adjusted later on. In the second stage, construction costs and procurement costs were adjusted based on the higher level of design completion, and the prices in the EPC contract were finalized accordingly. The progress of the project suggests that the flexible pricing method by stages is practical.

6.1.12. Project change control

As the project progresses, some adjustments will be necessary to deal with changing conditions. Project change control processes ensure that each change proposed during a project is adequately defined, reviewed and approved before implementation. The change control process helps to avoid unnecessary changes that might disrupt services and ensures efficient use of resources.

Change control processes typically involve the following steps:

(a) Proposing a change;
(b) Summarizing its impact;
(c) Making a decision;
(d) Implementing the change;
(e) Closing the change.

For NPP projects, changes can relate to project schedules, resources, costs, designs, materials or other items. Defined business processes need to be set up to assess and process such changes in an orderly manner. Table 22 details some of the risks and potential issues that may arise if this is not done. Section 6.2.4 of this publication discusses design change control in more detail.

6.1.13. Project delay/suspension provisions

Changing political environments or economic conditions may require an NPP project to be delayed or slowed down for a time or cancelled. Processes and commercial agreements should be put in place to ensure the securing and preserving of project SSCs and documentation in the event of a declared delay or suspension. Failure to do this risks making any project restart more complicated or expensive than

TABLE 22. PROJECT CHANGE CONTROL RISKS AND IMPACTS

Causes	Risks	Impacts
— No processes in place for project change control or non-adherence to established processes — People not aware/trained in change control procedures	— Uncontrolled cost increases — Excessive contract changes — Low value activities added to the project — Contract disputes and time consuming contract changes — Unclear current or final state of project design configuration	— Unplanned cost increases or delays during construction and potential project delays and cost overruns — Changes are made without approved budget allocation — Unauthorized changes are made that should not have been made, leading to further corrective action — Loss of plant configuration (see Section 6.2.5)

otherwise might be necessary since costly conditions assessments would be necessary to confirm that any work completed before the suspension would not need to be repeated and that adequate documentation for the as-constructed facility is available.

IAEA Nuclear Energy Series No. NP-T-3.4 [60] discusses some of the considerations related to restarting delayed nuclear projects. It lists many risks as applying to delayed projects, which are detailed in Table 23 below.

TABLE 23. PROJECT DELAY AND SUSPENSION RISKS AND IMPACTS

Causes	Risks	Impacts
— Construction risks — Underperformance of duties by the contractors — Contractor insolvency — Fluctuations in currency exchange rates with an adverse impact on the costs of imported equipment and services — Changes in specific legislation by the regulatory body — Adverse developments in the local labour market (shortages or increases in costs) — Delays due to suppliers of equipment or materials — Force majeure — Need for replacement of equipment after commissioning tests due to non-conformance	— Uncontrolled cost increases — Excessive contract changes	— Unplanned cost increases or delays during construction and potential project delays and cost overruns

6.2. ENGINEERING READINESS

Starting construction before the necessary engineering work is complete is a decision that carries a large risk. Engineering documentation needs to be available, proper constructability reviews should be done, and proper plans, processes and schedules should be in place for managing design changes and plant configuration during the construction process. The plant needs to have its various engineering programmes (e.g. ageing management, environmental qualification, in-service inspection, fire protection, chemistry, cybersecurity) in place as it goes into commercial operation. Hence any work required to support this needs to be planned and scheduled.

The CORR guidelines [43] refer to the following areas as being of special importance concerning engineering management within nuclear construction. Each will be discussed in the context of risk management:

(a) Engineering documentation;
(b) Feedback incorporated;
(c) Engineering planning;
(d) Design change process;
(e) Configuration management, controlled documents and records;
(f) Computer/cyber security;
(g) Delayed project (if applicable);
(h) Engineering programmes;
(i) Engineering quality.

6.2.1. Engineering documentation

A key objective of design is to provide the procurement and construction organizations with up to date design documents, specifications and drawings on time to implement construction. Design changes during the construction period have the potential to jeopardize project schedules and dramatically increase costs. At FCD, almost all design documentation, including related construction documentation, should be ready to support construction activities. Projects that proceed with significant design work still to be done are at extremely high risk. Experience from previous NPP construction projects indicates that a high level of design completeness before FCD, often with two years' worth of initial construction documentation, contributes positively to smooth project implementation. Due to their integration requirements, designs that use modularization extensively require higher design completion levels, such as 90% completion instead of 70% completion for stick build designs.

Engineering documentation for new NPP construction is generally categorized into four groups:

(a) Nuclear steam supply system design;
(b) Component design;
(c) Balance of nuclear island and conventional island design;
(d) Fuel and core design.

Specific examples of engineering documentation are provided in Appendix III. Table 24 details some risks and impacts related to engineering documentation.

TABLE 24. ENGINEERING DOCUMENTATION RISKS AND IMPACTS

Cause	Risk	Impact
— Engineering documentation not available or incomplete when needed to support construction	— Procurement activities delayed awaiting engineering input — Field activities delayed awaiting engineering input — Incorrect assumptions made related to engineering intent	— Project delays and cost overruns — Potentials safety issues or rework if assumptions are not validated or if work proceeds at risk before final engineering input

6.2.2. Feedback incorporated

Designers need to incorporate feedback from experience in designing, building, operating and decommissioning older NPPs into their designs for new NPPs. Incorporating feedback applies to both FOAK designs and proven designs, including improving a proven design.

6.2.2.1. First of a kind designs

Design risks for proven reactor designs are lower than those for FOAK designs (i.e. the first build of a reactor's type in the world). Even without FOAK risk, design changes can still lead to delays if site specific design work is not performed well.

In the case of a FOAK reactor, R&D and technical verification are important to minimize risk during the design phase. New design technologies, including the specific equipment and components to be used, need to be verified and tested. Discovery issues during such testing may lead to changes in equipment manufacturing technology and design parameters. To reduce risk, it is beneficial to complete the R&D, deployment, prototype equipment manufacturing, testing and verification, and detailed design before starting the construction project.

Design risk is relatively low for the case of a proven technology NPP built by an experienced supply chain. However, further design changes and delivery delays for documentation and drawings can still challenge the project if the design work is not well organized. All feedback from the reference power plant's operating experience and consequent improvements should be fully incorporated into the design. New requirements for nuclear safety authority and the new site design need to be understood, focused on, discussed and resolved as early as possible.

Some R&D items (e.g. a piece of new equipment, a new concrete structure) and improvements may be needed for a project, which may cause risks such as a possible delivery delay. A risk management process needs to be in place to identify, analyse and control such risks with the assistance of necessary experts. A risk management strategy should be implemented based on the risk's potential impacts on quality, safety, schedule and cost. Quantitative analysis should be conducted when necessary, including analysis tools such as GERT or Monte Carlo.

In general, the key to risk control for new technology is to take active and effective measures to ensure the rational cohesion of R&D, design improvement and construction. The progress of R&D for new technologies needs to be aligned with the project schedule.

Table 25 details some risks and impacts related to proven versus FOAK designs.

Some measures to reduce or mitigate the risks include the following:

— Understand and incorporate all the requirements of the nuclear regulatory authority in the early stages of design;
— Ensure that all feedback from the reference power plant's operating experience and consequent improvements are fully incorporated into the design;
— Ensure that site specific design work, especially for a new site, is well prepared and organized against the integrated project schedule;
— Prepare for the procurement of equipment and materials to support design interface exchange;
— Complete the R&D, prototype equipment manufacturing, testing and verification before the start of construction (see example below);
— Use risk analysis by experts or quantitative analysis, including the use of analysis tools such as GERT or Monte Carlo, to analyse any impacts (caused by R&D activities and improved items) on techniques, quality, safety, schedule or cost and then generate a ranking list of risks and take necessary measures accordingly.

TABLE 25. RISKS AND IMPACTS RELATED TO PROVEN VERSUS FOAK DESIGNS

<table>
<tr><th>Type</th><th>Cause</th><th>Risk</th><th>Impact</th></tr>
<tr><td>— Proven design</td><td>— Tight schedule for engineering and procurement before the start of construction
— Impact of incremental ‘minor’ improvements not fully assessed</td><td>— Delays for documentation and drawings or delays for equipment delivery
— Unanticipated operational or construction difficulties</td><td rowspan="2">— Delays in construction or commissioning activities, errors or rework, causing project delays, cost overruns or even project suspension</td></tr>
<tr><td>— First-of-a-kind</td><td>— As above, plus:
— Prototype equipment manufacturing, testing and verification not completed before the start of construction
— Potential for unanticipated issues arising during construction not factored into the schedule</td><td>— Large quantity of design changes
— Delays in equipment delivery</td></tr>
</table>

Example

The Sanmen unit 1 (AP1000 FOAK) project was delayed by 54 months against the project’s general duration baseline. As this was a FOAK project, prototype equipment manufacturing, testing and verification should have been completed to support long lead equipment manufacturing and design before FCD. As a module construction approach was employed, the design should have been conducted at a very detailed level to support procurement, construction and module prefabrication before FCD. If these requirements were not met, it would result in insufficient or inadequate preparatory work and pose a considerable risk to the project.

The main contributor to the delay was that prototype equipment (reactor coolant pump, canned pump) manufacturing, testing and verification were not completed before the start of construction.

The main reasons for project delay were as follows:

(a) Delivery of the reactor coolant pump (RCP) canned pump was delayed by more than 40 months. The RCP was prototype equipment, and so its manufacturing, testing and verification should have been completed before FCD. The testing and verification of the RCP started 4 months after FCD and took more than 73 months, four times more than the time allocated in the original schedule.
(b) NI design progress lagged seriously. The vendor did not conduct design work at a very detailed level before FCD. There was also a lack of design human resources and experience, which resulted in design documents and drawing delays and many subsequent design changes. These issues led to rework and schedule delays and consequently seriously impacted on the construction.
(c) There was a lack of sufficient human resources and experience within the project management organization for the first kind of project, so it was difficult to deal with the issues during the construction phase efficiently and in a timely manner;
(d) After the Fukushima nuclear accident, some new regulatory requirements were imposed, and some design improvements needed to be made to meet these new regulatory requirements. It took more time to implement such improvements, which also impacted on the construction.

This is one of the typical lessons learned from a FOAK project. The progress of R&D of new technologies was not matched with the project schedule and there was inadequate design preparation and inadequate long lead equipment procurement before FCD, posing considerable risks to the project. The risks were not identified and analysed comprehensively at an early stage. The countermeasures to reduce or mitigate the risks were not incorporated into the pre-project and construction schedules.

6.2.2.2. Existing design improvements

For new projects based on a previous design, there is potential to improve benefits in terms of cost, schedule, quality or safety. Owner/operators need to assess the relative benefits of such improvements and decide which of them are worthwhile to pursue.

One method to systematically assess these is through the establishment of a design improvement team. Such a team, led by the owner/operator organization, will assess the proposed design improvements against the reference power plant. The team reviews the proposed items against any new nuclear safety regulations, obtains operating experience feedback from organizations that operate similarly designed NPPs and from the NPP construction organization, obtains information related to new equipment manufacturing technology and any recent R&D findings related to the reference design, and assesses the potential costs and benefits of including such improvements within the new project.

The level of involvement of the owner/operator in this process may depend on the contract type. In a turnkey contract, the main contractor can manage design changes, and the owner/operator exercises the oversight function. The owner/operator will typically review any recommended design changes carefully and ensure that they have no negative impacts on the licensing basis, the interfaces, the supply scope, and the plant's operability and maintainability.

Design changes under review may be proposed at the system level (such as changes in performance, function, operating modes, control methods) or the component level (such as changes to service conditions, structures, materials or manufacturing methods). Even minor changes to service conditions may cause large cascading effects, even though the components themselves may not be physically changed. Therefore, design change control submissions for approval should include the design items themselves and any changes to operating, environmental and interface conditions.

As part of this process, design changes need to be graded and reviewed based on their impact on safety, reliability and economics. Verification and validation plans for key changes should be established. Such plans may include design examination, mock-up tests, trial production and additional performance tests at factories or on-site. Verification and validation plans should be reflected in the manufacturing or erection/construction schedule.

Engineering management is described briefly in Section 2.3 of IAEA Nuclear Energy Series NP-T-2.7 [39].

6.2.2.3. Construction feedback

Incorporating construction feedback into designs can significantly increase the safety and cost effectiveness of construction activities, reducing risks related to project delays, cost overruns and quality incidents. Such 'constructability' reviews, often held in a structured workshop setting involving designers and construction staff, cover the use of unique construction methods, site logistics, equipment access, site security planning, industrial safety and other aspects. Technical specialists with knowledge of ergonomics, industrial hygiene, human factors, fire protection, chemistry, procurement, training or other areas might also attend the meetings. Of particular interest is to ensure that safety considerations are not compromised during the modification's construction, operation or maintenance.

Section 6.3.3.2 of IAEA Nuclear Energy Series No. NP-T-3.3 [61] covers constructability reviews in detail, and Appendix IV of that publication provides an example of a related checklist.

6.2.3. Engineering planning and management

Poor engineering and design management can cause significant schedule delays in a project. Sources of such risks can include a lack of a shared methodology among all individuals involved in the design, lack of shared information, poor software and IT systems, and inadequate information management and control. The planning of engineering work needs similar attention to that of the construction field activities.

Poor design authorization, site approval, and licensing processes can lead to quality, cost and schedule problems. Other risks include the following:

— Selecting an unproven design can result in lower than the expected electrical output. Load/capacity factors may be low due to unexpected repairs and plant changes being needed following the plant's going into service. The selection of unproven equipment may lead to safety or production issues that will need to be addressed.
— Overdefined performance requirements can increase costs.
— Lack of attention to operability and maintainability is a risk that can materialize later during facility operation. It is important to involve future maintenance specialists and control room operators in the project as early as possible. Contributing factors to such shortcomings may be a lack of such staff in the project phase, time pressures, improper scheduling, insufficient budget, or elimination of suppliers responsible for maintenance.
— Poorly defined design requirements or poor methodologies for corrective action and change control can cause problems.

The design of an NPP requires the participation of many engineers and equipment suppliers and feedback from constructors, so design interface management is very important. Interface points and communication methods between the applicable organizations need to be defined at an early stage. Some important design interfaces are between the owner, the NPP vendor (who is usually the general design contractor and who owns or is closely related to the leading NPP design institute), the design subcontractors, equipment suppliers and construction contractors. This includes interdisciplinary interfaces (e.g. mechanical, electrical, civil, I&C) and interfaces between engineering and procurement. Dedicated interface engineers, software platforms and regular interface meetings are often useful in facilitating communication. Figure 24 shows an example of an engineering company's organizational interfaces for an NPP project.

Modularization offers potential improvements to critical path construction schedules because work can be completed off-site in a more controlled environment (e.g. a module construction shop) and reduce the level of field activities. Effective and well designed modularization may result in an overall reduction in the quantity of pipes, valves, hangers and other components that have to be installed on-site. This can be directly correlated to on-site schedule duration improvements. However, the design and equipment procurement for such modules needs to proceed in advance because an extremely high level of engineering and planning completion is required before construction. If this is not done, many of the benefits of modularization will be lost, since design rework will be encountered, and many construction activities will, by necessity, be moved into the less hospitable field environment [62, 63].

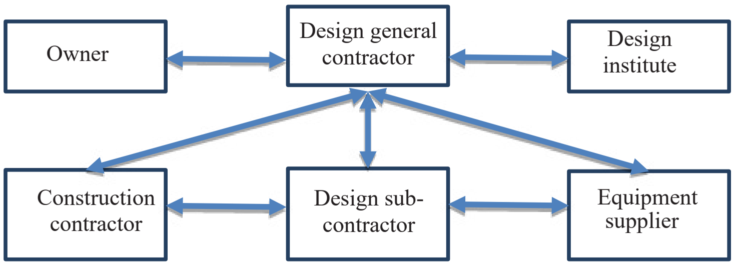

FIG. 24. Example of an engineering company's organizational interfaces for design.

Poor design interface management can result in procurement, installation or commissioning errors and rework, latent safety issues, loss of CM and loss of confidence by the regulator. In such an event, the licensing process for the NPP can be delayed.

Engineering management is described briefly in Section 2.3 of IAEA Nuclear Energy Series NP-T-2.7 [39]. That publication describes the phases of pre-construction planning and design change management processes. IAEA-TECDOC-1335 [64] and IAEA Safety Reports Series No. 65 [65] discuss CM in design.

Table 26 details some of the risks and impacts related to engineering planning.

TABLE 26. RISKS AND IMPACTS RELATED TO ENGINEERING PLANNING

Cause	Risk	Impact
— Lack of design planning — Tight design schedule — Lack of complete design inputs — Lack of validation and testing of designs — Overestimation of the level of design completeness (detailed designs and procurement specifications not available) — In the case of a FOAK project, the testing and verification of prototype equipment does not meet design schedule requirements	— Lower level of design completeness before FCD — Material or equipment not available when needed due to procurement delays	— Construction activities may be suspended after FCD due to a lack of drawings and documents — High levels of design changes during construction and commissioning — Unplanned cost increases or delays and, consequently, project delays and cost overruns

6.2.3.1. *Good practices*

Some good practices related to engineering management that were transferred from Olkiluoto 3 and Flamanville 3 to Taishan 1 and 2 and Hinkley Point C include the following:

— Analysis of difficulties encountered during detailed design, manufacturing and construction;
— Issuance of feedback sheets providing information related to designs and proposed solutions;
— Modifying and simplifying designs to improve constructability;
— Use of 3-D mock-ups to manage the layout interfaces;
— Validation of processes using a dedicated simulator;
— In-factory surveillance of off-site manufacturing;
— Involvement of local companies;
— Competences checked (code and standards);
— Organization of the subcontractor’s supply chain;
— Completion of basic design and a significant part of detailed design before the start of construction.

Some lessons learned and recommendations taken from NPP projects in China include:

— Strengthen communications with the design organizations. Take measures to reduce the number and impact of design changes to minimize the effect on manufacturing or construction. Consider establishing a separate organization to prioritize and address urgent design issues that are impacting on field activities.
— Learn from experience. Study the causes, impacts, and control measures of design changes and summarize the lessons learned. Develop measures to improve the design or the design process to help improve future projects.
— Focus on the impact of design changes on the project. Designers need to analyse the effects of changes on constructability, scheduling, costs and other areas. Ensure early identification of design changes

caused by interface information changes, design flaws, safety regulations or specifications. When a design change is caused by design optimization or the owner's new requirements, its feasibility and project impacts should be analysed carefully.
— Strengthen the design change implementation process. To ensure correct implementation of design changes, the design change management programme needs to have been established early and should follow the basic principle of 'closed loop management'. A dedicated department in charge of design changes should track and provide feedback related to the design changes.
— Establish a database that records the design change number, title, release department, issuer, starting time, receiving time, receiver, implementation personnel, end time and implementation problems (if any). Ensure that all design changes are implemented effectively.

An example from China related to addressing a design risk is described below.

Example

All piping supports over 16.5 m in reactor buildings were designed to be rooted in the steel containment liner. The risk of collisions between piping due to uncertainties was identified six months before piping construction. The issue could not be addressed quickly, directly affecting the prefabrication activities and site lifting of any steel containment liner over 16.5 m. To address this, a special coordination group was established to mitigate the risk. A detailed schedule was developed based on the construction process. Design department personnel were assigned to oversee completion and reported on the topic weekly. Any problems that arose received support from the applicable department as needed. Eventually, the risk was mitigated, and piping erection and lifting of steel containment liners >16.5 m were put back on schedule.

6.2.3.2. Use of simulators

The serial production of NPP units is probably never entirely possible. Site specific characteristics should be taken into account, and each regulatory body sets its requirements. Units on the same site usually have slight differences, and each unit's I&C systems may differ in significant aspects. Three types of simulators may be beneficial in the design phase:

(a) An effective design simulator that is capable of unit specific simulations should be purchased as early as possible. The detailed simulation models for the process systems (e.g. in APROS [66] code) and the real I&C software can radically shorten the time needed to design and verify different and separate I&C systems. Diversity is required in I&C systems, but diverse safety signals can control the same process components. Simulation helps to ensure the successful integration of the diverse systems.
(b) Training simulators, which use simplified process models and simulated I&C models because they have to operate in real time. They are needed later for training operators, but they are not capable of aiding in design because of the simplified models.
(c) A simulator that is similar to the design simulator but it is used to validate design changes.

Example

The effectiveness of the design process for the I&C systems in Olkiluoto 3 radically increased when a full scope design simulator was used by the designers [67].

