IAEA Nuclear Energy Series

No. NR-G-3.1

Sustaining Operational Excellence at Nuclear Power Plants

Principles and Challenges

IAEA
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IAEA NUCLEAR ENERGY SERIES PUBLICATIONS

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SUSTAINING
OPERATIONAL EXCELLENCE
AT 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-G-3.1

SUSTAINING OPERATIONAL EXCELLENCE AT NUCLEAR POWER PLANTS

PRINCIPLES AND CHALLENGES

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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.

Nuclear power plants play a vital role by providing a sustainable supply of non-carbon generated electricity. The safe and reliable operation of nuclear power plants is supported by advanced technologies and the continuous improvement of management practices. However, owner/operating organizations of nuclear power plants are facing critical challenges to their financial sustainability, particularly in competitive electricity markets, as well as decreasing or stagnating energy demand. They are now re-evaluating their business models, using more robust and resilient methods in their continuing efforts to meet the United Nations climate change goals as set forth in the Paris Agreement and to sustain operational excellence.

This publication provides nuclear industry leaders with guidance on sustaining operational excellence in a changing global business environment. Through the effective operation and management of nuclear power plants, the aim is to preserve the gains made in safety, performance and cost and to address the factors that affect these gains. In addition, this publication outlines steps to improve efficiency and performance, identifies potential barriers and proposes

actions to overcome those barriers in the quest for operational excellence at the plant, industry, national and international levels.

The IAEA officer responsible for this publication was A. Kawano of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Nuclear power plants have demonstrated improved performance in recent decades on account of management models and processes developed within the nuclear industry. Although nuclear power plants are operated as a stable baseload energy source, owner/operating organizations of nuclear power plants are challenged by higher upfront capital costs. However, they benefit from low operating costs and low emissions relative to other forms of baseload generation.

Nevertheless, the deregulation of energy markets, combined with low natural gas pricing and favourable treatment of wind and solar power generation, has narrowed or eliminated the benefit of low operating costs of nuclear power plants in many countries. The costs of nuclear power generation are driven primarily by labour and materials, with revenue affected by electricity market pricing and operational performance, including outage duration. Investments in long term operation and the implementation of necessary safety enhancements are also increasing costs. Owner/operating organizations of nuclear power plants are adapting business strategies to remain competitive, reduce production costs and increase the availability of energy and associated output.

A combination of enhancements in the human, technological, organizational and institutional aspects of nuclear power plant operations are therefore needed to address the challenges of sustaining operational excellence in the face of a changing global business environment. Business strategies include actions to ensure that cost reductions do not lead to a decline in performance. Efficiency gains need to be pursued through the harmonization of business functions and the use of innovative plant modernization (including data analysis and artificial intelligence); the reduction in the number of tasks; and the improvement of equipment reliability. Finally, policy makers need to be encouraged to recognize the contributions of nuclear power to a low carbon electrical grid.

The IAEA's Technical Working Group on Nuclear Power Plant Operations (TWG-NPPOPS) proposed the development of this publication to help the nuclear industry overcome the challenges posed by a changing global business environment.

1.2. OBJECTIVE

This publication aims to help owner/operating organizations of nuclear power plants become more efficient in their use of resources and more resilient

to a changing global business environment. It also aims to complement existing standards and guides on operational excellence [1–12].

This publication is targeted at senior executives of owner/operating organizations of nuclear power plants who are expected to make sound decisions to achieve and sustain operational excellence and to lead the response of their organizations to external challenges by championing actions within their own organizations; collaborating with other owner/operating organizations of nuclear power plants or through industry associations (e.g. Institute of Nuclear Power Operations (INPO), World Association of Nuclear Operators (WANO), reactor owners groups); and engaging key policy makers. The publication is applicable to operating nuclear power plants worldwide, particularly those that compete with other forms of energy. Newly constructed and soon to be operating nuclear power plants may also benefit from actions to preserve the original business case on which the project was developed and prepared for operation.

Owner/operating organizations of nuclear power plants do not operate in isolation, and sustaining operational excellence involves the participation and support of diverse stakeholders across various institutions. In this regard, this publication is also targeted at executives of other stakeholder organizations, to help them collaborate with, or otherwise engage as appropriate, the owner/operating organizations. These stakeholders include policy makers, regulatory bodies, vendors, designers, technical support organizations, and national and international industry associations. This publication is also intended to form a basis for the adoption of a consistent approach by owner/operating organizations of nuclear power plants, international organizations and Member States to facilitate collaboration and accelerate learning.