6.2.4. Design change process

A key part of change control of any NPP project is the control of design changes. Engineering management requires the control of design changes, control of the interfaces between organizations that can impact on the design, and ensuring design completeness before field activities commence. Constructors of NPPs have encountered long delays due to frequent design changes being needed during the construction process. To avoid such delays, engineering completeness before the first concrete pouring should be confirmed.

Once the construction starts, agile and responsive processes need to be in place to process design changes. These need to be established before construction as part of the engineering planning phase (Section 6.2.3). Dedicated staff are often needed to work with construction and commission staff and to assess and process such changes, since the original designers may still be engaged in designing later phases of the project. Table 27 lists some of the risks and impacts of an imperfect design change process.

TABLE 27. RISKS AND IMPACTS RELATED TO THE DESIGN CHANGE PROCESS

Cause	Risk	Impact
— Undocumented design change process — Lack of dedicated staff to process design changes — Pre-project planning activities not completed adequately to validate original design assumptions/ inputs	— Delays in construction or commissioning activities — Material associated with design change not available — New requirements from the regulator or owner identified late	— Construction or commissioning activities may be delayed due to a lack of drawings, documents or material — Rework of design, procurement, construction or commissioning — Unplanned cost increases and delays

Some methods to help reduce risks related to the design change process include:

— Strengthen design management from the source. Check design inputs and outputs periodically. Conduct quality assurance checks on the design management process regularly.
— Pay attention to early intervention. Prepare a ranked list of the pending design issues and plans to address them. Hold special sessions regularly to address supervision and consultation issues.
— Carry out experience feedback. Study the root causes, impacts and control measures for design changes and summarize the lessons learned.
— Review and challenge the need for design changes caused by a change in regulatory requirements, interface information, design flaws, specifications or the owner’s new requirements.
— Implement change tracking by a dedicated department in charge of design changes, with feedback related to design change implementation provided by them.

Engineering management is briefly described in Section 2.3 of IAEA Nuclear Energy Series NP-T-2.7 [39].

6.2.5. Configuration management, controlled documents and records

Processes for managing plant configuration, documents and records need to be established to minimize the risk of losing control of the plant’s design or field configuration. Loss of plant configuration, in which the physical plant becomes misaligned with the design documentation or operating procedures, can result in loss of regulatory confidence and the need for costly projects to restore configuration during later stages of the NPP’s life.

6.2.5.1. *Configuration management*

Configuration management is an essential component of NPP design, construction and operation. For new plants, a CM process should be set up as early as possible at the design stage. The plant's design bases and requirements should be established and documented, and the maintenance system for the whole life cycle of the plan should be established.

Configuration management refers to the process of identifying and documenting the features of the plant's physical assets, operating systems and procedures, and components. It also involves proper and routine management of changes to these characteristics by developing, evaluating, authorizing, publishing, applying, ascertaining, registering and integrating those variations into plant documentation. Deficiencies and errors in CM are a significant source of NPP events.

The concept of a CM recognizes that three elements need to be aligned: design requirements, facility configuration documentation and physical configuration.

(a) Design requirements are derived from standards, regulatory requirements and the design process. They impose limits on the final design, including the consideration of margins, and they are reflected in the design documentation.
(b) Facility configuration documentation is the set of all the documents containing configuration information defining how the plant is designed, how it is operated and how it is maintained.
(c) Physical configuration applies to the installed and subsequently commissioned SSCs and those items' operational configuration.

The configuration of an NPP is considered to be in alignment when elements conform, all changes are authorized and conformance can be verified from documents.

Some of the specific information that needs to be integrated into the CM system includes:

— Design data and engineering calculations;
— Design drawings;
— Plans;
— Vendor drawings;
— Layouts and schematics;
— Routing drawings;
— Process and instrumentation drawings;
— Electrical line drawings;
— Operation and performance data/records;
— Control processes;
— Maintenance information and procedures;
— Materials management systems;
— Final safety analysis report (FSAR).

An effective configuration control system can play a vital role in the reduction of risks in operational NPPs. Implementing a CM system in an older power plant, however, is highly challenging. The basic requirements include a firm understanding of existing systems; the ability to retrieve and consolidate the available documentation; the ability to verify and record the changes that have been implemented to date; and a process to take care of future modifications. The ultimate goal is to develop a comprehensive life cycle information repository for maintenance, modification and operation.

Table 28 lists some of the risks and impacts related to CM.

The IAEA has released numerous publications related to configuration management, including Refs [64, 65, 68, 69]. Several industry publications and standards are also available [70–74]. IAEA Nuclear Energy Series NP-T-3.21 [11] describes configuration data needs related to the procurement process.

TABLE 28. RISKS AND IMPACTS RELATED TO CONFIGURATION MANAGEMENT

Cause	Risk	Impact
— Poor configuration management and document management — Lack of dedicated staff to control configuration management	— Poor design — Poor project planning — Poor site supervision — Errors in field activities (e.g. wrong equipment worked on) — Loss of regulator confidence	— Reputation loss — Poor quality of construction — Non-conformance records — Schedule delays

6.2.5.2. Document and information management systems

During an NPP project, information is created, accumulated, classified, stored and distributed to the relevant parties. This information includes technical and project information (drawings, diagrams, tables, 3D models, descriptions, analysis reports, R&D reports, bills of material (BOM), etc.), enterprise or user related information (schedules, working processes, human resources, materials, resources, quality records, working materials), or it can be information contained in contracts (project budget, timelines, supply deadlines). Information about a plant may include its configuration details, operation, standard operating procedures for responding to emergencies and maintenance records.

Information may be specific to the various stages of an NPP project. At each stage, information has to be transferred to the following stage to consolidate it within the body of mandatory documentation collected during the whole NPP life cycle. Therefore, it is important to ensure that the information passing through various stages of an NPP project is compatible, correct, complete and up to date. High quality documentation makes the right information available to the right people at the right time, ensuring that the right decisions are made. Therefore, modern methods of information management in the development and construction of an NPP are based on the following principles:

(a) All information required during the NPP life cycle has to be clear and unambiguous;
(b) The form in which the information is presented has to be unified and standardized;
(c) Configuration management system should be in place to ensure that existing versions are kept up to date, approved and relevant;
(d) Information is only accessible to authorized parties.

Documentation challenges in the nuclear industry may include the following:

— Duplication of documents;
— Visibility of information;
— Security of critical information;
— Overhead costs of printing, reproducing and distributing paper documents;
— Document traceability years after the completion of a project;
— Increased chaos and inconsistencies due to a mix of homegrown solutions;
— Lack of integration between various departmental solutions within the same organization;
— Poor efficiency and accuracy of procedures;
— Stricter regulatory requirements and slow approval process.

A proper document management system (DMS) to deal with documentation needs is the route a few companies have taken in the nuclear industry. The trend to delay implementing a documentation standard is changing. With growing regulatory requirements, increasing numbers of companies are beginning to use technological solutions to manage their documents more efficiently. When choosing an electronic document management system, one has to ensure that it manages documents of all types and makes it easier for the user to understand the relationship between various documents. With users from numerous departments and teams, a document management system has to offer a user friendly interface that presents information easily based on the user's roles and requirements.

Throughout an NPP's life cycle, information is created by workers, lessons are learned and best practices are created. For the survival and growth of the nuclear industry, it is critical to store and pass on this information in various stages of a project's life cycle. With the vast knowledge and human experience in the nuclear industry environment, there is a need for a method that will easily organize and capture the information.

With the use of an electronic document management system, the pressures of maintaining volumes of records and managing information can be reduced.

Table 29 lists some of the risks and impacts related to document and information management system.

TABLE 29. RISKS AND IMPACTS RELATED TO DOCUMENT AND INFORMATION MANAGEMENT SYSTEMS

Cause	Risk	Impact
— Lack of a DMS — DMS not integrated with other enterprise software systems — Multiple DMSs used by project participants	— Loss of configuration control of documents — Inefficient processing of documents (manual transfers between systems and applications) — Loss of knowledge/lack of knowledge transfer between project phases or between project participants	— Poor work quality — Increased costs and schedule delays — Errors or rework due to knowledge loss

IAEA-TECDOC-1335 [64] provides some recommendations for document management systems, while IAEA-TECDOC-1284 [75] addresses:

> "all aspects of documentation associated with various life-cycle phases of NPPs and the information technology (IT) that are relevant to the documentation process. It also provides a guide for planning, designing, and executing an IT documentation project. Examples are given to demonstrate successful implementations at plants. Finally, it discusses the issues related to the application of the IT in NPPs and the trends for applications of the IT at NPPs as well as the technology itself."

6.2.6. Computer/cyber security

The commercial nuclear power industry continues to move forward with digital instrumentation and control (I&C) upgrades and new builds using digital technology. Computer software, firmware and integrated circuits are increasingly used within SSCs. As nuclear facilities install such digital I&C systems, attention to computer security has intensified, as clear and recurring vulnerabilities of computer systems come to light. Malicious exploitation of these vulnerabilities has been witnessed with growing frequency and impact. Additional complications are seen compared to older analogue designs, including requirements for analysis of software failure modes and software development processes. Both safety related and non-safety related systems can be affected.

The development process for digital I&C systems should systematically address potential security vulnerabilities at each stage of the life cycle to meet confidentiality, integrity and availability requirements.

Computer security should now be a part of the overall security programme at a plant. The tools for identifying threats, assessing security positions and building barriers include technical tools, such as intrusion detection, virus scanners, firewalls and encryption, as well as administrative tools, such as the application of security zones, security management systems and access control (i.e. passwords and biometric identification).

The development and implementation of a computer security programme plan includes the performance of an overall risk analysis. This risk analysis document:

(a) Defines the scope of the security risk analysis for each system;
(b) Identifies the key threat groups and the security risks associated with them;
(c) Provides a risk management summary of the security requirements to manage each risk and implement countermeasures;
(d) Maintains the confidentiality of cyber designs and test results, which inhibits progress in developing design criteria.

The development of regulations, guidance and standards to maintain computer security is evolving. Computer security vulnerability might be significantly reduced if such regulations, guidance and standards are followed rigorously and if computer security programs for new systems and plants are developed.

Computer security for NPPs extends beyond considering the safety and non-safety systems that provide control and indication functions. This challenges the vendor, end user and regulator to extend the regulatory umbrella to non-safety systems for this subject matter.

Table 30 lists some of the risks and impacts related to computer/cyber security.

TABLE 30. RISKS AND IMPACTS RELATED TO COMPUTER/CYBER SECURITY

Cause	Risk	Impact
— Lack of protection for the introduction of viruses or malicious code such as the SQL Slammer worm and Stuxnet — Lack of assessment of special characteristics of computer/digital controls	— External malicious control of or ransom attacks on plant or business systems — Unanticipated failure modes of computer or digital based systems (as opposed to analogue systems) — Unanticipated introduction of computer or digital based systems into plant — Data transfer rates may not be able to accommodate newly developed control systems — Inconsistencies in data synchronization across plant networks — Potential for common cause failure	— Destruction of data and file systems/harmful actions/disruption — Replication by email or Internet/excessive traffic /abusing network write access — Remote control of infected computers/ concealment of symptoms — Bandwidth consumption/system resource (CPU, memory) depletion — Impact on maintenance activities — Loss of reliability of the digital I&C systems — Latent nuclear safety impacts due to unanticipated performance during abnormal conditions

Section 6 of IAEA Nuclear Energy Series No. NP-T-3.21 [11] discusses special considerations for procuring systems containing software and items containing software. Numerous IAEA Safety Standards (e.g. Refs [76–80]) provide guidance in this area, and various Member State and international standards and regulations are available, including Refs [81–86]. Design and operating organizations need to have dedicated resources available that are experts in computer software for NPPs and cybersecurity issues and incorporate cyber risk analyses into their overall risk strategies.

6.2.7. Delayed project (if applicable)

The restarting of NPP projects with delays of several years from the original scheduled commercial operation date presents particular management issues. Delayed NPP projects inherit some particular risks, primarily related to the plant condition. The NPP's partially built SSCs may have degraded during the delay period, key documentation may have been lost, and staff familiar with the design or the plant's status may no longer be available. A thorough assessment of the state of the SSCs and their associated design documentation should be performed before committing to such a project.

IAEA Nuclear Energy Series No. NP-T-3.4 [60] discusses delayed projects in detail.

6.2.8. Engineering programmes

Engineering programmes help to ensure that an NPP, when operating, continues to perform at high safety and reliability levels. Such programmes can include electrical, mechanical, instrumentation and control and civil inspection and maintenance programmes, chemistry programmes, fire protection, ageing management, environmental qualification, valve programmes and periodic/in-service inspections (ISIs), among others. Many of these programmes require that a set of baseline data be recorded at the start of the NPP's life, or certain construction samples be stored for future research and development. At the start of construction, these programmes need not be fully defined; however, they need to be developed to a state where these vital initial data and samples can be captured as construction and commissioning progresses. Such requirements should be identified by the owner/operator as early as possible and be incorporated into the development of the IMS by the general contractor. This identification will ensure that the baseline data can be recorded during construction and transferred to the owner/operator when the project has been completed. If this work is not done, there is a risk of additional costs or a reduction in predicted NPP life.

Table 31 lists some of the risks and impacts of engineering programmes related to the construction phase. During later phases of an NPP's life, engineering programmes can be seen as a risk mitigation tool to help keep the plant safe and reliable.

Table 31. RISKs AND IMPACTS RELATED TO engineering programmes

Cause	Risk	Impact
— Need for baseline data for engineering programmes not assessed for the construction phase, leading to: — Baseline data for SSCs not recorded during construction or commissioning — Construction material samples not preserved	— Initial SSC state may need to be estimated based on future measurements or conservatively estimated based on most likely data, but not planned and estimated	— Additional costs for future measurements or conservative engineering assumptions may be necessary, which may, in turn, limit the life of SSCs to a shorter duration than would otherwise be possible

6.2.9. Engineering quality

Methods to manage engineering quality should be established before construction begins. This allows the design and construction organizations to gather feedback on design issues, address systemic problems as the project progresses and make the later stages of the project and any future projects go more smoothly. Poor engineering quality risks a project having massive cost and schedule issues.

Some good engineering quality measures include having low numbers of engineering, design or specification errors and low numbers of design scope changes. Other useful metrics measure the timeliness and completeness of responses received from design for in-progress work.

Table 32 lists some of the risks and impacts of inadequate engineering quality.

TABLE 32. RISKS AND IMPACTS RELATED TO ENGINEERING QUALITY

Cause	Risk	Impact
— Lack of detail in issued designs (design knowledge gaps) — Time pressures — Inexperienced design personnel — Poor communication of vendor/manufacturer information — Inadequate prototype verification and testing — Inadequate factory acceptance testing — Inadequate design tools	— Errors or omissions in issued designs, or in construction — Staff interpretation of design information — Delays in waiting for design clarification — Failures observed during commissioning or operation — Need to procure additional material	— Cost increases, rework schedule delays or latent design errors

6.3. PROCUREMENT, MATERIAL AND SUPPLY CHAIN READINESS

Unavailability of material, either long lead or commodity items, can lead to immediate project delays, inefficiencies and cost overruns. Close attention to the procurement process both before and during construction is a crucial risk mitigation method.

IAEA Nuclear Energy Series No. NP-T-3.21 [11] discusses procurement issues in detail. In the context of construction, the CORR guidelines [43] refer to the following areas as being of special importance concerning procurement, material and supply chain readiness. Each will be discussed in the context of risk management:

(a) Equipment and material availability;
(b) Procurement procedures and plans;
(c) Packaging, warehousing and transportation;
(d) Material inspection;
(e) Quality assurance and quality surveillance.

6.3.1. Equipment and material availability

Without equipment and material, progress on an NPP project will quickly stop, or an operating one will eventually shut down due to lack of a needed repair. A lack of required equipment or material is thus a key risk that has to be managed. Some key issues to be managed include the delivery cycle for long lead equipment, new suppliers, localization of procurement, import/export controls and bulk material management. Each of these will be discussed in the following subsections.

6.3.1.1. Delivery cycle for long lead equipment management

Long lead equipment needed for NPP construction requires special attention. Major equipment, such as reactor vessels, steam generators, reactor coolant pumps and turbine generators, are long lead items. Their delivery can require at least 60 months’ lead time. Procurement schedules need to consider the capabilities of the supply chain and the manufacturing cycle for such equipment. Suppliers may need extensive interfaces and communication with design organizations.

Usually, a lengthy contracting process for the NPP precedes the start of construction. If the conditions are favourable (e.g. the NPP is assured to proceed), an authorization to proceed can be issued to the selected main contractors for the procurement of long lead equipment even before the construction contract is awarded, so as not to jeopardize the overall schedule.

The delivery cycle for long lead equipment should be evaluated according to product maturity, historical data, experience and suppliers' capacity. If performance requirements are changed compared to standard products, the impact on equipment manufacturing should be analysed carefully to reduce or mitigate potential delay risks.

For long lead equipment, experienced manufacturers should be requested. In terms of supplier selection, technology, schedule, quality and costs should be evaluated comprehensively because delivery on time is usually more important than cost savings. In some jurisdictions, design institutes, main vendors and main subcontractors need to be certified by the nuclear safety authority, which needs to be considered in project planning.

Table 33 describes some of the risks and impacts related to long lead equipment procurement.

TABLE 33. RISKS AND IMPACTS RELATED TO LONG LEAD EQUIPMENT PROCUREMENT

Cause	Risk	Impact
— Lack of well-prepared procurement planning — Very tight schedule for procurement — Lack of qualified vendors — In a FOAK project, testing and verification of prototype equipment is not completed before FCD — Lack of clearly defined acceptance criteria	— Equipment delivery delay — Interface exchange delay — Failures during factory or site acceptance testing	— Delay of construction or commissioning activities after FCD leading to project delays and cost overruns — Delay of documents and drawings

Digital control systems (DCSs) are widely used in current NPP projects around the world. The main function of a DCS is to monitor and control plant operation, including control and monitoring of the NI, CI and BOP equipment. DCSs require special attention due to their complex technology. An integrated schedule that identifies all DCS related activities and logic relations at all stages of design, procurement, construction and commissioning is recommended.

Some measures to reduce or mitigate the risks can include the following:

- An authorization to proceed can be issued to the selected vendors to start the manufacturing work before the contract is awarded. This approval can help meet the needed site delivery date for the applicable long lead equipment.
- Due to the complicated interface of DCSs and the necessity to manage their manufacturing processes, selecting a vendor with previous success in supplying an NPP project is recommended.
- The signing of contract for auxiliary equipment that will be monitored or controlled by the DCS should be approximately one year before FCD to meet the DCS's design and manufacturing requirements. Auxiliary equipment procurement should be well planned and implemented.
- Selection of equipment that has been proven under the same environment and working conditions (e.g. stress levels, water chemistry) as those present at existing NPPs can help reduce equipment related risk.
- Some large containers or modules may need to be installed early in a project. Thus, the design and procurement of preinstalled equipment or the module need early attention.
- Due to long supply chains, all regulatory requirements and inspection methods should be transmitted to subsuppliers. Periodic inspection and evaluation of subsupplier performance is needed, so arrangements for on-site inspections need attention.
- Redundant procurement is recommended for high risk equipment. If the increased cost is acceptable, then the additional equipment can be used in the next project or as spare parts.

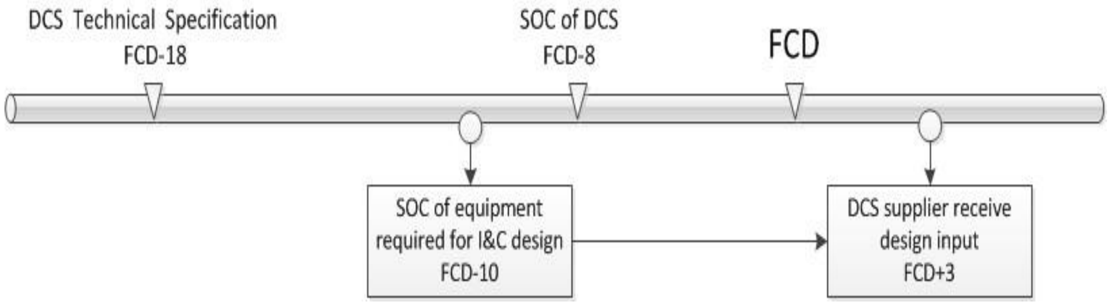

FIG. 25. Example of a typical DCS integrated engineering flow programme. SOC, signing of contract.

Example

Redundant procurement modes were used for the reactor coolant pumps (RCPs) for the Hualong 1 project. To mitigate the risk of RCP delivery delays, three extra pumps were purchased from other suppliers, who were not the original suppliers. Because of the uncertain loading input of an RCP in the early design phase, the increased load margin was insufficient. This issue eventually led to disruptive changes in the pump shell design and resulted in a ten month delay.

Example

The DCS design and manufacturing schedule for Hualong 1 is controllable based on the integrated schedule. At present, a typical DCS integrated engineering flow programme (Fig. 25) is shown as follows. For a proven reactor, the suggestion for the date of the signing of the contract of DCS is not later than FCD−8. For a FOAK reactor, the contract signing date for the DCS should be much earlier. In the case of Hualong 1, the contract of DCS was signed 19 months before FCD.

Example

During the construction of PWR NPP projects in China, the procurement of auxiliary equipment was arranged, as shown in Fig. 26. This example shows the relations between the procurement of auxiliary equipment and subsequent inputs to the DCS vendor. It indicates that the signing of the contract (SOC) with vendors of auxiliary equipment should not be later than FOD−10. All of the dates — the specific + or − numbers of months — are parts of the DCS schedule, which was developed based on DCS site delivery date (SDD) FCD+35 to meet interface exchange and site installation requirements. Such due dates would be discussed and agreed upon during the supply contract negotiation. The SDD is linked to general construction duration (from FCD to end of performance test). Here the general construction duration is 62 months.

Note that there are many different kinds of auxiliary equipment. SOC with vendors or providing inputs by vendors subsequently are usually conducted in batches. SOC with vendors of the last batch of auxiliary equipment should not be later than FCD−10, and vendors should provide their inputs for the last batch to the process designer no later than FCD−5.

6.3.1.2. New suppliers, techniques and technologies

Equipment from new suppliers, new techniques and new technologies are among the primary risk sources for delay of design interface and equipment delivery procurement management. These risks should be identified in advance.

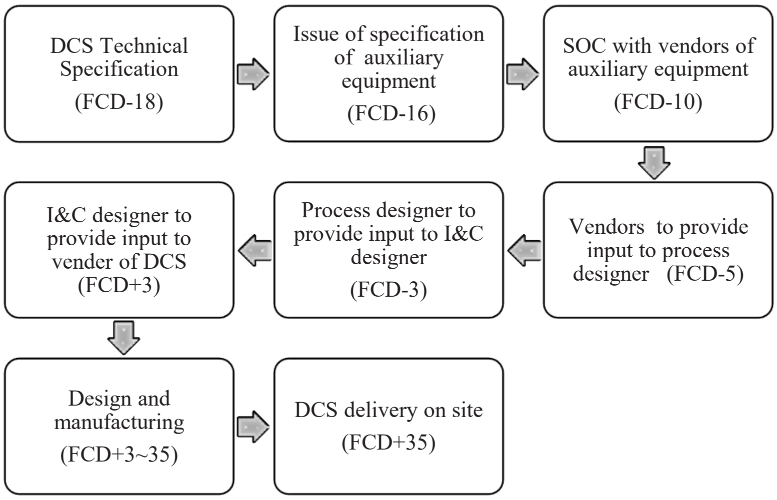

FIG. 26. Procurement process for long lead DCS equipment used in China.

Mock-up or simulation processes are effective risk identification methods, including simulations of technology, scheduling, cost and quality. To manage equipment from a new supplier, new techniques, or new technologies more effectively and reduce or mitigate the risk, it is recommended to have a close partnership between the architect–engineer and the applicable vendors.

Table 34 details some of the risks and impacts related to new suppliers or technology.

TABLE 34. RISKS AND IMPACTS RELATED TO NEW SUPPLIERS OR TECHNOLOGY

Cause	Risk	Impact
— New techniques and new technologies have not been proven — Lack of qualified vender — No experience feedback	— Quality issues — Design interface delay — Delay of equipment delivery	— Delay of construction or commissioning activities and rework may lead to project delays and cost overruns

Some measures to reduce or mitigate these risks can include the following:

— Perform a sand table simulation drill jointly through the project team, designer and potential vendors to identify the risks and analyse their impact on schedule, cost and equipment quality to generate a ranking list of risks. Prepare countermeasures to control the risk.
— Develop a close partnership between the owner/general contractor and the applicable vendors. For equipment with difficult techniques, there is the option for two vendors to carry out R&D simultaneously in the beginning and to choose the first one to complete the test as the final supplier for the project.
— Foster communication between designers and potential vendors regarding the technological requirements of specification at an early stage.
— Conduct a risk analysis based on GERT or PERT technology for prototype equipment in which extensive R&D is needed (see example).

Example

For prototype equipment in which extensive R&D is needed, it is suggested to conduct risk analysis based on graphical evaluation and review technique (GERT) or programme evaluation and review

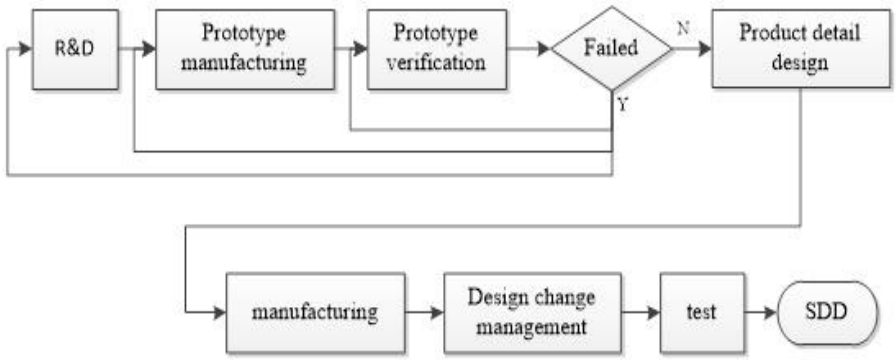

FIG. 27. Risk model with probability branch.

TABLE 35. RISKS AND IMPACTS RELATED TO PROCUREMENT LOCALIZATION

Cause	Risk	Impact
— Lack of efficient evaluation of local supplier's capability — Lack of skilled local manufacturing capability — Scope of localization not matching the capability of local suppliers — Contract with NI vendor not aligned with localization goals — Reactor design selected does not maximize the potential for localization	— Quality issues with equipment, material or construction — Delivery delays for equipment or material — Contract disputes regarding localization activities — Jurisdiction not receiving maximum localization benefits	— Delay of construction or commissioning activities and rework, which may lead to project delays and cost overruns — Loss of government or other stakeholder support if localization targets are not met — Less local production than might otherwise be possible

technique (PERT) technology. The risk analysis would evaluate whether the expected manufacturing schedule and delivery date can be met. There are three stages to construct one piece of prototype equipment, each with its own risks. The three stages are R&D (designing), manufacturing and prototype verification. If the prototype verification fails, one needs to redesign or remanufacture the prototype again. A risk model is shown in Fig. 27.

6.3.1.3. Procurement localization

In many countries, the requirements for localizing procurement are defined during the development of the nuclear power programme. Risks and mitigating actions related to equipment localization should be assessed. Measures may include only introducing proven technology, a gradual introduction of local products, or establishing a joint venture company to ensure knowledge transfer. Depending on the proposed jurisdiction, certain reactor designs can be more favourable to local manufacturing of components or reactor fuel.

IAEA Nuclear Energy Series Nos NG-T-3.4 [87] and NP-T-3.21 [11] discuss procurement localization issues in some detail.

Table 35 details some risks and impacts related to procurement localization.

Some measures to reduce or mitigate these risks can include the following:

— Prepare a localization strategy based on the national long term NPP programme and the prevailing local infrastructure;
— Incorporate localization potential into the reactor type selection process;

- Perform localization in a step by step manner;
- Use joint ventures to introduce proven technology into the local economy;
- Make decisions on the scope of localization based on a comprehensive analysis of the status of domestic industrial infrastructure and local suppliers' capabilities;
- Analyse the risks associated with quality issues and delays in delivery for potentially localized items. Take proactive measures to control the risks;
- Gather feedback and lessons learned from localization in other jurisdictions;
- Communicate with the regulatory body at an early stage regarding any requirements surrounding the local vendor's qualifications.

6.3.1.4. Import of equipment restricted due to export control policy

Some countries may not have the ability to import some types of important nuclear components when developing an NPP project. In such projects' procurement planning phase, restricted imports should be analysed closely, as restricted imports could seriously restrict the project's progress. Perform this analysis as early as possible to identify any potential design changes or additional R&D related to restricted equipment replacements. To avoid or reduce this risk, design changes may be necessary, or R&D may need to be performed by non-restricted parties.

When the global political situation is tense and global markets are unstable, restricted imports may change rapidly. It is essential to keep the risk analysis of restricted imports up to date.

Table 36 details some of the risks and impacts related to import controls.

TABLE 36. RISKS AND IMPACTS RELATED TO IMPORT CONTROLS

Cause	Risk	Impact
— Limitations to importation of some types of components of the nuclear island	— Components not available after the start of construction — Design rework to adapt to available components	— Potential project delay or suspension

Some measures to reduce or mitigate this risk include:

- In the project's procurement planning phase, restricted imports should be analysed closely to generate a list of restricted items;
- This should be analysed as early as possible before starting the project so that any potential design changes or additional R&D related to restricted equipment can be performed to seek alternative equipment;
- To avoid this risk, design changes may be necessary, or R&D may need to be performed by non-restricted parties.

6.3.1.5. Bulk material management

Bulk material management has a significant impact on a project's overall progress, especially for auxiliary piping erection. Due to the large quantities of materials needed, the numerous interfaces involved and the high quality requirements, the management of bulk materials can be challenging. The prefabrication work is especially important because it can have a direct impact on the auxiliary piping construction necessary to support the construction of systems.

Some risks and impacts related to bulk material management are detailed in Table 37.

TABLE 37. RISKS AND IMPACTS RELATED TO BULK MATERIAL MANAGEMENT

Cause	Risk	Impact
— Lack of planning and preparation and poor execution of bulk materials procurement — Long repurchase cycle for materials that have run out	— Bulk material delivery delay — Low match rate of delivered materials with the needed material — General materials shortage — Materials fail to meet construction requirements	— Delay to construction (e.g. auxiliary piping prefabrication) and erection of relevant systems — Increasing difficulty of scheduling and cost management — Possible project delays

The bulk and raw materials used in NPP construction (e.g. cement, steel, aggregate) have specific technical requirements. Conformance to these requirements needs to be confirmed before use; however, bulk material procurement schedules and process management are often ignored. Issues with delays in receipt of bulk materials will gradually disrupt a construction schedule. To respond to this risk, measures should be taken related to design, procurement and quality control. Some recommendations for risk reduction include:

— Complete a bulk materials list: based on the data from a reference plant, create a bulk material database, considering any supplementary quantities and design changes in ongoing projects;
— Procure a reasonable amount of bulk material based on construction experience (incorporating margins for expected losses and design changes);
— Optimize the bulk material procurement process to shorten the procurement time: take preventive measures to make the related drawing issue date and material delivery date appropriate to support scheduled erection work;
— Strengthen bulk material delivery management — order at least 50% of the total supply of bulk materials with the first bulk materials order. Ensure that the site delivery date of the first bulk materials supply supports prefabrication and construction preparation;
— Strengthen the management of the construction subcontractor: track and control the material supplied by the erection subcontractor. Adjust delivery schedules based on the actual construction process;
— Set up a quick supplementary procurement process.

Example

During the construction of Fuqing units 1 and 2, the shortage of bulk material, including piping, fittings, fasteners and galvanized sheets, was severe and had a significant negative impact on piping and support prefabrication, which are prerequisites for system erection. System erection is critical to the project schedule because completing ~85% of the system erection means that the project can progress to the cold function test. This key milestone indicates the start of commissioning, which indicates the importance of bulk material supply. The primary cause of the bulk material shortage at Fuqing units 1 and 2 was that the bulk material list was based on a low level of design completion and did not fully reflect the category and quantity actually needed. The incomplete bulk material list resulted in additional procurement, which resulted in material being delivered late. For nuclear class 2 and 3 carbon steel seamless tubes, more than eight additional procurements were conducted. The other procurements took a long time because permission from the regulatory body was required before the vendors started manufacture. A high level of design completion is a vital prerequisite for preparing a complete bulk material list; that is one of the reasons why a high level of design completion before FCD is needed.

TABLE 38. RISKS AND IMPACTS RELATED TO SPARE PARTS AVAILABILITY

Cause	Risk	Impact
— Lack of consideration of construction or operations spare parts needs during original equipment purchasing — Operations systems for managing spare parts not set up during construction	— Lack of parts to repair or replace damaged or worn out equipment	— Delays in construction activities or operations repairs — Increased costs during construction or NPP shutdown during operation

TABLE 39. RISKS AND IMPACTS RELATED TO PROCUREMENT PLANS AND PROCEDURES

Cause	Risk	Impact
— Initiating procurement without planning or with poor planning — No structured processes for vendor selection and evaluation	— Prematurely reducing the number of potential bidders (poor market research) — Optimal contract not achieved — Poor scope definition — Vendor/supplier complaints of unfair treatment	— Less chance of receiving quality product or services at the best price — Product received does not meet all requirements — Poorly written contract — Cost increases to deal with unsatisfied vendors

6.3.1.6. Spare parts availability

Spare parts are needed to support ongoing plant operation and maintenance and during the construction and commissioning process. Once installed, SSCs may fail or may require maintenance at any time, and having an adequate supply of spare parts available at all times is a necessary risk reduction mechanism.

Necessary spare parts lists need to be prepared as part of the initial SSC design, and an initial set ordered as part of (or concurrently with) the initial NPP contract.

Some risks and impacts related to spare parts availability include those shown in Table 38.

6.3.2. Procurement procedures and plans

Defined procurement procedures and plans help to enable smooth and efficient equipment and material delivery and help reduce the risk of such items not arriving when needed. A typical procurement plan would include consideration of such items in the purpose and scope of each procurement; available suppliers; the recommended procurement approach; roles and responsibilities; risks; and an evaluation process [11].

Some risks and impacts related to procurement procedures and plans include those shown in Table 39.

Section 3 of IAEA Nuclear Energy Series NP-T-3.21 [11] discusses the procurement process and various aspects of procurement planning.

6.3.3. Packaging, warehousing and transportation

Proper packaging, warehousing and transportation are essential for ensuring that the SSCs being ordered are in the proper state for use in the NPP and that the risks of theft, degradation or damage are minimized. Material risk management relates to minimizing the risk of loss or damage to the needed material during all NPP project phases. This may occur due to any of the following:

— Physical damage during material transportation or handling;

— Physical damage or material degradation during storage (including field storage locations);
— Theft of material;
— Misplacement or loss of material due to inadequate tracking;
— Inability to use material due to loss of related quality or production records.

Table 40 details some of the risks and impacts associated with packaging, warehousing and transportation.

Some measures to manage vulnerable equipment more effectively and to mitigate risks include the following:

— Develop a list of vulnerable construction and testing equipment and components by consulting the manufacturers and personnel experienced in operation, construction and commissioning;
— Reduce the risk of damage or degradation by strengthening storage and security controls during equipment storage, transportation, construction and testing;
— Ensure appropriate inspections and tests are performed at points of material turnover (see Section 6.3.4).

Sections 3.8 and 3.11 of IAEA Nuclear Energy Series NP-T-3.21 [11] discuss methods to ensure that materials remain suitable for use.

6.3.4. Material inspection

A robust material inspection programme, both at the factory and upon receipt at the NPP, is essential to ensure material quality and minimize risk. Section 3.10 of IAEA Nuclear Energy Series NP-T-3.21 [11] discusses material acceptance, inspection and receipt methods.

Table 41 details some of the risks and impacts associated with material inspection.

TABLE 40. RISKS AND IMPACTS ASSOCIATED WITH PACKAGING, WAREHOUSING AND TRANSPORTATION

Cause	Risk	Impact
— Physical damage during transportation or warehousing due to physical trauma, improper packaging or unsuitable environmental conditions — Expiration of item shelf life — Theft or loss of unsecured material	— Equipment/parts and materials are broken, damaged, missing or otherwise inadequate to support fabrication or installation on-site	— Delays to construction or commissioning activities; may cause rework, creating difficulties with scheduling and cost management — Extra costs as the material may need to be purchased again

TABLE 41. RISKS AND IMPACTS ASSOCIATED WITH MATERIAL INSPECTION

Cause	Risk	Impact
— Poor receipt inspection processes or practices — Inadequate inspection facilities — Poorly written or missing acceptance criteria — Lack of training of inspectors	— Materials accepted that are inadequate to support fabrication or installation on-site — Counterfeit or fraudulent items installed in facility	— Delays of construction or commissioning activities; may cause rework, creating difficulties with scheduling and cost management — Extra costs as the material may need to be purchased again — Latent defects in installed SSCs

TABLE 42. RISKS AND IMPACTS ASSOCIATED WITH QUALITY ASSURANCE AND SURVEILLANCE

Cause	Risk	Impact
— Poor processes for quality assurance or surveillance — Personnel not trained in proper quality assurance or surveillance processes or responsibilities — Independence of inspectors/surveillance staff from installers/constructors/manufacturers not maintained	— Equipment/parts and materials are broken, damaged, missing or otherwise inadequate to support fabrication or installation on-site — Loss of regulatory confidence	— Delays of construction or commissioning activities; may cause rework, creating difficulties with scheduling and cost management

6.3.5. Quality assurance and quality surveillance

Quality assurance and surveillance of the manufacturing and production process are essential to ensure that quality products are delivered to the NPP. Some processes that are typically employed include having:

— Supplier and sub-supplier qualification and auditing programmes in place;
— Source and receipt inspection programmes in place;
— Non-conformance processes in place.

Section 3.5.2 of IAEA Nuclear Energy Series NP-T-3.21 [11] discusses establishing acceptance criteria, and Section 3.10 discusses material acceptance, inspection, receipt methods and the handling of non-conformances. Quality management of the entire NPP project is discussed further in Section 6.7.

Table 42 details some of the risks and impacts associated with quality assurance and surveillance.

Some measures to reduce or mitigate quality related risks include the following:

— Implement a strong, integrated quality management system (QMS). The relevant requirements should be transferred to all vendors and subcontractors within the supply chain. Periodically evaluate the effectiveness of the QMS.
— Establish a quality non-conformance management process that includes classification, grading, opening, report approval, a closing process, handling, verifying, tracking, cancelling and statistical analysis.
— Establish a detailed oversight process for the owner and general contractor. The owner, general contractor and vendors should have adequate skills and means to verify whether the corrections of non-conformances are acceptable.
— Identify and analyse the root causes of non-conformances to document feedback and lessons learned.
— Implement inspection and verification of construction activities through process control activities.
— Ensure that quality management staff can cope with quality issues independently without undue influence.
— Include pre-approved quality assurance plans (QAPs) as a part of tender specifications if they are available. A list of vendors for all the critical items/materials should be also provided.

TABLE 43. RISKS AND IMPACTS RELATED TO SITE INFRASTRUCTURE

Cause	Risk	Impact
— Lack of focus on on-site infrastructure requirements during early project development — Lack of coordination with external parties responsible for key permanent infrastructure (typically external government agencies) — Lack of planning related to required on-site temporary infrastructure — Lack of coordination between the owner and NPP vendor regarding vendor infrastructure needs and related construction and transportation methods	— Inefficient or delayed construction activities caused by unavailability of required infrastructure — Rework associated with delay to the provision of required infrastructure	— Project delays or cost increases

6.4. CONSTRUCTION READINESS

The CORR guidelines [43] refer to the following areas as being of special importance in evaluating nuclear construction readiness. Each will be discussed in the context of risk management:

(a) Site infrastructure requirements;
(b) Regulatory requirements;
(c) Tools availability;
(d) Construction sequencing;
(e) Security and safeguards requirements;
(f) Construction execution plans and procedures;
(g) Environmental management;
(h) Safety management;
(i) New construction practices and technology.

6.4.1. Site infrastructure requirements

Water, electricity and road, rail or water access are important prerequisites for developing on-site construction. New NPP sites are often far from currently developed areas, meaning that there may be no infrastructure on or near the site. Adequate transportation capacity by vessels to a nearby harbour, by train and by trucks is necessary, as are suitable temporary or permanent storage facilities for the large number of components that are needed to construct and operate the facility.

The need to construct temporary and permanent local infrastructure can increase the overall project construction time. Unreasonable general site layout may cause difficulties in on-site management and increase project costs and security risks. Temporary infrastructure can include accommodation facilities, concrete mixing stations, civil engineering laboratories, steel structure workshops and steel processing workshops. Permanent infrastructure includes roads (including those capable of transporting heavy components), rail lines, harbour facilities, electrical grid connections and warehouses. Both require the coordination of numerous organizations and companies. Such an infrastructure has to be planned and implemented in an organized fashion, taking into account the planned construction sequence.

Some risks and impacts related to site infrastructure are shown in Table 43.