This publication assumes that a nuclear power plant and its owner/operating organization are already performing at high levels in their implementation of existing standards, guides and industry programmes. It is important that all aspects of maintaining a healthy safety culture are preserved, as described in many IAEA and industry publications (see, for example, Refs [13–15]). Leaders need to recognize that external factors and their own messaging or initiatives may have unintended negative outcomes that require monitoring to detect early signs of a decline in performance and any impact on the safety culture.

Finally, this publication describes areas that owner/operating organizations of nuclear power plants ought to examine or pursue and suggests actions. Many of the areas or issues addressed in this publication are topics in their own right. It is expected that owner/operating organizations of nuclear power plants or industry associations will utilize available resources and develop more detailed evaluations and a course of action.

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

1.3. SCOPE

The areas and actions that are described in this publication are intended to sustain and further improve the competitiveness and safety of nuclear power plants, owner/operating organizations of nuclear power plants, and the nuclear industry as a whole. They have been selected on the basis of experience gained from over five decades of nuclear power plant operation, demonstrated continuous improvement and international collaboration. The approach and scope have been developed and reviewed by the members and observers of TWG–NPPOPS.

This publication provides guidance for nuclear power plants and their owner/operating organizations already performing at high levels on how nuclear power plants can remain a safe and cost effective energy alternative in a portfolio of competing energy sources and a dynamic business environment. The best strategy for nuclear power plants that have not yet achieved operational excellence remains first to apply resources towards its attainment, as described in IAEA and industry publications [1–12].

Recommended areas and actions are prioritized to first prevent a decline in performance and then to establish a foundation for sustained performance by following the core principles discussed in Section 2. These principles provide an early ‘symptom based’ indication of precursors to a decline in performance, including as a result of unintended negative outcomes from messaging or initiatives by leaders. Suggested actions are provided to maintain these principles and detect changes. A publication issued by INPO [16] describes five core values common to nuclear power plants that have sustained operational excellence for extended periods.

Innovation, data sharing and supply chain harmonization are areas in which owner/operating organizations of nuclear power plants and/or industry associations can potentially improve both cost competitiveness and performance in response to market conditions and other competitive challenges. Efficiency can be enhanced by focusing on the following areas:

— Developing a culture of innovation;
— Optimizing performance through data sharing;
— Reducing costs through supply chain harmonization.

Suggested actions focus on broader industry collaboration in each area, the use of emerging technologies, and the leveraging of gains made in comparable or similar industries such as the aviation or oil and gas sectors.

Regardless of actions taken by owner/operating organizations of nuclear power plants, market pricing and regulation can still create conditions that result in the premature removal of nuclear power plants from service. Responding to misperceptions of the value provided by nuclear power plants, market conditions or policies that favour other forms of energy can help to address factors that could lead to the early shutdown of operating nuclear power plants. Engaging policy makers to promote the sustainability and expansion of the fleet of operating reactors can contribute to policies and market conditions that can impact future growth. Potential actions in response to the current nuclear environment are primarily external to owner/operating organizations of nuclear power plants, and therefore not detailed in this publication. Instead, several considerations are provided as starting points for engagement.

1.4. STRUCTURE

This publication consists of four sections in addition to this introduction. Section 2 discusses the principles that can contribute to a decline in a plant's performance and provides guidance on possible actions for mitigating such a decline. Section 3 describes the potential areas for improving both cost competitiveness and performance, lists the barriers to realizing results, and provides guidance on possible actions that can be taken by industry leaders to sustain operational excellence. Section 4 provides guidance on how to engage policy makers to sustain and expand the fleet of operating reactors. Section 5 summarizes this publication.

As shown in Fig. 1, the three main sections of this publication address activities that are completely within the control of the owner/operating organizations of nuclear power plants (Section 2); that involve interaction with closely linked stakeholder organizations (Section 3); and that involve interaction with all other stakeholders (Section 4). Together, the relationships and interactions between stakeholders are vital for sustaining operational excellence.