6.4.2. Regulatory requirements

Multiple permits and licences are typically needed for construction to proceed. These can include siting/building permits/orders, environmental permits and approvals, hazardous materials and waste approvals, national security related approvals, nuclear regulatory and licence requirements, and other requirements as defined by local laws, rules, codes, standards and regulations. A full assessment of all such requirements needs to be made as a risk mitigation exercise because the lack of a single approval could result in significant project delay.

Some risks and impacts related to regulatory requirements are shown in Table 44.

TABLE 44. RISKS AND IMPACTS RELATED TO REGULATORY REQUIREMENTS

Cause	Risk	Impact
— Focus placed on the nuclear regulator as the only regulator of importance on an NPP project — Lack of a detailed review of all regulatory requirements that might impact on the project — Lack of coordination with regulatory bodies concerning their needs for training and familiarization and the required response times and milestones for regulatory approvals	— Inefficient or delayed construction activities caused by the unavailability of necessary regulatory approvals	— Project delays or cost increases — Loss of regulator confidence or disputes

6.4.3. Tools availability

Nuclear construction requires specialized tools and support equipment to be available when needed. Such tooling can range from small portable calibration and test equipment through specialized installation tooling up to very large heavy lift cranes. Construction planning, scheduling and assessment need to consider the availability of all needed tooling so that the risk of tooling related delays is minimized. Additional tooling may need to be purchased to ensure parallel activities can proceed as needed and to accommodate tooling unavailability due to required repairs.

Some risks and impacts related to tools availability are shown in Table 45.

TABLE 45. RISKS AND IMPACTS RELATED TO TOOLS AVAILABILITY

Cause	Risk	Impact
— Lack of detailed planning related to tooling availability — Lack of sufficient quantity of tools to progress parallel activities	— Inefficient or delayed construction activities caused by the unavailability of required tooling	— Project delays or cost increases

6.4.4. Construction sequencing

Analysis of the sequence of construction activities is important to ensure that the required materials, human resources, and tools and equipment are available when needed so that the risk of project miscoordination or delay is minimized. Items to be considered include design and material availability, large equipment deliveries, staging requirements, construction/module sequencing, tooling and craning requirements, trade availability and weather. Modern 4-D modelling software is available to analyse the construction process of the facility over time. It can help coordinate the resources needed to support construction on a given day.

Some risks and impacts related to construction sequencing are shown in Table 46.

TABLE 46. RISKS AND IMPACTS RELATED TO CONSTRUCTION SEQUENCING

Cause	Risk	Impact
— Lack of detailed planning related to construction sequencing	— Inefficient or delayed construction activities caused by the unavailability of required resources, material, tools or equipment	— Project delays or cost increases

TABLE 47. RISKS AND IMPACTS RELATED TO SECURITY AND SAFEGUARDS

Cause	Risk	Impact
— Lack of assessment of site security requirements for construction or operation — Lack of assessment of IAEA safeguards requirements during the design phase	— Loss or theft of material — Security or safeguards incident — Regulatory non-acceptance of security or safeguards measures — Security or safeguards requirements need to be added later at a higher cost	— Project delays or cost increases — Loss of public or regulator support. — Delay to plant startup

6.4.5. Security and safeguards requirements

A lack of attention to security and safeguards issues can lead to a risk of increased costs due to design rework, delays in obtaining materials or personnel, or a loss of material or equipment due to theft. Some issues to be considered include site security requirements, material tracking and control, inspection and transfer requirements, control and identification of the site boundary, IAEA safeguards requirements, clarifying any personnel clearance requirements with the security regulator and requirements related to incoming vehicle inspections.

Some risks and impacts related to security and safeguards are shown in Table 47.

The IAEA published extensive material related to security requirements in its Nuclear Security Series, including Refs [79, 80, 88–91]. IAEA Safeguards issues are discussed in Nuclear Energy Series publications [92–94].

6.4.6. Construction execution plans and procedures

Construction planning is an important way to mitigate project risk. Requirements should be included in construction planning, such as scope, object, organization and construction section planning. During the planning phase, risk identification and analysis should be performed, and corresponding countermeasures should be incorporated into construction planning. Experienced experts should be invited for evaluation to ensure the adequacy of the plan. High risk activities such as heavy lifts require special attention due to the risk of quality problems, equipment damage or personnel injuries.

The management of the installation of large components (e.g. reactor pressure vessel, steam generators, large modules) and the erection of safety grade civil structures is important to prevent unnecessary corrective maintenance and plant changes in the operation phase. Typical recommendations are as follows:

- To cope with many construction risks, mitigating actions need to be combined with quality control;
- A system of experience feedback from construction activities needs to be in place to help ensure improvements in construction processes;
- The safety measures in the construction plan and technical safety documents need to be reviewed to strengthen process control;

— All management procedures need to be implemented strictly with a focus on the selection of high risk works;
— On-site monitoring methods should be increased and regulatory effectiveness enhanced.

Without proper precautions, foreign material can inadvertently be introduced into manufactured components or open systems during manufacturing and construction. This foreign material may later cause equipment damage during commissioning or operation. These objects may include construction material, tools, consumables or other items. Vendors and construction and maintenance organizations need to establish foreign material exclusion (FME) programmes to minimize the potential for foreign material introduction and to inspect or clean critical systems before plant operation. The suitability and effectiveness of these procedures need to be assessed regularly. IAEA-TECDOC-1970 [95] provides detailed guidance on FME management for NPPs.

Constructability reviews by the NPP designer, with experienced construction contractors, are an important part of the design and construction planning process. These are especially important for a FOAK plant, system or component. Otherwise, there may be serious impacts on construction timelines.

Some risks and impacts related to construction execution plans and procedures are shown in Table 48.

TABLE 48. RISKS AND IMPACTS RELATED TO CONSTRUCTION EXECUTION PLANS AND PROCEDURES

Cause	Risk	Impact
— Poor design for constructability — Insufficient experimental validation — Insufficient consideration of high altitude operation of the use of heavy equipment or special tools — Insufficient consideration of potential safety issues during construction — Unsuitable or ineffective FME procedures for manufacturing and installation — Lack of proper FME precautions — Interaction of parallel construction activities not assessed	— Implementation of a design may not work as planned — Quality issues during construction or commissioning — Personnel injuries or material damage — Inefficient construction methods are needed to complete the installation — Foreign materials, including tools, consumables, construction material or other items, inadvertently introduced into equipment/systems — Multiple demands for the same resources, tooling or spaces	— Serious impacts on subsequent construction, increasing difficulties of scheduling and cost management, possibly leading to project delays — Equipment damage or a serious threat to safe operation — Costly or difficult replacement of or repairs to damaged equipment

Some measures to reduce or mitigate these risks include the following:

— Advance communications with the constructors and regulator regarding construction methods;
— Joint research and studies related to constructability by the designer and experienced construction contractors at each design stage;
— Provide processes for special oversight of high risk construction activities;
— Complete experimental validation before implementation;
— Establish programmes and procedures, including education and training programmes, to minimize the potential for foreign material introduction and to inspect, clean or recover foreign material from equipment before delivery (at the vendor factory) and later before commissioning and operation. These should include endoscopic inspection of visually inaccessible areas;
— Regularly assess the suitability and effectiveness of FME management procedures.

Example

CNPE catalogued many risks that occurred frequently during the construction phase and published them as a high risk worklist. This project mainly focused on the important work during the construction of NPP, including civil construction, erections of NI, CI and BOP, electrical erection, welding and material management. Approximately 300 kinds of quality problems were identified in the list, and remedial measures were taken.

6.4.7. Environmental management

Construction projects need environmental management programmes and practices to protect the surrounding environment during the construction phase. Poor environmental stewardship risks losing public or other stakeholder support for the project and can contribute to project approval delays or cancellations. The ISO 14000 Standard series [96] provides a framework to reduce industrial waste and environmental damage.

Table 49 describes some of the risks and impacts related to environmental management.

TABLE 49. RISKS AND IMPACTS RELATED TO ENVIRONMENTAL MANAGEMENT

Cause	Risk	Impact
— Lack of a detailed environmental management programme	— Environmental remediation related rework or enforcement notices — Environmental damage to plants or wildlife — Environmental impacts due to emissions during the construction project (including noise, vibration, dust) due to the source of building materials and their production methods, or due to construction waste	— Project delays due to lack of environmental regulatory approvals — Loss of public or other stakeholder support — Unnecessary adverse environmental impacts

IAEA Nuclear Energy Series No. NG-T-3.17 [97] provides detailed guidance on strategic environmental assessment for nuclear power programmes and describes some environmental impacts during NPP construction, operation and decommissioning.

6.4.8. Safety management

It has been shown that projects with superior industrial safety practices tend to show better cost and scheduling performance. Thus the proper management of industrial safety risks can improve overall NPP project performance. There is a strong relationship between safety performance and the degree of owner involvement, and improved safety performance is possible through specific owner practices [98, 99].

IAEA Nuclear Energy Series No. NP-T-3.3 [61] provides good practices for industrial safety management at nuclear facilities. The publication incorporates recommendations on occupational safety and health management systems from the International Labour Organization. Such occupational safety and health management systems need to be integrated into the affected organizations' overall management system.

IAEA Safety Standards require occupational health and safety management during all phases of an NPP's life.

Table 50 describes some of the risks and impacts related to industrial safety.

TABLE 50. RISKS AND IMPACTS RELATED TO INDUSTRIAL SAFETY

Cause	Risk	Impact
— Lack of planning, oversight, protective equipment, worker knowledge or behaviour, or emergency response	— Personnel injuries or death — Equipment or material damage	— Project delays due to incident investigation or work stoppages — Temporary or permanent loss of trained resources — Increased costs related to worker accident claims and remedial measures

Typical good practices for the management of industrial safety during construction are as follows:

— Use a job safety analysis (JSA) to plan work from an industrial safety perspective[10].
— Identify and evaluate hazards according to the tasks being performed. Pay special attention to high hazard work.
— Identify high frequency construction risks and establish specific programmes to mitigate them. Such risks can include exit passageways, scaffolding and springboards, protection of holes and temporary electricity supplies.
— Perform regular statistical analysis of events and near misses. Analyse management methods, organizational systems, personnel qualifications, safety training, equipment
— management, group safety management, exposures to high frequency hazards and weaknesses in contractor performance.
— Set up regular meetings, reporting and communications mechanisms.
— Establish a site safety training experience centre. Such a centre can orient and train new workers in proper safety practices and behaviours. Some centres can provide practical experience with safety incidents or events in a controlled manner, with participants feeling the process and consequences of risky behaviour through physical sensation.
— Implement processes to address health–safety–environment (HSE) controls during construction. The '6S lean management' process described in [61] can be a valuable part of the management system.

Example

The 6S management specific process for the Fuqing NPP project is shown in Fig. 28. It was designed to improve the management of the project.

6.4.9. New construction practices and technologies

Incorporating new construction technologies such as automatic welding, mass concrete, or modular construction can benefit cost, quality and schedule. There are, however, implementation risks. The technology may not work as designed, the construction trades may not be fully familiar with its use, or the applicable regulator may not yet accept the technique. Risk analyses can assist in identifying these issues before technology deployment so that mitigating actions can be taken. Advance communications with regulators, experimental validation, hiring of technology experts, and training and mock-up facilities are some potential mitigation methods. IAEA Nuclear Energy Series No. NP-T-2.5 [100] discusses

[10] JSA is a proven process for addressing and controlling hazards to reduce personal injuries. Different jobs have their unique hazards based on the work, the workers and the surrounding environment. A JSA is performed to analyse the hazards and to develop measures to control the identified hazards. JSAs should be improved continuously based on feedback from previous jobs.

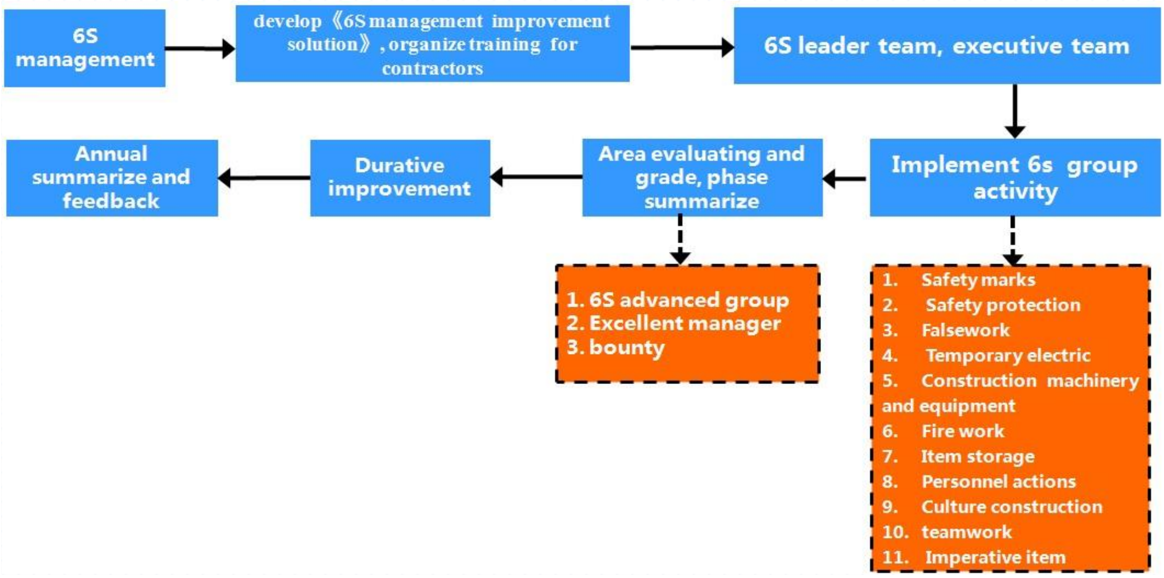

FIG. 28. Example of the 6S management process.

construction technologies for NPP projects. Table 51 lists some of the risks and impacts associated with new construction technologies.

TABLE 51. RISKS AND IMPACTS RELATED TO NEW CONSTRUCTION TECHNOLOGIES

Cause	Risk	Impact
— The regulatory body may not accept new technology for implementation — Insufficient experimental validation of technology — Contractors are unfamiliar with technology	— Delay in approval for the use of technology — Technology may not work as designed	— Cost increases and schedule delays

Some measures to reduce and mitigate the risks associated with new technology include:

— Perform risk analyses to identify risks before technology deployment so that mitigating actions can be taken;
— Communicate planned technologies to be used with regulators well in advance;
— Validate technologies experimentally before deployment;
— Hire technology experts to assist in deployment;
— Construct training and mock-up facilities if needed;
— Facilitate cooperation between the owner, general contractor and subcontractors on the implementation of new technologies;
— Include the estimated cost of new construction technologies in advance and ensure that funds are in place to support its development;
— Highlight the importance of quality control throughout the process of technology development and deployment;
— Ensure that the project schedule reflects the technology development process.

Example

Automatic welding technology was used in the case of the main loop pipe of Fuqing units 1 and 2. This new technology's implementation risks were identified as being experimental validation of the technology and regulatory body acceptance. A task force including the general contractor (as the leader), the installation contractor and the design institute was set up, and mitigating measures were taken. It took three years to carry out R&D and testing to validate the technology. The task force communicated actively with the regulatory body and submitted a technology analysis report for review and approval. During implementation, all the welding work was programmed and automatically sequenced, so that the risk of human error was greatly reduced. The automatic system worked well and helped save 28 days on the critical path compared to a manual welding process.

Example

Several new construction technologies were introduced as part of the Fuqing unit 5 NPP project. These included introducing the main heavy component, double shell construction logic and anti-plane containment shell construction. As new construction technologies, it was uncertain as to whether such construction activities could be implemented smoothly. Hence constructability had to be studied very carefully. The reviews and other research were conducted jointly by the designer and the civil/erection contractors in the design phase. It took several months and was iterated many times before the construction scheme for each activity was finalized. Before the implementation, a thorough review of prerequisites, including organization, drawings and documents, quality planning, training of workers and supporting facilities, was conducted to make sure they were ready. During implementation, the construction scheme, including its quality plan, was implemented strictly, and added supervision was put in place. The completed construction indicates that the new construction technology was implemented smoothly as planned.

6.5. CONSTRUCTION COMPLETION ASSURANCE/SYSTEM TURNOVER PROCESS

The CORR guidelines [43] refer to the following areas as being of special importance in evaluating the readiness of the construction completion and system turnover process. Table 52 discusses each of these issues in the context of risk management:

(a) Process defined;
(b) Walkdown processes;
(c) Hold points;
(d) Open item tracking;
(e) Labelling and control of boundaries;
(f) Inaccessible items;
(g) Interim maintenance during construction.

6.6. COMMISSIONING RISK MANAGEMENT

Commissioning is the phase where NPP design requirements are verified, and compliance with applicable nuclear safety laws and regulations is confirmed. Commissioning engineers need to be familiar with the SSCs that they are commissioning and able to handle technical problems based on their experience. For new nuclear power programmes, commissioning experience may be in short supply and may need to be supplemented by outside experts.

TABLE 52. CONSTRUCTION COMPLETION RISK ITEMS

Construction completion issue	Description	Risk of not addressing the issue
Process defined	Having a managed process for construction turnovers to operation	Inefficient turnover processes Industrial or nuclear safety events related to staff working on the wrong equipment
Walkdown processes	Pre-commissioning walkdown processes	Work turned over for commissioning before it is ready (causing delays or events)
Hold points	Review process before proceeding to commissioning	Work turned over for commissioning before it is ready (causing delays or events)
Open item tracking	System to maintain a list of work to be performed by construction before or after system turnover	Important work lost track of and not performed
Labelling and control of boundaries	Methods to ensure the division of equipment ownership between construction and commissioning are defined	Industrial or nuclear safety events related to staff working on the wrong equipment
Inaccessible items	Final inspections or work related to systems that will become inaccessible following plant startup (typically high radiation areas)	Increased difficulty or expense to assess plant conditions later in plant life
Interim maintenance during construction	Processes to perform the maintenance needed on SSCs by construction organization before turnover	Critical equipment may degrade between the period of installation and turnover to operations

Effective commissioning management systems can help to control the overall risk. These systems include processes to manage commissioning organization, including the methods to commission and hand over individual systems, preparation and scheduling of work, addressing of human factors, security, licensing issues, first aid and emergency response, and preparation of commissioning handover material and documentation. IAEA Nuclear Energy Series Nos NP-T-2.10 [101] and NG-T-2.2 [22] and Safety Standards SSG-28 [102] provide information and guidance on commissioning.

An important consideration during the commissioning phase is the changing nature of the work environment. During commissioning, many different individuals and workgroups will be on the project site. These include construction trades, suppliers, equipment technicians, commissioning engineers, operators, transportation companies and others. The industrial environment is very complex and rapidly changing as new systems are brought into service. In addition to the typical construction risks (e.g. heavy machinery, lifting and hoisting) discussed in Section 6.4.8, high temperatures, high pressures, loud noises and harmful gases begin to appear in the facility. It is important to ensure that high industrial safety standards and practices are in place and that work is planned and executed in a coordinated manner. This planning reduces the risk of project disruptions due to personnel injury or equipment damage. Guidance is available in IAEA Nuclear Energy Series No. NP-T-3.3 [61] and in Section 6.4.8 of this publication.

Similar to the readiness reviews that are recommended for the construction stage, IAEA Nuclear Energy Series No. NP-T-2.10 [101] recommends that to reduce risk, commissioning readiness should be assessed in a structured manner. It states that:

"Readiness subjects related to the commissioning and the related turnover to operations process can include:

- Definition of formal roles and responsibilities for commissioning;
- Existence of formal documented processes for plant testing of equipment and systems;
- Existence of maintenance procedures, tooling, and call-ups to support systems being placed into service;
- Existence of formal processes for documenting commissioning completion and system availability for service and for transferring such information to records;
- Verification that commissioning completion activities and records will provide assurance that system design requirements are met;
- Verification that test requirements and methods are well-defined and independently reviewed, ensuring test results are validated against acceptance criteria;
- Verification that processes are in place for tracking and completing open items to be carried into the operational phase;
- Verification that processes are in place for ensuring commissioning completion activities are complete prior to turnover of systems;
- Verification that adequate processes are in place to establish and maintain effective boundaries between turned over and not turned over SSCs;
- Verification that necessary regulatory and plant interface prerequisite activities have been completed (e.g. NPP regulatory authority approvals have been obtained, commitments have been met (nuclear, environmental, grid connection, etc.), interface protocols and procedures are in place);
- Verification that necessary operational procedures for items such as worker protection, tagging and preventive maintenance are in place prior to handover to operations;
- Verification that processes are in place for addressing non-conformances and corrective actions, including independent and senior management oversight."

Table 53 lists some of the risks and impacts associated with commissioning.

Some measures to mitigate commissioning risks include the following:

- Assess commissioning readiness using a structured process that ensures that construction activities have been properly completed, the plant configuration is documented and the commissioning tests are appropriate (refer to NP-T-2.10 [101]).
- Ensure that the regulatory body is aligned with the planned commissioning approach well in advance.
- Ensure (in the design phase) that appropriate design verification and reviews were performed to minimize the potential for errors being detected during commissioning.
- Analyse the nuclear safety risk of individual tests in a commissioning test programme with a PSA model to prevent unnecessary testing and risks. Some tests may be sources of risks that are greater than the benefits of their results. Significant commissioning tests can include such items as scram tests or loss of load tests.
- Ensure sufficient design construction and procurement resources are available to address issues arising during commissioning that need support.
- Create a commissioning risk control plan that includes plans for emergency actions and first aid.
- Identify and evaluate possible risks to other on-site operating units throughout the commissioning process. Take appropriate preventive actions and include necessary actions in emergency plans.
- Clearly define the roles and responsibilities of commissioning and operating staff during the commissioning process, especially concerning specific equipment ownership and operation.
- Begin simulator training of control room operators well in advance, and involve operating and maintenance staff in commissioning activities to develop their plant knowledge. Activities may

TABLE 53. RISKS AND IMPACTS RELATED TO COMMISSIONING

Cause	Risk	Impact
— Commissioning results do not meet design requirements or are otherwise unexpected, necessitating rework by design, construction or commissioning staff — Delays in previous project phases (e.g. design, procurement or construction) that require changes to allow commissioning to proceed (e.g. needing to substitute a part to perform the function of a part that is unavailable) — Poor plant configuration management during construction that requires extensive verification to confirm field conditions — The need for new or repeated tests as specified by the authorities or other stakeholders — Improper test arrangements or commissioning processes that may damage SSCs or injure personnel — Unfamiliarity with new SSCs, leading to human performance errors — Unavailability of sufficient trained personnel — Impacts on other units on a multiunit site due to common systems (e.g. demineralized water, domestic water, pressurized air and other gases, electrical systems, common containment systems) not assessed — Unavailability of required tooling or test equipment — Unanticipated changes in the working environment due to the changing nature of hazards and changing personnel on-site	— Rework by design, construction or commissioning staff — Need to revalidate plant configuration through detailed field walkdowns or documentation reviews — Damage to SSCs — Injuries to personnel — Negative impacts on other operating units (e.g. unit trips) — Delays due to unavailability of personnel, test equipment or tooling	— Cost increases and schedule delays — Personnel injuries or equipment damage — Nuclear safety or production incidents in operating units —

include field walkdowns, checking technical documents, safety analysis reports, system analyses, failure mode and effect analyses and operational procedures.

— Pay special attention to industrial safety during commissioning due to the dynamically changing nature of workplace hazards and the personnel involved.

Example

The CNPE commissioning team produced 62 professional risk control plans based on experience feedback. One example was the main feedwater pump switching test plan. In the commissioning preparation phase of the project, the plan was modified based on the new project's specific conditions. Once implemented, the plan would save preparation timework efficiency, improve industrial safety, reduce the likelihood of losing control of field activities, reduce commissioning time and reduce the chance of introducing non-conformances.

6.7. QUALITY MANAGEMENT AND RECORDS

Quality assurance (QA) covers all policies and systematic activities implemented within a quality management system. QA frameworks include:

— Determination of adequate technical requirements for inputs and outputs;

— Certification and rating of suppliers;
— Testing of procured material for its conformance to established quality, performance, safety and reliability standards;
— Proper receipt, storage and issue of material;
— Auditing of the process quality;
— Evaluation of the process to establish required corrective response; and
— Auditing of the final output for conformance to technical, reliability, maintainability and performance requirements.

Quality assurance can benefit from risk analysis that can determine the most problematic areas, where quality problems are most likely to occur. Risk informed graded quality assurance has been applied to safety related SSCs for decades [103], but it is also possible to apply it to the delivery of non-safety related SSCs.

Quality surveillance is a subset of quality assurance. Quality surveillance plans and records document the following information:

(a) The methods of supervision used — for example, prearranged, special, random or other supervision;
(b) The scope of inspections — for example, personnel qualifications, engineering tools, equipment characteristics, materials used, documents, site management, procedures and records;
(c) Preparation (‘prior control’) activities — document preparation, pre-job briefings, supervisory activities, starting conditions, raw material acceptance records and quality plan approvals;
(d) Implementation (‘process control’) activities — notifications, supervisory methods, testing methods, problem handling and correction, filing of ‘corrective action requests’ (CARs) or ‘observation’ (OBN) reports;
(e) Follow-up (‘post control’) activities — acceptance documentation, record filing, trend analysis and non-conformance handling.

The regulatory body will typically set its control points for critical activities that it may wish to witness due to its due diligence responsibilities. These can include the first concrete pour for the nuclear island, welding of critical pipelines, reactor dome lifting and other activities. Non-routine inspections may also be performed.

The outcomes of risks related to the project schedule and cost are easily realized during the construction project. However, the outcomes of some quality related risks may be realized later during commissioning, operation, or even in the decommissioning phase. Their total impact on the life cycle cost of these later risks can be remarkable, as latent quality issues can result in low capacity factors or unit shutdowns.

IAEA Safety Standard GSR Part 2 [17], Leadership and Management for Safety, provides requirements that support establishing, sustaining and continuously improving leadership and management for safety and an integrated management system. It emphasizes that leadership for safety, management for safety, an effective management system and a systemic approach (i.e. an approach in which interactions between technical, human and organizational factors are duly considered) are all essential to the specification and application of adequate safety measures and to the fostering of a strong safety culture. Having an effective management system, including quality management processes that extend to the management of and management by contractors and subcontractors, is essential for a successful NPP project.

The CORR guidelines [43] refer to the following areas as being of special importance for quality management and records within nuclear construction:

(1) Quality assurance and controls;
(2) Independent assessments;
(3) Non-conformance and corrective action programmes;

(4) Construction experience;
(5) Quality surveillance and construction inspection;
(6) Controlled documentation and records.

Table 54 details some of the risks and impacts associated with quality management.

TABLE 54. RISKS AND IMPACTS ASSOCIATED WITH QUALITY MANAGEMENT

Cause	Risk	Impact
— Lack of an effective quality assurance management system and quality control system — Poor processes to manage quality issues	— A high rate of quality incidents or non-conformances	— Project delays or cost overruns associated with rework or repairs necessary to recover the necessary quality — Latent quality defects that become apparent later in the NPP's life, impacting on safety or economics

Some measures to reduce or mitigate quality related risks include the following:

— The owner should prepare a quality management plan for the project, including vendors and subcontractors, according to the regulatory authority's requirements.
— Build and implement a robust and integrated quality management system (QMS). The relevant requirements should be transferred to all vendors and subcontractors within the supply chain.
— The effectiveness of the QMS should be evaluated periodically.
— Establish a quality non-conformance management process that includes classification, grading, opening, report approval, closing process, handling, verifying, tracking, cancelling and statistical analysis.
— Establish the expectation that vendors and contractors have to report, handle and correct identified non-conformances without hesitation.
— Establish a detailed project oversight process to periodically evaluate the effectiveness of the QMS (refer to Section 6.1.9). Independent assessments should investigate and focus on the causes of quality related errors and non-conformances and make recommendations to help prevent reoccurrence. Assessment may also focus on more generic topics, such as the overall quality programme completeness, personnel qualifications and training, supplier performance and management or the quality of inspection reports.
— Establish and processes for the management of quality incidents and non-conformance reports (NCRs). Such a process includes steps for reporting, opening, handling, verifying and closing of events, classification/grading and statistical analysis of events, and approval of reports. IAEA standards and other publications [11, 17, 38, 99, 100, 102–104] provide requirements and guidance in this area.
— Ensure that construction experience is incorporated into designs and planned construction methods to improve construction processes' safety and efficiency and reduce the risk of quality issues, errors and non-conformances (refer to Section 6.2.2.3).
— Implement quality surveillance by inspecting manufacturing or construction activities as they occur or following their completion to ensure that any critical attributes related to the work have been performed correctly. Such surveillance may be performed by independent individuals within the construction organization, by the owner/operator, by a third party organization and, in some cases, by individuals within the regulatory body.
— Implement a strong, controlled document and records management system to ensure a smooth transition from construction to commissioning to operation. This means that processes are documented and systems are in place for acceptance, storage and revision control of controlled documentation

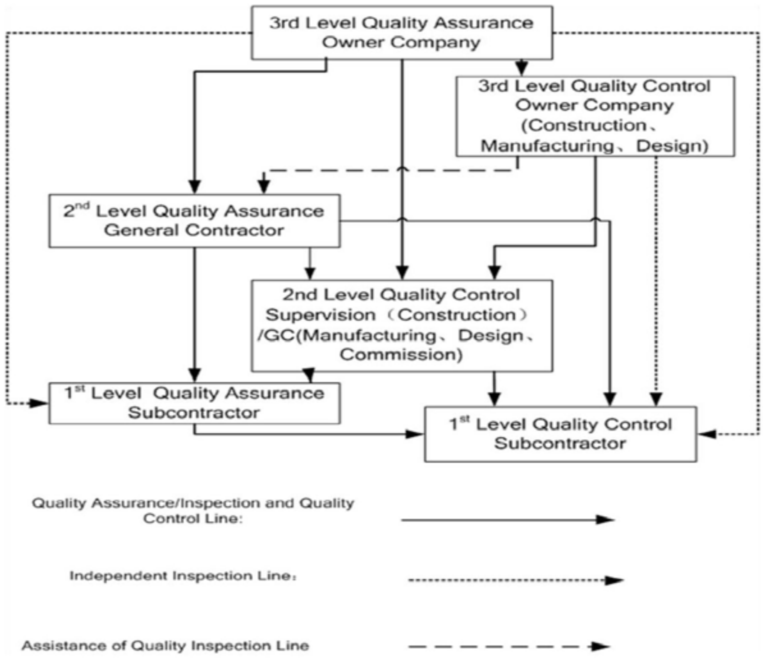

FIG. 29. Three level quality control system.

and records related to procurement, plant configuration, construction, commissioning, testing and maintenance. Some key construction related documentation includes material and field quality records such as material history dockets, pressure boundary documents, welding records, factory acceptance test (FAT) results, installation records, calibration results and turnover records [48].

— Ensure that quality staff can cope with quality issues independently without undue influence.
— Hire experienced quality staff for on-site and manufacturing inspections.
— Incorporate quality management best practices within the project management system.

A three level quality management process applied to an NPP project implemented by CNPE provides a clear division of interface among participants (Fig. 29).

6.8. HUMAN RESOURCES AND TRAINING

Nuclear projects place great demands on a country's workforce, and a plan for human resources development and training is essential. Project delays can result from not having adequately trained staff for the construction, commissioning and operation of the facility. Nuclear operators have experienced challenges related to an ageing workforce, declining student enrolment and the resultant risk of losing accumulated nuclear knowledge and experience for expanding or newly established nuclear programmes [21].

It is not realistic to expect that a Member State or organization initiating a nuclear power programme will, in the beginning, have personnel with all the competence needed to implement it. A shortage of qualified managers, technical staff and workers is thus a risk for NPP construction. Before starting NPP construction, the necessary personnel need to be trained, assessed and qualified before starting their work.

The CORR guidelines [43] refer to the following areas as being of special importance to human resources and training within nuclear construction:

(a) Hiring, development and training;

(b) Personnel qualification;
(c) Human performance;
(d) Health and safety training;
(e) Personnel availability;
(f) First line supervision and management.

Some risks and impacts related to human resources and training in these areas are shown in Table 55.

TABLE 55. HUMAN RESOURCES RELATED RISKS AND IMPACTS

Cause	Risk	Impact
— Lack of planning for HR development, recruitment and training — Ageing workforce — Decline in student enrolment — Training not linked to requirements/not performance based — Organizational culture not supportive of safety and high standards — Workers not trained in human performance and error reduction tools — First line supervisors not trained in or supportive of improving the management system and the culture for safety — Occupational health and safety not emphasized — Local/regional/international job market competition for needed resources — Multicultural challenges — Language barriers — Different beliefs (e.g. cultural norms, religion)	— Resources not available when needed — Loss of nuclear knowledge — Lack of new or replacement resources for hiring — Workers not knowledgeable in required performance standards — Poor quality work/increased errors and non-conformances — Increased numbers of industrial accidents and near misses — Miscommunication or lack of cooperation between workers or organizations	— Project delays and cost increases — Rework, equipment damage, safety events or radiological releases — Latent quality issues that may lead to nuclear safety or production issues — Personnel injuries

Some measures to help mitigate these risks include the following:

— Develop a national system for providing human resources. Ensure that human resources plans assess the external job market, economics, competing projects, labour availability, demographics and the time needed to develop new staff.
— Initially use turnkey projects that allow the time and means to develop competence in the newly established organizations.
— Recruit competent staff for the commissioning and later stages of a nuclear facility operation.
— Use international networks (such as provided those by the IAEA) and owners' groups (organizations or facilities with similar technologies that share experiences and even resources) to acquire knowledge.
— Partner with vendors, regulatory bodies, nuclear facility operating organizations, educational institutions from the other Member States, academic and trade organizations in establishing training and qualification programmes and in ensuring resource availability.
— Develop training using a systematic approach and incorporating performance based elements such as simulator training, realistic drills or hands-on maintenance training.
— Ensure that newcomers to the industry, including managers and first line supervisors, receive training in error reduction tools and safety culture to ensure that human performance and safety culture is engrained throughout the organization. This can be especially challenging for contractor workforces who may be less familiar with work in a nuclear environment.
— Reinforce the need for nuclear facility managers to demonstrate high standards and be everyday role models for their personnel.

— Ensure that high standards and training for health and safety are part of the overall approach to construction readiness.
— Ensure that the NPP vendor appreciates cultural differences and promotes creativity and motivation through effective leadership, crosscultural communication, mutual respect and reconciliation.

IAEA Nuclear Energy Series No. No. NG-G-2.1 [21] discusses how to manage human resources in the field of nuclear energy. IAEA Nuclear Energy Series No. NP-T-3.27 [104] covers human performance issues related to nuclear facility operation. Numerous safety guides and publications cover the topic of safety culture, including Refs [17, 105, 106].

7. OPERATION PHASE RISKS

The operation phase is the only phase in the life cycle when the NPP produces and sells electricity, and its cash flow is usually positive. All other life cycle phases support the operation phase and incur costs that have to be paid for with operation phase revenue. All risks in the operation phase contribute to events that cause a decrease in positive cash flow. These events include losses of production, planned outages, unplanned outages and forced power reductions, whether due to internal and external reasons. Therefore, it is important to optimize the NPP processes and systems in the preparation and design phases so that potential losses of production are minimized, and the time needed for refuelling, testing and maintenance is optimized.

Wrong decisions made in the design and construction phases can increase the risk of production losses and cost increases in the operation and decommissioning phases. Early analysis of such risks can allow for their suitable prevention or mitigation. Reviewing risk prevention strategies over an entire facility's life is normally better than reviewing such strategies separately at each stage.

7.1. SAFETY

As mentioned in Section 1.3, the risks associated with nuclear and radiation safety are not comprehensively discussed in this publication. Risk analysis in the context of nuclear and radiation safety is covered in detail in the IAEA Safety Standards and other supporting publications, such as Technical Documents (TECDOCs) and Safety Reports, while various safety related discussions feature throughout this publication. Therefore, this section aims to briefly summarize the relevant references in this field.

As mentioned in Section 2, risk analysis for NPPs from a safety point of view is typically implemented using the probabilistic safety assessment (PSA) framework, which is explicitly required as a part of the safety assessment process [107] and is extensively used in design [76] and operation [108].

As stated in GSR Part 4 (Rev. 1) [107], the main objective of the probabilistic safety assessment is:

> "to determine all significant contributing factors to the radiation risks arising from a facility or activity, and to evaluate the extent to which the overall design is well balanced and meets probabilistic safety criteria where these have been defined."

PSA represents a comprehensive and structured approach for numerical risk evaluation through identification of potential failure scenarios leading to the undesired end state. From safety perspectives the undesired end states vary and could represent reactor core damage, fuel damage, radioactive release, number of fatalities, etc.

The PSA model represents the logical plant response model for the initiating events with the potential development of accident sequences leading to an undesired end state (e.g. core damage).

The logical model represents potential failure in plant structures, systems and components, as well as potential human failure events. The input to the model quantification is compiled from the frequencies of initiating events, reliability parameters and human error probabilities. Quantification of the PSA model results in an integrated estimate of the corresponding risk metrics corresponding to the undesired end state (e.g. core damage frequency, large early release frequency). The results derived for the risk metrics consist of the various contributors to the final result, which allows analysts to understand the contribution to the risk from various aspects (e.g. initiating events, human failure events, system failures). Thus, the main outcome of risk analysis in this context is the risk profile for a given NPP, which can support the relevant decision making process extensively (starting from the early design stage throughout the entire life cycle of the NPP).

The methodological aspects of the development and application of a PSA are provided in detail in IAEA Safety Guides SSG-3 [12] and SSG-4 [13]. Various supporting publications (TECDOCs and Safety Reports) have been published by the IAEA or are currently being developed. These publications aim to elaborate on specific PSA topics, such as:

— Quality of PSA models [109];
— Integrated risk informed decision making [110];
— Risk aggregation for nuclear installations [111] ;
— Multi-unit probabilistic safety assessment [112–114];
— Seismic risk analysis [115];
— Human reliability analysis [116].

7.2. PRODUCTION AND OPERATIONS POLICIES AND PROGRAMMES

Risk reduction related to operating cost increases and losses of production is a constant focus of operating organizations. Improvements in these areas can be accomplished by increasing electricity output (via increasing capacity factors or unit output through engineering changes) or lowering the cost of inputs (labour, material, fuel, insurance, etc.). Some techniques in use are described below.

7.2.1. Maintenance and refuelling outage policies

Each NPP operating organization has its strategies for short, medium and long term outage planning. Extensive and comprehensive preplanning is needed to optimize outage durations, avoid outage extensions, ensure the plant's safe and reliable operation, and minimize radiation exposure to personnel. Adverse events such as maintenance errors, operator errors or equipment failures can cause outages or outage extensions.

Optimizing a preventive maintenance programme is an effective way to streamline maintenance and decrease the likelihood of failures that impact on production. Optimization also includes the balancing of maintenance costs and loss of production. The design of SSCs should be optimized so that any operation limits and conditions facilitate on-power maintenance and testing. Risk informed approaches such as integrated risk informed decision making (IRIDM) should be considered. The process for on-line maintenance should be considered, and any necessary monitoring systems ought to be considered in the design.

Long term outage planning can begin during the preparation phase based on experience from other operating NPP units of similar design. Owner/operator groups (e.g. the Canada Deuterium–Uranium (CANDU) Owners Group, the Pressurized Water Reactor (PWR) Owners Group, the Boiling Water Reactor (BWR) Owners Group) and operator organizations (e.g. WANO, INPO) are a good source of experience data.

The choice of a fuel cycle or planned outage cycle may have a significant impact on life cycle costs. In recent years, operating organizations have taken innovative approaches to extend the duration between major outages and shortened such outages' average duration.

The LCC analysis should consider the length of refuelling and maintenance outage periods as a probability distribution. The selection of the fuel cycle or maintenance outage schedule (12, 18, 24 months or longer) will be optimized during operation. In the preparation phase, the most suitable one should be selected based on the LCC analysis. Fuel cycle risk is discussed in IAEA-TECDOC-1806 [117].

Example

The BWR units Olkiluoto 1 and Olkiluoto 2 in Finland started operation in the early 1980s. During the first years of operation, they had over 30 days of outages annually. However, the design of the units allowed for much shorter outages. Intensive long term outage planning, together with plant changes, resulted in three types of outages:

(a) A refuelling only outage for one week every second year;
(b) A refuelling and maintenance outage for two weeks every second year;
(c) A long outage including plant changes and replacement of main components over three weeks every ten years.

In addition, much maintenance is performed during on-power operation. The capacity factors have been >90% continuously over several decades. Probabilistic availability analysis was performed for Olkiluoto 1 and 2 when they had been in operation for almost 20 years. This helped in streamlining maintenance, maintenance cost optimization and life cycle cost optimization of plant changes.

Example

The European Utility Requirements [14] are intended to be used as a basis for the plant contract. They include the description of one important tool in the design phase, probabilistic performance analysis (PAA) (see Ref. [14], Chapter 2.2), which can be used to show analytically that the plant is capable of the required capacity factors. This approach has been used in the Olkiluoto 3 project.