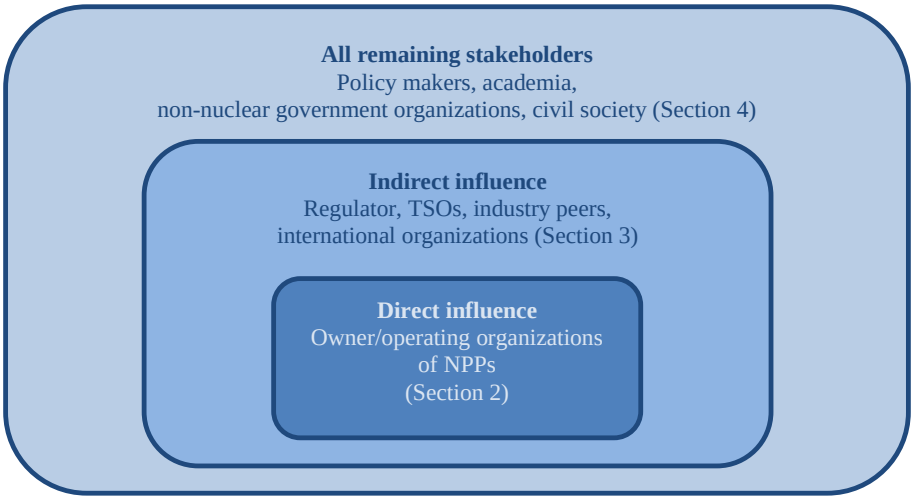

FIG. 1. Interrelations between stakeholders for sustaining operational excellence. NPP – nuclear power plant, TSO – technical support organization.

2. KEY PRINCIPLES TO SUSTAIN PERFORMANCE

The careful implementation by nuclear industry leaders of business strategies in response to a changing global business environment is necessary to preserve gains made in safety, performance and cost and to avoid a decline in performance. External factors and perceptions by personnel can also change behaviours, which may lead to a decline in performance. It is vital for leaders and managers at nuclear power plants to establish a system to monitor performance, and to take corrective action if early signs of a decline in performance are detected, in the following four core areas:

(1) Integrated plant knowledge;
(2) Culture for learning and performance improvement;
(3) Pride in one's profession and work;
(4) Reliability of the equipment.

This section discusses these areas, all of which have the potential to affect a plant's performance, and suggests actions for mitigating any decline in operational excellence.

2.1. INTEGRATED PLANT KNOWLEDGE

2.1.1. Background

A plant's performance can be affected if personnel in key positions do not possess an integrated knowledge of the plant's systems, equipment and management processes. Integrated plant knowledge refers to the ability to understand the interaction between the plant's systems and equipment, personnel performance, management systems or procedures and business decisions. A decline of integrated plant knowledge was highlighted as one of the causes of the 2011 accident at the Fukushima Daiichi nuclear power plant in Japan [17].

Integrated plant knowledge requires an understanding of the integration of business, technology and staff behaviour. It also requires the continuous development of personnel to enable better decision making. It is important that the policies for training, development and selection of staff be implemented holistically, with adequate indicators to gauge penetration across the entire organization. All staff, particularly leaders and managers, need to understand the basis on which important decisions are made.

2.1.2. Challenges that can lead to a decline in operational excellence

Many issues or challenges can trigger a decline in operational performance at a nuclear power plant. They include the following:

— The implementation of technical innovation and alternative business strategies can lead to reductions in staffing levels to lower costs. This can disrupt human resource planning, such as for recruitment, succession and knowledge transfer.
— The availability of skilled persons in specialized areas can be jeopardized by alternative business strategies to execute work processes (e.g. procurement), or an overhaul by external companies, or both.
— The need to respond to commercial market conditions may result in a realignment of the qualifications and positions of managers, from the board-room down through the organization, with a loss of focus on maintaining operational excellence.
— Investment in training, succession, recruitment and leadership development may be postponed or cancelled in order to maintain competitiveness.
— Leaders and managers might not take responsibility for ensuring that training is used as a tool for continuous performance improvements, which includes both personnel and facility performance.

2.1.3. Possible mitigating actions

A range of possible mitigating actions are available. They include the following:

— Prepare detailed long term staff plans and employee demographics and gain a detailed understanding of key competencies and knowledge. These are required to assist in planning for job rotation, recruitment, succession, collective agreements with trade/labour unions, purchasing agreements with suppliers of services and personnel, and collaborative agreements with universities, colleges and other industry groups.
— Ensure that training and empirical assignments include an integrated understanding of diverse aspects of the business, including human, organizational and financial aspects as well as technical bases.