7.2.2. Spare parts policy

Spare part availability impacts on both operation and safety because a lack of necessary parts can increase the risk of unplanned production losses. Similarly, spare parts inventory impacts on the commercial aspects both as a threat (excessive spare parts inventory) and an opportunity (minimizing downtime).

The cost of spare parts should be included in the LCC analysis as an initial investment and periodic maintenance material cost. Unplanned outage risks and equipment purchase risks may be related to the most expensive spare parts, such as the main generators, diesel or standby generators, large transformers, or large pumps and motors. However, a lack of even relatively inexpensive spare parts in critical systems can be highly important, especially if their delivery time is long.

Spare part inventory optimization is done most effectively for an entire enterprise, not only for a single unit or plant. Cooperation and data sharing between utilities, industries and even countries can assist. Support from senior management of the operating organizations, the vendor community and associated organizations such as owners groups is often necessary to put collaboration mechanisms in place.

Analysing operational risks such as single point vulnerabilities (SPVs) is an important step in this process. Spare parts inventory planning, based on component failure rates and repair times, is a natural extension of current risk analysis techniques. To reduce the volatility of performance due to inventory management both the frequency and severity dimensions need to be addressed.

Spare part optimization may become important in LCC analysis if the utility is building its first unit, if the unit is located far away from other units of the same type or if the unit is FOAK in the world. IAEA Nuclear Energy Series No. NP-T-3.21 [11] provides guidance on the entire procurement process, including issues related to spare parts, obsolescence and inventory management.

7.2.3. Configuration management programme

As described in Section 6.2.5, maintaining proper NPP CM and strong records and document management systems is very important for NPP production and operation. Deficiencies and errors in CM are a major source of NPP events.

Many NPPs have had to initiate resource intensive CM restoration projects to demonstrate that the plants remained operating within their design bases following years of operation. Such projects often require operations personnel to walk down and document the state of thousands of items of installed equipment and components, designers to update and approve as-installed design documentation, and others to document the approved bills of material for equipment installed in the facility.

As described earlier, the IAEA has released numerous publications related to configuration management, including Refs [64, 65, 68, 69]. Several industry publications and standards are also available [70–74]. IAEA Nuclear Energy Series NP-T-3.21 [11] describes configuration data needs related to the procurement process.

7.2.4. Engineering programmes

As described in Section 6.2.8, engineering programmes are essential for the long term safety and productivity of the NPP. Baseline programme data are gathered during the construction and commissioning phases. Following commissioning and throughout the plant's lifetime, such programmes require oversight and ongoing analysis to ensure that any problems affecting the plant are addressed before they lead to production or safety issues. The most relevant of these programmes are discussed in the following subsections.

7.2.4.1. In-service inspection of the piping programme

In-service inspection (ISI) is an important part of an NPP defence in depth programme to ensure its safe and reliable operation. The purpose of ISI is to detect the degradation of the piping components. Traditional ISI programmes were developed using deterministic approaches.

In an NPP, the main asset of the reactor is the piping system. Inspections are performed during a shutdown, and only a portion of the piping components is inspected. The approach involves a high cost for plant operation due to the outage time involved.

However, as probabilistic approaches have been developed, risk insights have increasingly been used to optimize ISI programmes by focusing resources on the most risk significant locations. The result is risk informed in-service inspection (RI-ISI) [103, 118–120]. Industry experience has shown that degradation occurs wherever the conditions necessary for a particular mechanism exist.

RI-ISI helps implement focused inspection and maintenance schedules and reduces their cost, personnel requirements, radiation dose consumption and outage time. It also increases the overall safety of the plant by detecting degradation more effectively. A comprehensive RI-ISI programme will develop improved procedures to identify where the greatest likelihood of damage/failure associated with a significant leak rate is located in the plant and then provide quantitative measures of the associated risks. The RI-ISI programme and its contribution to risk reduction can be presented explicitly in the LCC calculation.

7.2.4.2. *Condition monitoring programmes*

The efficient operation of an NPP depends upon the condition of its critical equipment. Therefore, good condition monitoring is essential to detect defects early on and carry out predictive maintenance. Numerous well established techniques are available for on-line monitoring (OLM) of the condition of equipment and systems in NPPs. Some of the techniques that can be used for condition monitoring include:

- — Vibration monitoring;
- — Fatigue monitoring;
- — Acoustic monitoring;
- — Lubrication analysis;
- — Infrared diagnosis;
- — Loose parts monitoring;
- — Reactor noise analysis;
- — Motor electrical signature analysis;
- — Modelling techniques.

Decisions on purchasing the instrumentation to allow for such diagnostics can be made in the design phase, where possible, because it may be more difficult and expensive to install such equipment later. Costs will be minimized if such equipment can be included as part of the original plant purchase specification.

The decision to include advanced diagnostic equipment should be based on the LCC analysis, where risks are evaluated based on failure and maintenance information, maintenance plans, cost of work and spare parts, and the predicted future electricity price.

A critical activity at an NPP is monitoring equipment conditions, looking for early warning signs and identifying abnormalities. Due to safety and economic reasons, diagnostic and monitoring systems are of growing interest in NPPs. Key components of NPPs are the primary and secondary loops, main coolant pumps, recirculation pumps, turbines, freshwater pumps and feedwater pumps.

Monitoring and fault diagnosis of rotating machinery has gained wide attention for its significance in preventing catastrophic accidents and guaranteeing sufficient maintenance. Vibration analysis is also the key predictor of machine health in NPPs and is being used to monitor critical rotating machinery's predictive maintenance and condition monitoring.

It is sometimes impossible to modify the rotating machinery later without remarkable costs. In the LCC analysis, it is important to also consider secondary risks due to missiles from the rotating machinery.

IAEA Nuclear Energy Series No. NP-T-3.8 [121] covers maintenance optimization programmes for NPPs, including information on condition monitoring.

7.3. MITIGATION AND REDUCTION OF OPERATIONAL RISKS

The evaluation and mitigation of risks during the operational phase is a daily activity at NPPs. Plant conditions, such as equipment status, planned maintenance, planned modifications, staff availability and external events all require continual evaluation and assessment. Operating organizations use systems and processes to perform these assessments, which are discussed in the following sections.

7.3.1. Enterprise risk management

Enterprise risk management (ERM) is the process of planning, organizing, leading and controlling the activities of an organization to minimize the effects of risk on an organization's capital and earnings. Enterprise risk management includes strategic, operational and financial risks, in addition to risks associated with accidental losses.

The ERM process should have a computerized tool, where information on each on-line risk is available for authorized persons who need it. The risk information includes, for example, risk identification, qualitative and quantitative risk evaluation on likelihood and consequences, means to reduce the risk, mitigation and recovery plans, and the owner of each risk.

Risk management should be an essential part of the enterprise management process. The company's top management should be aware of the analysed risks to aid in their decision making. Risks from the construction and commissioning phases should be transferred to the operational organization as part of the plant turnover. The operational risks identified in the project phase should be updated regularly during the operation phase, and the prevention and mitigation plans, as well as the possible losses, should be considered in the business planning.

The categorization of risks in the operation phase may be different from that in the project phase. One possibility is to categorize risks according to strategic goals to find the owner for each risk.

7.3.2. Information sharing

The sharing of information among the global operator community may help avoid unnecessary risks, as other members may already have solved certain issues. Several years before the start of commercial operation, the owner and coming operator of the new plant should join WANO and the applicable reactor type owner's group. These organizations support their members with operating experience, peer reviews and assist visits, as necessary.

7.3.3. Corrective action programme

The United States Nuclear Regulatory Commission (USNRC) Glossary [122] defines a corrective action programme as:

> "The system by which a utility finds and fixes problems at the nuclear plant. It includes a process for evaluating the safety significance of the problems, setting priorities in correcting the problems, and tracking them until they have been corrected."

Every nuclear plant operator needs to have a system to identify and feedback the lessons learned from operating experience and implement effective corrective actions to prevent safety events from reoccurring. An effective operating experience programme also includes a proactive approach to prevent the first time occurrence of safety events [123].

IAEA TECDOC-1458 [123] says that:

> "The international nuclear organizations have established initiatives in the area of operating experience feedback, implementation of corrective actions and identification of good practices (e.g. IAEA, WANO, INPO, etc.). These identified good practices may be useful in assisting with the determination of corrective actions.
>
> "These initiatives have been mainly focussed on the operational nuclear power plant activities. However expanding these initiatives to all process activities in design, construction, operation and decommission, including all facilities and nuclear installations, power plants, research reactors, fuel cycle facilities, waste treatment process, etc. will be beneficial. These will be of interest to owners, operators, vendors, manufacturers, contractors, and the regulatory authorities in enhancing nuclear safety performance."

Beneficial use of operational experience for corrective actions is not restricted to lessons learned from safety significant events. Important lessons can also be learned from situations of lower significance or consequence (low level events and near misses) that had the potential to develop into safety significant events but were prevented from doing so because of plant design features or preventive actions by an operator. IAEA-SR-73 [124] describes the key elements for establishing and enhancing the low level events and near misses portions of existing operational experience (OE) programmes.

IAEA TECDOC-1458 [123] also says that:

> "It is important to use industry OE information when selecting corrective actions … When implementing corrective actions that have been effective at other sites, care is taken to ensure that the corrective actions would be compatible with the station's design, local environment, resources and culture."

The use of corrective action programmes in the design and construction phase may reveal corrected or at least tracked problems. The information collected within the corrective action programme during the design and construction phases, possibly with cooperation between supplier and owner/operator, should be transferred into the operation phase. The documented in-depth analysis from the design phase may be useful during operation, for example when evaluating suggested plant changes.

The implementation of a corrective action programme to enhance operational safety is presented in IAEA-TECDOC-1458 [123].

7.4. FINANCIAL/COMMERCIAL RISK MANAGEMENT

Operating organizations need to take measures to manage financial and commercial risk. Changes can occur in the electricity market, in the broader economy or the political environment, making the plant more or less economical to operate. There are numerous examples of NPPs that could operate safely and reliably that have been shut down for economic reasons (e.g. due to long term low wholesale price of electricity) despite safe and reliable operation.

Safety improvements based on worldwide operating experience may require financial investments over a facility's life. This risk should be considered in the preparation phase, but it may be difficult to evaluate it quantitatively as part of LCC analysis.

An example of this is the lessons learned following the Fukushima Daiichi NPP accident in March 2011, which resulted in owner/operators needing to improve systems to address catastrophic events, including enhanced flooding, earthquake and emergency preparedness, spent fuel storage pool instrumentation and containment venting systems. The incident also increased research efforts towards multiunit site risk analysis. The PSA technique had been successfully applied to evaluate the risk associated with the operation of NPPs for several decades; however, it is now being extended to multiunit PSAs [125].

IAEA-TECDOC-1209 [3] lists the following financial/commercial risks during operation:

(a) Financial market risks that arise from changes in the prices of assets and liabilities;
(b) Credit risks that can arise due to counter parties' unwillingness or inability to fulfil their contractual obligations or due to borrower's downgraded credit rating;
(c) Liquidity risks;
(d) Financial operations risks.

Financial market risks and credit risks should be considered in the design phase and taken into account in the LCC calculations.

8. DECOMMISSIONING PHASE RISKS

8.1. DECOMMISSIONING RISKS

For normal shutdown situations a licensee needs to choose one of two main decommissioning strategies, namely immediate and deferred dismantling [126, 127]. The selected strategy is described in a preliminary decommissioning plan that includes a cost estimate for the required decommissioning activities. Such a plan will initially be developed in a preliminary form during the design stage of an NPP [128]. The preliminary decommissioning plan and associated cost estimate need to be updated regularly throughout the operating lifetime of the facility and to be updated to a final decommissioning plan once the end of operation has been reached.

In the context of decommissioning projects, two major categories of risk may be distinguished: strategic risk and operational risk [129]. Strategic risks are those more likely to be of concern during the planning phase of decommissioning — typically concerning issues that may be beyond the control of the licensee — while operational risks are those more likely to be relevant to the actual implementation of decommissioning activities — typically concerning issues amenable to control by the licensee.

Decommissioning is inherently a dynamic process, significantly different in nature from the operating phase of a nuclear facility and involving significant uncertainties in the planning and execution of decommissioning projects. Accordingly, a periodic review and update (as appropriate) of risks and assumptions needs to be undertaken, to reflect any relevant changes in the configuration of the facility, the maturity of the project, and the hazards and complexities found with the decommissioning tasks.

In general, the application of risk management as part of decommissioning follows the same general approach as in other project phases, comprising the following principal steps:

(a) Determine the context underlying a risk;
(b) Qualitatively or quantitatively assess a risk, taking both the severity of impact and the likelihood of occurrence into consideration;
(c) Develop a treatment plan for controlling the risk (e.g. through actions to reduce probability and/or impact);
(d) Develop a plan to ensure that the risks are systematically monitored, reviewed and revised, as necessary.

As an output of the risk management process, it is general practice to develop a risk register where threats and opportunities are listed, together with other related information, such as treatment strategies and any associated actions. To help ensure the effectiveness of the risk register, it needs to be updated regularly based on the output of the monitoring and review process. It is important that risks not be deleted from the risk register, even if they no longer require explicit attention — owing, for example, to the fact that they have expired or are no longer relevant. The preferred approach is to simply record a change in the status of the risks in the risk register. This approach will ensure that a complete record of the risks is maintained for possible future use (e.g. as input for other decommissioning projects undertaking risk management).

In addition to the above, contingency plans should be prepared based on the eventuality that certain risks could be realized. It is also advisable that attention be given to communications and consultations about the risks to ensure that stakeholders are fully aware of the circumstances surrounding project risk. Risk assessments should be periodically reviewed and updated during plant operation and up to the point where the plant is shut down for decommissioning. The probability and consequences related to newly identified risks, and the success in mitigating previously identified risks, should be determined. Peer evaluation throughout a plant's life cycle, which has been adopted in the European Union in recent years [130], may be considered to be a good practice.

Many of the generic risk types applicable to decommissioning are the same as those occurring at earlier stages of the facility lifetime; these may include the following 'risk families' [129]:

— Initial condition of facility;
— End state of decommissioning project;
— Management of waste and materials;
— Organization and human resources;
— Finance;
— Interfaces with contractors and suppliers;
— Strategy and technology;
— Legal and regulatory framework;
— Safety;
— Interested parties.

Special attention should be given to risks that may be of a more specific nature during decommissioning rather than during the rest of the plant life cycle: regulatory risks, risk of plant degradation, radiological risk and human resource risks. Some of the critical risk families are discussed below in the context of these specialized risks in decommissioning.

8.1.1. Initial condition of the facility

Decommissioning cost estimates are generally highly sensitive to the assumed inventory of radiological and other hazardous materials, and to the state of buildings and major equipment such as cranes. Before commencing decommissioning, the owner of the plant needs to evaluate these SSCs and the site. Workers will continue to be exposed to the decay of radioactive materials in the decommissioning stage and minimizing the personnel dose to be as low as reasonably achievable will be an ongoing goal.

Historical site assessment (HSA) and characterization can lead to a good characterization of radiation risks and help control the plant personnel's radiation exposure during decommissioning. The technique was used successfully during the decommissioning of the Maine Yankee facility in the United States of America [131]. Some good practices for reducing the risk that was documented include:

— Compile the HSA while the plant is still in operation;
— Keep good records on radiological and non-radiological spills and excavation activities;
— Record the movement and disposal of soils during plant modifications;
— Maintain a file of site aerial photos and pictures of SSCs over time;
— Include questions on spills, leaks and related events in employee out processing forms.

Example

At one European decommissioning site, inadequate knowledge of site history resulted in work stoppages when unexpectedly high dose rates were discovered in the spent fuel pool [132]. The selected decommissioning strategy was based on available radiological survey information with conditions as they existed when the facility was in operation. Further research identified that the radiation source was the neutron activation of concrete surrounding the spent fuel pool. The project plan for this area was modified, with work continuing using remote dismantling methods.

Example

One licensee utilized remote camera technology to reduce dose by installing closed circuit television systems for job oversight. This technology saved a significant dose due to the reduced number of personnel. Another licensee experienced a threefold increase in the general area dose rate after the water had been drained from the steam generators' secondary side [133].

8.1.2. End state of the decommissioning project

A key prerequisite for developing a decommissioning plan is the selection of the end state to be achieved on completion of decommissioning. Having obtained general agreement with relevant regulatory authorities and with other concerned stakeholders on the end state, the precise criteria demonstrating that the end state has been achieved also need to be agreed (e.g. in terms of residual levels of radioactivity that may be considered insignificant). Any significant changes to the assumed end state and associated criteria at the detailed stages of decommissioning planning may have important cost implications. The main IAEA Safety Standard related to decommissioning is SSG-47 [134].

Example

Demolition costs may be estimated based on an assumption that a certain residual level of radioactivity in the facility would be considered acceptable by the regulatory authorities and other concerned stakeholders. However, lower levels of residual contamination may be demanded either in the building structure, foundations or surrounding soil. This requirement may increase the cost due to decontamination and radiological protection significantly.

8.1.3. Organization and human resources

Decommissioning projects are dynamic, and the skillsets and expertise needed by the site change through different facility phases. Facility owners need to determine which personnel and skills are essential to maintain or expand during decommissioning while concurrently reducing the pool of non-essential personnel. A general good practice is to establish a robust and equitable retention programme, ideally before the shutdown or early in the decommissioning phase [131, 135]. Additionally, the announcement that a facility will be permanently shut down affects on-site morale and the licensee should prepare for this [136].

A significant management challenge for licensees is the risk concerning retaining high quality personnel after shutdown has been declared. Frequently, the most qualified candidates have options to move on to new opportunities versus staying at a site where they are working until the conclusion of employment. Furthermore, the new uncertainty causes additional stress due to the uncertain financial future of the staff. Some sites establish programmes to retain key employees, with senior management (CEO, CFO, VP) providing oversight as to which positions continue to be needed and for what duration [131, 135].

To retain essential personnel, one company provided a severance or early retirement programme that was linked to staff remaining on the decommissioning project for a prescribed period. Staff deciding to leave the organization while their services were still required forfeited the severance package [131].

8.1.4. Finance

Financial risks in decommissioning are discussed in IAEA-TECDOC-1476 [137]. Decommissioning a facility is a complex and long term project that affects the licensee and the local community [137]. Decommissioning funds should be established early in the life of a nuclear facility. Cost and schedule estimates for decommissioning require regular review and adjustment to ensure that licensees will have adequate funds and capability to complete the decommissioning project [138].

Decommissioning costs are normally recovered during the revenue generating period of a facility life cycle. A decommissioning fund thus accumulates over time until the start of decommissioning.

It is often very difficult to estimate the appropriate costs for decommissioning during the early stages of a plant's life. The decommissioning funds required in the future are influenced by changes in interest rates, how aggressively the decommissioning fund is managed, requirements for fund payments, material and equipment costs, staffing costs, changes in decommissioning strategies and other factors. Earlier than planned plant shutdowns, such as some experienced following the Fukushima accident, can leave much lower decommissioning funds to complete decommissioning activities.

Approaches to managing decommissioning funds vary by country. Some countries allow investing in financial derivatives, which could be used as a hedging tool. Some countries accumulate the decommissioning funds as provisions in the debit account, which can be converted into decommissioning funds immediately by issuing bonds. Other countries use earned surpluses for their decommissioning funds. The regulatory payments to the decommissioning fund should be included in the LCC calculation.

8.1.5. Legal and regulatory framework

Decommissioning planning normally assumes that the legal and regulatory requirements applicable during implementation will be those in force at the time the plan is being developed. The plans also typically include assumptions about the time needed to obtain regulatory approvals to proceed beyond key project milestones. In practice there is inevitably a possibility that legal and regulatory requirements may evolve, and that the time taken to conduct regulatory reviews of key submissions will take longer than anticipated. Although such risks are outside the direct control of the plant operator, they need to be addressed as strategic risks to the project, for example in terms of contingency planning [139, 140].

9. CONCLUSIONS

Risk management should be integrated into NPP projects from the very beginning to be effective. Decisions made early in a project can substantially affect an NPP's life, including the final decommissioning period. Even though an NPP's lifetime may be long, with the net present value of end of life risks being low, it is worth considering all such risks during the early stages to allow for the implementation of low cost mitigation strategies.

Life cycle cost analysis is a useful tool for evaluating all risks on an economic and financial basis. In conjunction with PPA, which is a tool for analysing production loss uncertainties, it can be used to optimize many decisions related to a project. Such decisions can be related to design approaches, procurement strategies, spare parts approaches, bid selections, maintenance strategies, condition monitoring approaches, risk mitigation strategies and others.

Risks are always in the future, but the understanding of future changes continuously based on experience. Therefore, risk management should be based on the best current knowledge. Different risks are important in different phases of the life cycle. Nonetheless, all risks in the future should be assessed and evaluated.

Each risk, identified in detail or not, needs to be assigned an owner. Ownership of specific risks should be clearly defined in agreements between the owner and suppliers. Some risks that have an impact on both parties may need to be jointly managed.

Adequate time should be allocated for the planning and preparation of a project before the actual construction starts. The following activities are of particular importance:

(a) Finalizing the design as early as possible;
(b) Resolving potential regulatory uncertainties;
(c) Qualifying the new design features and technologies;
(d) Building competent organizations;

(e) Specifying the responsibilities of parties;
(f) Ensuring the availability of qualified designers, constructors and manufacturers to implement the project;
(g) Establishing quality management systems that emphasize the strong management of supply chains.

Appendix I

SAMPLE RISK MATRIX AND NPP PROJECT RISK LIST

This appendix provides a sample risk register (Table 56) associated with an NPP project and a resultant risk matrix (heat map, Fig. 30). The likelihood and impact ratings identified in Table 56 should be taken as sample data and would change depending on the specific project being evaluated.

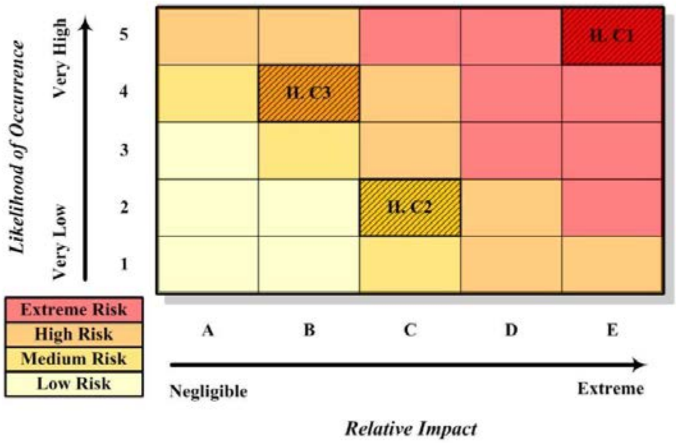

FIG. 30. Graphical presentation of results from Table 56.

TABLE 56. TYPICAL NPP PROJECT RISKS

Category	Likelihood of occurrence (L)						Relative impact (I)					Baseline	Coordinate	Remarks
	Very low → Very high						Negligible → Extreme							
	n.a.	1	2	3	4	5	A	B	C	D	E			
Source of risk														
1. Sources of strategic risks														
Government policy change														
Changes in public acceptance														
Limitation of vendor selection					X				X				4.C	
Selection of FOAK														
Project management organization														
Stable licensing process														
Improper time schedule (P)					X					X			4.D	
Improper interface among industry actors (P)			X						X				2.C	
Vendor — many simultaneous projects (P)	X													
Fuel cycle			X						X				2.C	
Fuel procurement		X							X				1.C	
Waste management policy		X									X		1.E	

TABLE 56. TYPICAL NPP PROJECT RISKS (cont.)

Category	Likelihood of occurrence (L)						Relative impact (I)					Baseline	Coordinate	Remarks
	Very low → Very high						Negligible → Extreme							
	n.a.	1	2	3	4	5	A	B	C	D	E			
Financing provision			X								X		2.E	
Poor estimating cost (P)														
Environmental impact														
Safety culture														
Localization capabilities														
2. Source of project risk														
Undefined objectives		X									X		1.E	
Lack of infrastructure														
Lack of preparations to start the project														
Unproven management system without the integration of major milestones														
Inadequate work breakdown			X							X			2.D	
Poor estimation of costs, resources			X							X			2.D	
Poor teamwork or lack of coordination			X								X		2.E	
Poor design management, procurement management			X								X		2.E	

TABLE 56. TYPICAL NPP PROJECT RISKS (cont.)

Category	Likelihood of occurrence (L)						Relative impact (I)					Baseline	Coordinate	Remarks
	Very low → Very high						Negligible → Extreme							
	n.a.	1	2	3	4	5	A	B	C	D	E			
Labour unrest or strikes by unions or contractors				X						X			3.D	
Substandard performance of NPPs			X								X		2.E	
Poorly defined design requirements		X									X		1.E	
Lack of qualified resources or contractors		X								X			1.D	
Lack of attention to operability and maintainability		X									X		1.E	
3. Sources of preparation risk														
Poor financing model														
Lack of political stability and support														
Poor public acceptance and communication														
Multiple proven vendors														
Proven design														
Effective regulatory environment														
Fair contract structure														

TABLE 56. TYPICAL NPP PROJECT RISKS (cont.)

Category	Likelihood of occurrence (L)						Relative impact (I)					Baseline	Coordinate	Remarks
	Very low → Very high						Negligible → Extreme							
	n.a.	1	2	3	4	5	A	B	C	D	E			
Domestic stakeholder management														
Effective long term nuclear power development plan														
Reactor type selection														
Site selection														
Environment with potential radioactive consequences														
External human event risk, such as civil aviation, military facilities														
External event risks, such as earthquakes, tsunamis, floods, extreme weather conditions and other natural risks														
Equipment transportation														
Electricity market														
General project schedule planning														
Licence application														
Effective long lead equipment procurement planning														

TABLE 56. TYPICAL NPP PROJECT RISKS (cont.)

Category	Likelihood of occurrence (L)						Relative impact (I)					Baseline	Coordinate	Remarks
	Very low → Very high						Negligible → Extreme							
	n.a.	1	2	3	4	5	A	B	C	D	E			
Effective long lead equipment procurement process														
Construction contract bidding and signing														
Site work and nuclear island negative excavation														
Insufficient preparation of design														
Equipment localization														
Project estimation														
4. Sources of construction risk														
Schedule delay				X					X				3.C	
Many design changes														
Poorly defined design requirements			X								X		2.D	
Over-defined performance requirements		X								X			1.D	
Lack of qualified resources or contractors		X									X		1.E	

TABLE 56. TYPICAL NPP PROJECT RISKS (cont.)

Category	Likelihood of occurrence (L)						Relative impact (I)					Baseline	Coordinate	Remarks
	Very low → Very high						Negligible → Extreme							
	n.a.	1	2	3	4	5	A	B	C	D	E			
Lack of manufacturing, design, human capabilities to support new NPP project		X									X		1.E	
Inexperienced project managers and project leaders		X								X			1.C	
Lack of knowledge of OPEX of an NPP (O)		X									X		1.E	
Use of unproven equipment or facilities		X									X		1.E	
Lack of supply chain: domestic and foreign companies		X								X			1.D	
Labour unrest or strikes by unions or contractors				X						X			3.D	
Quality control and management		X									X		1.E	
Poor quality of components		X									X		1.E	
Working attitude/foreign workers — non-conformance			X							X			2.D	
Understanding codes/standards		X								X			1.D	
Poor communication			X							X			2.D	
Poor configuration management			X							X			2.D	

TABLE 56. TYPICAL NPP PROJECT RISKS (cont.)

Category	Likelihood of occurrence (L)						Relative impact (I)					Baseline	Coordinate	Remarks
	Very low → Very high						Negligible → Extreme							
	n.a.	1	2	3	4	5	A	B	C	D	E			
Poor methodology for corrective action and change control when feedback is available		X									X		1.E	
Freedom of inspection		X									X		1.E	
Infrastructure issues		X								X			1.D	
Grid stability and capacity (O)			X							X			2.D	
Transportation and logistics issues			X						X				2.C	
Inadequate work breakdown														
Poor planning or definition of project tasks			X						X				2.C	
Lack of an integrated data system														
Lack of pending design issue control methods														
Poor design interface management														
Incomplete technology decision making system														
Effective design change control process														

TABLE 56. TYPICAL NPP PROJECT RISKS (cont.)

Category	Likelihood of occurrence (L)						Relative impact (I)					Baseline	Coordinate	Remarks
	Very low → Very high						Negligible → Extreme							
	n.a.	1	2	3	4	5	A	B	C	D	E			
Poor bulk material management														
New construction technology implementation														
5. Sources of operational risk														
Unclear responsibilities and authorities		X								X			1.D	
Unrealistic schedule		X								X			1.D	
Documentation of design not transferred to the owner/operator			X							X			2.D	
Frequent design change			X								X		2.E	
Lack of supply chain			X							X			2.D	
Add new safety features after Fukushima accident					X					X			4.D	
Quality control and management		X							X				1.C	
Poor quality of components		X							X				1.C	
Understanding code/standards		X								X			1.D	
Poor configuration management			X							X			2.D	

TABLE 56. TYPICAL NPP PROJECT RISKS (cont.)

Category	Likelihood of occurrence (L)						Relative impact (I)					Baseline	Coordinate	Remarks
	Very low → Very high						Negligible → Extreme							
	n.a.	1	2	3	4	5	A	B	C	D	E			
Poor methodology for corrective action and change control		X								X			1.D	
Safety culture		X									X		1.E	
Low plant performance														
Nuclear event elsewhere														
Fuel supply chain														
6. Risk of human resources														
Retirement of professional staff			X						X				2.C	
Lack of training			X								X		2.E	
Loss of specific industry		X							X				1.C	
Lack of safety culture and quality culture		X									X		1.E	
Lack of companionship			X							X			2.D	
Transition management from operation to decommissioning														
Turnover from commissioning to operation														

TABLE 56. TYPICAL NPP PROJECT RISKS (cont.)

Category	Likelihood of occurrence (L)						Relative impact (I)					Baseline	Coordinate	Remarks
	Very low → Very high						Negligible → Extreme							
	n.a.	1	2	3	4	5	A	B	C	D	E			
7. Commercial/financial risks														
Volatility of prices of resources			X							X			2.C	
Volatility of prices, quantity of electricity on the market				X					X				3.C	
Volatility of exchange rates				X					X				3.C	
Volatility of interest rates			X							X			2.D	
Risk bearing of investors (shareholders, financial institutions)			X							X			2.D	
Ability to fulfil the contractual obligations			X						X				2.C	
Capital additions due to nuclear event			X								X		2.E	
Lifetime based financial analysis (from preliminary works to decommissioning)				X					X				3.C	
Use of value at risk methodology by energy companies														
Carbon price					X				X				4.C	
Early permanent closure														

TABLE 56. TYPICAL NPP PROJECT RISKS (cont.)

Category	Likelihood of occurrence (L)						Relative impact (I)					Baseline	Coordinate	Remarks
	Very low → Very high						Negligible → Extreme							
	n.a.	1	2	3	4	5	A	B	C	D	E			
Owner's credit														
Impact of other resources														
Cost of insurance														
Capability of insurances														
8. Sources of decommissioning risk														
Alternatives decision (DECON, SAFESTOR, ENTOMB)	X										X		1.E	
Decommissioning fund estimation					X					X			4.D	
Schedule estimation					X					X			4.D	
Supply chain: procurement of equipment			X						X				2.C	
Design changes			X						X				2.C	
Contractor performance		X								X			1.D	
Spent fuel management (handling, storage, etc.)		X									X		1.E	
Workforce management (skilled and experienced)				X					X				3.C	

TABLE 56. TYPICAL NPP PROJECT RISKS (cont.)

Category	Likelihood of occurrence (L)						Relative impact (I)					Baseline	Coordinate	Remarks
	Very low → Very high						Negligible → Extreme							
	n.a.	1	2	3	4	5	A	B	C	D	E			
Characterization (legacy findings)					X					X			4.D	
Large component removal (RV/RVIs, S/G)		X								X			1.D	
Waste management				X						X			3.D	
Licensing (acceptance of the final decommission plan, etc.)		X									X		1.E	
Safety: radiation protection of the workers, residents and environment					X						X		4.E	
Site restoration (green field or brown field)		X									X		1.E	

Note: n.a.: not applicable.

Appendix II

RISK MESSAGES FROM SELECTED IAEA INFRASTRUCTURE BIBLIOGRAPHY ITEMS

Table 57 provides a cross-reference to IAEA infrastructure related publications and the risk messages contained therein.

TABLE 57. IAEA INFRASTRUCTURE RELATED PUBLICATIONS

Infrastructure area	Title	Publication No.	Risk message	Ref.
National position	Building a National Position for a New Nuclear Power Programme	IAEA Nuclear Energy Series No. NG-T-3.14	National position is frequently cited as one of the most challenging issues for States embarking on nuclear power programmes during Integrated Nuclear Infrastructure Review Missions. It requires coordination across many institutions and long term government attention. Stable long term development planning is one of the most important risk hedging activities for an NPP project A pre-feasibility study can provide valuable insights into the benefits, risks and barriers of a nuclear power programme The long term nuclear power development plan is usually defined at the national level and will indicate the number of NPPs to be constructed and their siting	[141]
	Responsibilities and Functions of a Nuclear Energy Programme Implementing Organization	IAEA Nuclear Energy Series No. NG-T-3.6	The nuclear energy programme implementing organization (NEPIO) has a key role in developing and maintaining the infrastructure to support an NPP programme. Such infrastructure sends an important signal to stakeholders, including potential project investors, and reduces construction and operational risk	[142]
	Alternative Contracting and Ownership Approaches for New Nuclear Power Plants	IAEA-TECDOC-1750	A key aspect of all contracts will be how they allocate risk. Different approaches can facilitate NPP projects by allocating each risk to the stakeholder in the best position to manage it	[143]
Nuclear safety	Establishing the Safety Infrastructure for a Nuclear Power Programme	Safety Standards Series No. SSG-16 (Rev. 1)	Describes how national infrastructures to address safety risks are implemented, along with specific actions	[144]

TABLE 57. IAEA INFRASTRUCTURE RELATED PUBLICATIONS (cont.)

Infrastructure area	Title	Publication No.	Risk message	Ref.
	Basic Safety Principles for Nuclear Power Plants	INSAG Series No. 12 (Rev. 1)	A report on safety principles for electricity generating NPPs. Describes the use of PSAs to evaluate design changes, to make operational decisions concerning maintenance planning and scheduling. This is relevant to develop risk informed nuclear safety regulations and increasingly analyse shutdown, startup and risks of operation at low power. Indicates that “All individuals concerned need constantly to be alert to opportunities to reduce risks to the lowest practicable level.”	[145]
	Strengthening the Global Nuclear Safety Regime	INSAG Series No. 21	Indicates that, concerning precursor events, “By taking action to eliminate the risk factors early and to prevent the recurrence of similar events, one can significantly reduce the probability of serious accidents.” Emphasizes the importance of operating experience feedback in providing both positive (good practices) and the negative (root cause) aspects to ensure that it effectively reduces and eliminates risks	[146]
	Fundamental Safety Principles	Safety Standards Series No. SF-1	Indicates that (footnote omitted) “radiation risks to workers and the public and to the environment that may arise from these applications have to be assessed and, if necessary, controlled.”	[147]
Management	Initiating Nuclear Power Programmes: Responsibilities and Capabilities of Owners and Operators	Nuclear Energy Series No. NG-T-3.1 (Rev. 1)	Discusses contract models and financial risks of procuring and developing NPP projects. Indicates owner/operators should incorporate a risk management function within their organizational structure	[148]
Management	Preparation of a Feasibility Study for New Nuclear Power Projects	Nuclear Energy Series No. NG-T-3.3	The type of reactor, self-reliance strategy, distribution and plan of NPP projects around the country, funding requirements, nuclear liability regime, proposed fuel supply, waste and decommissioning plans and electricity market rules would be reviewed as part of a project’s pre-feasibility study. Performing a feasibility study is a way to help identify project risks	[149]

TABLE 57. IAEA INFRASTRUCTURE RELATED PUBLICATIONS (cont.)

Infrastructure area	Title	Publication No.	Risk message	Ref.
	Commissioning Guidelines for Nuclear Power Plants	Nuclear Energy Series No. NP-T-2.10 (mainly for phase 3)	Discusses several risks that can be encountered during commissioning. Examples include overlapping of activities, risks associated with unexpected test results and rework. Specific methods to reduce risk are identified (e.g. establishing a commissioning committee for oversight)	[101]
	Project Management in Nuclear Power Plant Construction: Guidelines and Experience	Nuclear Energy Series No. NP-T-2.7	Recommends establishing a project risk analysis team and a risk reduction programme. Identifies risks associated with manufacturing, sub-suppliers and construction. Recommends formal risk analysis as a method of cost control and to help manage contingency funds	[39]
	Invitation and Evaluation of Bids for Nuclear Power Plants	Nuclear Energy Series No. NG-T-3.9	Recommends that owners should request bidders to provide a risk management programme and a preliminary project risk analysis. Indicates that contracts should have a balanced risk distribution to help ensure project success. Recommends that uncertainties and risks associated with bids be formally evaluated	[150]
Management	The Management System for Nuclear Installations	Safety Standards Series No. GS-G-3.5	Indicates that poor risk analysis processes for safety related risks can indicate a decline in safety culture. Indicates that managers should have “An understanding of the risks within the manager’s own area of responsibility”. Provides details on certain specific risks to be managed (e.g. health and safety, loss of knowledge, technological obsolescence, project management risks, information technology risks). Recommends project risk management plans, workplace risk analyses, control and supervision of contractors and using risk analysis techniques as part of corrective action programmes	[38]

TABLE 57. IAEA INFRASTRUCTURE RELATED PUBLICATIONS (cont.)

Infrastructure area	Title	Publication No.	Risk message	Ref.
	Leadership and Management for Safety	Safety Standards Series No. GSR Part 2	This “establishes requirements for the responsibility for safety and for protecting people and the environment against radiation risks as an overriding priority” and indicates that “managers at all levels in the organization develop and maintain an understanding of radiation risks and potential consequences”, while “**The management system shall be developed and applied using a graded approach**” and requirements can be graded according to risk.	[17]
	Application of the Management System for Facilities and Activities	Safety Standards Series No. GS-G-3.1	Indicates that “Resources should be applied and focused where they are necessary on the basis of aspects such as safety significance and risks.” Gradation of risk processes should include those outsourced to other organizations Indicates that economic risk should (among other factors) be considered “In determining to what extent a process should be documented”.	[37]
Management	Development and Implementation of a Process Based Management System	Nuclear Energy Series No. NG-T-1.3	Identifies risk analysis as a fundamental step in preparing a business case for a process based management system. Provides an annex that addresses some aspects of risk management related to the implementation of process based management systems	[151]
	Use of a Graded Approach in the Application of the Management System Requirements for Facilities and Activities	IAEA-TECDOC-1740	Provides practical guidance to assist users of GS-R-3 (superseded by GSR Part 2) in developing and applying a grading method appropriate to the risks, complexity and significance of the activities of an organization	[152]

TABLE 57. IAEA INFRASTRUCTURE RELATED PUBLICATIONS (cont.)

Infrastructure area	Title	Publication No.	Risk message	Ref.
Funding and financing	Managing the Financial Risk Associated with the Financing of New Nuclear Power Plant Projects	Nuclear Energy Series No. NG-T-4.6	A lack of understanding of financial risk management by project sponsors may result in their failure to secure sufficient funding to allow their project to proceed. Given the large capital expenditures involved in NPP projects, managing the various risks that can lead to financial losses is key to project success. Perceived failure to mitigate and allocate risk effectively will ultimately lead to high and potentially prohibitive financing costs because funders will demand a higher return on the funds they commit to a project if they perceive that risks have not been mitigated and allocated appropriately	[28]
Funding and financing	Financing of New Nuclear Power Plants	Nuclear Energy Series No. NG-T-4.2	Provides options for both government and industry concerning nuclear power plant financing and risk mitigation for the government and industry. Risks related to the financing of a project include the composition and risk appetite of the investors (governmental and non-governmental), their debt paying and investment ability, and the potential for financial market changes (e.g. interest rate and exchange rate risks, the broader insurance market). The financing risk is influenced by the potential for project delays and cost overruns. The direct and indirect costs of delays can lead to legal disputes between the involved parties	[153]
	Issues to Improve the Prospects of Financing Nuclear Power Plants	Nuclear Energy Series No. NG-T-4.1	Describes mechanisms to reduce investment risks for NPP projects. These include political, legal and regulatory mechanisms, technical mechanisms, commercial and financing mechanisms, and contracting strategies. Insurance as a risk mitigation tool is discussed in an appendix.	[44]
	Financial Aspects of Decommissioning	IAEA-TECDOC-1476	Describes financial risk management topics related to decommissioning, including the risks of various contract types, structuring of decommissioning funds and the time over which they are accumulated, using safety analyses in supporting decommissioning planning and the use of proven decommissioning technologies	[137]

TABLE 57. IAEA INFRASTRUCTURE RELATED PUBLICATIONS (cont.)

Infrastructure area	Title	Publication No.	Risk message	Ref.
Funding and financing	Cost Considerations and Financing Mechanisms for the Disposal of Low and Intermediate Level Radioactive Waste	IAEA-TECDOC-1552	Discusses risk issues related to establishing waste management funds (risk of returns, liquidity, sharing of risks, ring fencing of funds). Recommends programme risk analysis to assess the risk and sensitivities associated with each cost item in the disposal of low and intermediate level radioactive waste	[154]
	Nuclear New Build: Insights into Financing and Project Management	OECD/NEA No. 7195	Provides details on the risk exposure of various investor groups based on electricity price scenarios and the impact of price volatility on nuclear projects	[155]
	Nuclear Power Economics and Project Structuring	WNA (2017 edn)	The report identifies the key risks associated with an NPP project and how these may be managed to support a business case for nuclear investment	[34]
Legal framework	Handbook on Nuclear Law	IAEA Non-serial Publications	A basic feature of nuclear energy legislation is its dual focus on the risks and benefits associated with operating NPPs. Protection against risk requires the complex questions of nuclear liability to be addressed. A comprehensive international legal framework has been developed to help address this	[156, 157]
	Handbook on Nuclear Law: Implementing Legislation	IAEA Non-serial Publications		
Safeguards	Guidance for States Implementing Comprehensive Safeguards Agreements and Additional Protocols	Services Series No. 21	Provides an overview of safeguards obligations of Member States. Involving the IAEA in incorporating safeguards requirements into nuclear facility design can reduce cost and schedule risks in incorporating them later	[92]
	International Safeguards in Nuclear Facility Design and Construction	Nuclear Energy Series No. NP-T-2.8	Involving the IAEA in incorporating safeguards requirements into nuclear facility design can reduce cost and schedule risks in incorporating them later	[93]
	International Safeguards in the Design of Nuclear Reactors	Nuclear Energy Series No. NP-T-2.9	Involving the IAEA in incorporating safeguards requirements into the design of NPPs can reduce cost and schedule risks in incorporating them later	[94]

TABLE 57. IAEA INFRASTRUCTURE RELATED PUBLICATIONS (cont.)

Infrastructure area	Title	Publication No.	Risk message	Ref.
Regulatory framework	Establishing the Safety Infrastructure for a Nuclear Power Programme	Safety Standards Series No. SSG-16	Provides actions to implement IAEA general safety requirements related to establishing the national safety infrastructure. Allows for the targets for regulatory control to be considered based on a probabilistic assessment of risks. Emphasizes the need to communicate the benefits and risks of nuclear energy	[144]
	Managing Regulatory Body Competence	Safety Report Series No. 79	Competence needs should be addressed in accordance with the perceived risk to the regulatory body's objectives and the overall importance of safety. Risk analysis and knowledge of PSA techniques are fundamental competences	[158]
Radiation protection	Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards	Safety Standards Series No. GSR Part 3	A comprehensive standard to address risks associated with radiation sources in various exposure situations	[159]
Electrical grid	Electric Grid Reliability and Interface with Nuclear Power Plants	Nuclear Energy Series No. NG-T-3.8	Risk analysis shows that the risk of station blackout is a significant contributor to the calculated core damage probability. NPP developers need to evaluate the risk of losing off-site power, while grid maintenance activities need a risk analysis. Provides some methods to reduce these risks	[160]
	Non-Baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operations	Nuclear Energy Series No. NP-T-3.23	Provides considerations regarding the economic viability of flexible operations and impacts on life cycle costs	[161]
Human resource development	Workforce Planning for New Nuclear Power Programmes	Nuclear Energy Series No. NG-T-3.10	Identifies that "Trying to develop national capability extensively during the project for a first NPP may create unacceptable risks in terms of time and cost." Identifies certain risks associated with recruitment, staff retention, knowledge loss and other areas	[162]

TABLE 57. IAEA INFRASTRUCTURE RELATED PUBLICATIONS (cont.)

Infrastructure area	Title	Publication No.	Risk message	Ref.
Human resource development	Managing Regulatory Body Competence	Safety Report Series No. 79	Competence needs should be addressed in accordance with the perceived risk to the regulatory body’s objectives and the overall importance of safety. Risk analysis and knowledge of PSA techniques are fundamental competences	[158]
	Managing Human Resources in the Field of Nuclear Energy	Nuclear Energy Series No. NG-G-2.1	Recommends “conducting risk assessments to determine the potential for loss of critical knowledge caused by the loss of experienced personnel; and to enable nuclear organizations to utilize this knowledge to improve the competence of new and existing personnel”. Identifies some error prevention techniques to minimize risks	[21]
	Commissioning of Nuclear Power Plants: Training and Human Resource Considerations	Nuclear Energy Series No. NG-T-2.2	Identifies potential risk areas related to training and human resources during the commissioning phase	[22]
Stakeholder involvement	Stakeholder Involvement Throughout the Life Cycle of Nuclear Facilities	Nuclear Energy Series No. NG-T-1.4	Public acceptability can be a significant risk for nuclear programmes, and the public may overestimate the inherent risk of an NPP’s operation. Proper communication is, therefore, a key determinant for public acceptability The public may have limited information or basic knowledge about nuclear energy. Individuals may worry about the development of nuclear energy. Various measures should be taken by government authorities and NPP owner/operators to enhance the population’s understanding and establish active and transparent communication with the public	[16]
Stakeholder involvement	Communication and Consultation with Interested Parties by the Regulatory Body	Safety Standards Series No. GSG-6	Identifies the importance of communicating the “**possible radiation risks associated with facilities and activities, and about the processes and decisions of the regulatory body.**”	[163]
	An Overview of Stakeholder Involvement in Decommissioning	Nuclear Energy Series No. NW-T-2.5	Decision making processes related to decommissioning are highly dependent on stakeholder involvement, significantly when risks and benefits are shifted over time	[58]

TABLE 57. IAEA INFRASTRUCTURE RELATED PUBLICATIONS (cont.)

Infrastructure area	Title	Publication No.	Risk message	Ref.
	Communication and Stakeholder Involvement in Environmental Remediation Projects	Nuclear Energy Series No. NW-T-3.5	There is a risk that environmental remediation projects will fail if they do not respect social, environmental, political and economic dimensions. This requires open, clear and mutually agreed communication lines among stakeholders within a well defined legal framework	[59]
Site and supporting facilities	Site Survey and Site Selection for Nuclear Installations	Safety Standards Series No. SSG-35	Identifies that there are risks associated with land acquisition and demolition work on previously used land. Recommends a demolition organization be set up	[41]
	Managing Siting Activities for Nuclear Power Plants	Nuclear Energy Series No. NG-T-3.7	Risks include safety related site risks (e.g. accidents or external events with radioactive consequences for people or the environment) and non-safety related site risks (e.g. equipment transportation risks, electricity market changes and public acceptance)	[42]
Site and supporting facilities	Site Evaluation for Nuclear Installations	Safety Standards Series No. SSR-1	“In determining the scope of the site evaluation, a graded approach shall be applied commensurate with the radiation risk posed to people and the environment.” “The population density, population distribution and other characteristics of the external zone, in so far as these could affect the feasibility of planning effective emergency response actions [reference omitted], and the need to evaluate the risk to individuals and to the population.” High impact, low probability events need to be evaluated as part of the screening process	[40]
Environmental protection	Managing Environmental Impact Assessment for Construction and Operation in New Nuclear Power Programmes	Nuclear Energy Series No. NG-T-3.11	Thorough analysis of environmental protection requirements and a sound legal framework reduces the uncertainty associated with the other project risks. Stakeholder involvement throughout preparation of the draft environmental impact assessment report can reduce the risk of major conflicts in later stages of public participation	[164]

TABLE 57. IAEA INFRASTRUCTURE RELATED PUBLICATIONS (cont.)

Infrastructure area	Title	Publication No.	Risk message	Ref.
	Strategic Environmental Assessment for Nuclear Power Programmes: Guidelines	Nuclear Energy Series No. NG-T-3.17	Risk analysis is a strategic environmental assessment method that focuses on assessing the strategic risks of different sites and associated technology options	[97]
	Regulatory Control of Radioactive Discharges to the Environment	Safety Standards Series No. GSG-9	Discusses planned exposures and practical considerations related to authorizations for radioactive discharges using a graded approach	[165]
Emergency planning	Considerations in Emergency Preparedness and Response for a State Embarking on a Nuclear Power Programme	EPR-Embarking 2012	Focuses on providing the public with a plain language explanation of the hazards in a radiation emergency, actions they can take to reduce their risk and actions being taken by officials on their behalf during a potential or actual radiation emergency	[166]
Emergency planning	Preparedness and Response for a Nuclear or Radiological Emergency	Safety Standards Series No. GSR Part 7	Covers protective actions and other response actions to avoid or minimize biological effects and risks to the public	[167]
	Arrangements for Preparedness for a Nuclear or Radiological Emergency	Safety Standards Series No. GS-G-2.1	Emphasizes informing the public and media in plain language of the risks and their actions during a nuclear or radiological emergency	[168]
Nuclear security	Establishing the Nuclear Security Infrastructure for a Nuclear Power Programme	Nuclear Security Series No. 19	Uses a graded approach to security risk management. Indicates that “The responsible competent authority should consult widely to help it identify threats to be considered in the national threat assessment and apply a risk informed approach to considering them” and that “The State should take action to ensure that risk management measures that are beyond the DBT and are the responsibility of the State are appropriately identified and action is taken by the State to manage these measures.”	[169]
Nuclear fuel cycle	Options for Management of Spent Fuel and Radioactive Waste for Countries Developing New Nuclear Power Programmes	Nuclear Energy Series No. NW-T-1.24	Discusses options for waste management and proliferation risk issues	[170]

TABLE 57. IAEA INFRASTRUCTURE RELATED PUBLICATIONS (cont.)

Infrastructure area	Title	Publication No.	Risk message	Ref.
Radioactive waste management	Options for Management of Spent Fuel and Radioactive Waste for Countries Developing New Nuclear Power Programmes	Nuclear Energy Series No. NW-T-1.24	Discusses options for waste management and proliferation risk issues	[170]
	Policies and Strategies for the Decommissioning of Nuclear and Radiological Facilities	Nuclear Energy Series No. NW-G-2.1	Discusses how decommissioning strategies have different associated major hazards and risks	[126]
Radioactive waste management	Policies and Strategies for Radioactive Waste Management	Nuclear Energy Series No. NW-G-1.1	A general aim in managing radioactive waste is to reduce the associated risks to as low a level as is practicable and justifiable through appropriate processing, containment and eventual disposal	[171]
	Disposal Approaches for Long Lived Low and Intermediate Level Radioactive Waste	Nuclear Energy Series No. NW-T-1.20	To satisfy the as low as reasonably achievable (ALARA) principle, measures necessary to reduce risk should be taken until or unless the cost of those measures, whether in money, time or resources, is disproportionate to the reduction in risk	[172]
Industrial involvement	Industrial Involvement to Support a National Nuclear Power Programme	Nuclear Energy Series No. NG-T-3.4	An increased level of desired localization for an NPP project can increase the project's risk profile, especially where the local organizations have little nuclear experience. Localization can involve technical development, labour force development, equipment manufacturing and construction	[87]
Procurement	Procurement Engineering and Supply Chain Guidelines in Support of Operation and Maintenance of Nuclear Facilities	Nuclear Energy Series No. NP-T-3.21	Procurement data needs for the operational phase are substantial and should be addressed as part of the contract language for the original NPP purchase. Addressing cybersecurity and counterfeit and fraudulent item risks requires special care	[11]

Appendix III

Examples of Engineering documentation related to NPPs

This appendix provides examples of engineering documentation required to construct and operate an NPP in Table 58.

TABLE 58. DOCUMENTATION EXAMPLES

Documentation group	Necessary to	Examples
System design	— Establish design criteria covering requirements, design parameters and codes and standards — Perform design functions that result in the detailed technical documents required for the specifications that set the requirements for system and component fabrication, installation and operation — Perform analysis required for licensing and performance — Establish design and interface requirements for supporting systems and equipment, which, if met, will allow the system to perform as required These activities are conducted for all functional disciplines for each major system in the nuclear steam supply system (NSSS) design scope	(a) Designs related to: (i) Fluid systems: (ii) Reactor coolant system (iii) Reactor cavity filtration system (iv) Chemical and volume control system (v) Safety injection system (vi) Shutdown cooling system (vii) Emergency feedwater system (viii) Containment spray system (b) Instrumentation and controls: (i) Plant control system (ii) Reactor monitoring system (iii) Plant monitoring system (iv) Plant protection system (vi) Advanced control complex (c) Mechanical system: (i) Reactor coolant system arrangement and support system (ii) Reactor refuelling system (iii) Multistud tensioner (iv) Special fuel handling tools (d) Support activities: (i) In-service inspection tools (ii) Safety analyses (iii) Performance analyses (iv) Material and chemical support (vi) Accident evaluations (vii) Normal operation, seismic and postulated pipe break analyses (i) Probabilistic safety analyses
Component design	Component design activities include all the necessary activities required to design the component so that the hardware will meet the system design specifications. Examples of these include: — The preparation of other requirements, such as QA, cleaning, painting and packaging of hardware	The major components of the NSSS, which may include: — Reactor vessels — Reactor internals — Pressurizers — Fuel channels — Calandria — Steam generators — Reactor coolant piping — Major component supports — Special tools

TABLE 58. DOCUMENTATION EXAMPLES (cont.)

Documentation group	Necessary to	Examples
	— The preparation of design drawings — The completion of support analyses, such as seismic, structural, thermalhydraulic and fracture analyses, which provide proof that the design will perform as required — The preparation of other requirements, such as QA, cleaning, painting and packaging of hardware	— Control element assemblies and drives — Reactor fuel assemblies — Special equipment — Reactor coolant pumps — Advanced control complexes
Balance of nuclear island and conventional island design	The design focuses on those systems and components of the balance of nuclear island (BONI) and conventional island (CI)	— Electrical system involving cabling layouts in containment, protective relays, raceways, switchgear and various BONI instrumentation — Mechanical systems consisting of NI auxiliary systems, main steam and feedwater, steam cycle systems, CI auxiliary systems, radwaste systems, service and chilled water and instrument supply air — Civil/structure design analyses — Heating, ventilation and air conditioning (HVAC) design and analyses of system requirements and layouts and components, ducting and supports — Fire protection system and hazards analyses for fire, missiles, etc. — Radiological design and analyses — Electrical design and analyses — Fuel pool and related systems
Fuel and core design	Fuel and core design consist of the various design and analysis activities to support performance verification, fabrication, setpoints and startup, licensing and fuel management for a broad range of fuel cycles using qualified computer codes and methodologies	— Generation of fuel cross-sections — Analyses, including seismic, of mechanical integrity under various core conditions — Startup test predictions and preparation of the core data — Fuel multicycle scoping analyses and refuelling designs — Testing and evaluation of fuel thermalhydraulic, mechanical and material attributes

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LIST OF ABBREVIATIONS

CI	conventional island
CM	configuration management
CNPE	China Nuclear Power Engineering
CPM	critical path method
DCS	digital control system
EPC	engineer, procure and construct
EVA	economic value added
EVMS	earned value management system
FCD	first concreting date
FME	foreign material exclusion
FOAK	first of a kind
GERT	graphic evaluation review technique
HSA	historical site assessment
HSE	health safety and environment
HVAC	Heating, ventilation and air conditioning
IMS	information management system; includes design management systems, procurement management systems and schedule management systems
ISI	in-service inspection
JSA	job safety analysis
LCOE	levelized cost of electricity
NCR	non-conformance report
NI	nuclear island
NPP	nuclear power plant
NPV	net present value
OLM	on-line monitoring
PERT	project evaluation review technique
PPA	probabilistic performance assessment
PSA	probabilistic safety assessment
QA	quality assurance
QC	quality control
RAB	regulated asset base
RCP	reactor coolant pump
RFP	request for proposal
RI-ISI	risk informed in-service inspection
SPV	single point vulnerability
SSC	system, structure and component
WBS	work breakdown structure

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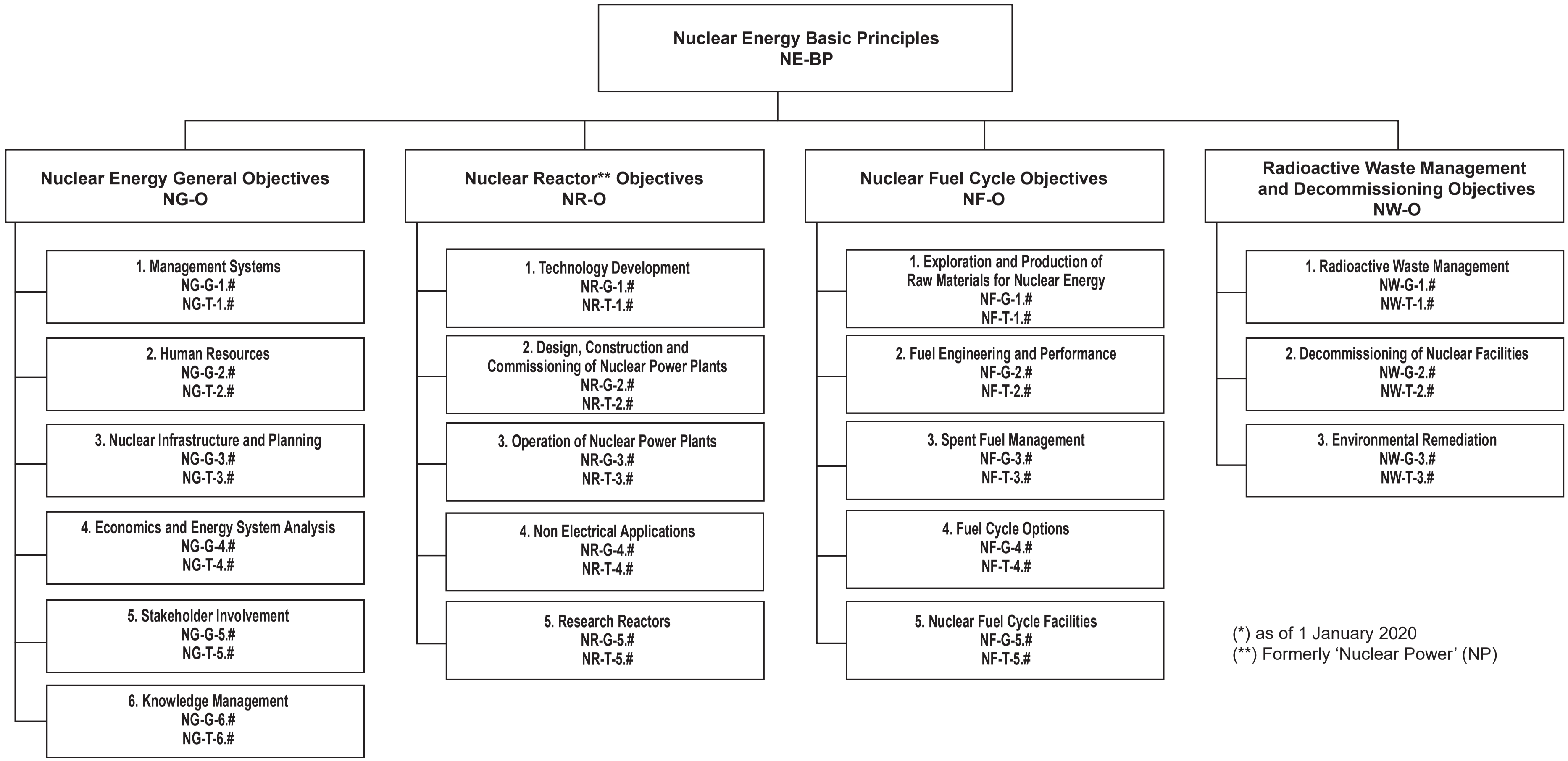

(*) as of 1 January 2020
(**) Formerly 'Nuclear Power' (NP)

Key

BP: Basic Principles
O: Objectives
G: Guides and Methodologies
T: Technical Reports
Nos 1–6: Topic designations
#: Guide or Report number

Examples

NG-G-3.1: Nuclear Energy General (**NG**), Guides and Methodologies (**G**), Nuclear Infrastructure and Planning (topic **3**), **#1**
NR-T-5.4: Nuclear Reactors (**NR**), Technical Report (**T**), Research Reactors (topic **5**), **#4**
NF-T-3.6: Nuclear Fuel (**NF**), Technical Report (**T**), Spent Fuel Management (topic **3**), **#6**
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