2.2. CULTURE FOR LEARNING AND PERFORMANCE IMPROVEMENT

2.2.1. Background

In this publication, the term ‘learning’ refers to the act of acquiring and implementing knowledge to sustain or improve nuclear power plant performance. A culture for learning and performance improvement is key to sustaining operational excellence and increasing competitiveness. Station documentation (e.g. procedures, design documents) and training programmes are important indicators of embedded learning. Learning includes, but is not limited to, the following activities:

— Learning from station operating experience through an effective corrective action programme that captures the root causes of significant or notable events to ensure that they are not repeated.
— Learning from industry operating experience through the sharing of such experience or through benchmarking between utilities and between countries by industry associations (e.g. INPO, WANO, owners groups); by intergovernmental organizations (e.g. IAEA, OECD Nuclear Energy Agency); and by regulators.

Benchmarking and information exchange also provide an opportunity for nuclear power plant staff to detect early signs of a decline in operational excellence by gauging how their plant is performing relative to others. Furthermore, these

activities provide an effective means of strengthening networks, retaining knowledge across the industry and mitigating the loss of competence.

2.2.2. Challenges that can lead to a decline in operational excellence

Reductions in operating budgets and/or numbers of staff, if not carefully managed, can inadvertently have the following consequences:

— Reduced effectiveness of the station corrective action programme. Perceptions that the nuclear power plant cannot support improvements may result in any of the following:
  - A reduction in the number of reports on station events;
  - A reduced rigour in the evaluation of station events;
  - An increased likelihood of closing out corrective actions before they are fully implemented.
— Reduced attendance at information exchange forums and fewer benchmarking activities.
— Deferrals of staff training and/or deferrals in updating refresher training material.

2.2.3. Possible mitigating actions

A range of possible mitigating actions are available. They include the following:

— Ensure that communications relating to cost competitiveness from the senior leadership and line management include a description of where and how cost reductions will be made. This ensures that staff do not make decisions that have the potential to compromise a culture of learning and performance improvement.
— Provide reassurance that, despite economic pressures, senior leadership will remain committed to a culture of learning and performance improvement through a corrective action programme, benchmarking, information exchange and training.
— Develop and regularly monitor metrics to detect early signs of a decline in performance of the above mentioned processes and programmes essential for sustaining a culture of learning and performance improvement.
— Adopt the use of new training tools such as simulators, mock-ups and virtual reality and augmented reality applications. These will create variety and improve the effectiveness of training, and may even improve access to learning opportunities.

2.3. PRIDE IN ONE'S PROFESSION AND WORK

2.3.1. Background

One of the attributes of nuclear power plants operating at a high level of performance is the pride exhibited by all staff members in their professions and work. This includes looking for opportunities to improve and expand skills through day to day activities in the field; looking beyond the boundaries of specific tasks to develop a more integrated knowledge of station systems and equipment; and being personally accountable for work undertaken and the performance of assigned systems or equipment. Examples include the following:

— Operators, maintainers and those who support them exhibit pride in their profession by acquiring an understanding of the performance of the systems or equipment; developing a capability to recognize, during routine surveillance or maintenance activities, if equipment is not operating optimally; and initiating an action to have this corrected.
— Engineers exhibit pride in their profession by developing a detailed understanding of the design basis and safety basis of their systems and components and of the factors that influence operating margins in the near and long term; and by demonstrating accountability for the performance of the nuclear power plant.

2.3.2. Challenges that can lead to a decline in operational excellence

Plant management may decide to outsource maintenance, engineering or other activities traditionally performed by plant personnel to external technical support or service organizations. If not carefully managed, this has the potential over a period of months or years to erode an individual's professional skills in areas critical to operational excellence.

2.3.3. Possible mitigating actions

A range of possible mitigating actions are available. They include the following:

— Identify those staff positions and areas of maintenance, operation or engineering that are critical or vulnerable to reductions in personnel. If it is not practical to fill these positions internally, contracts with external service suppliers need to include provisions for retaining the skills of individuals in

their chosen profession, as well as a culture reflecting pride in the particular skill.
— Provide incentives to staff and ensure that they are invested in the success of their organization.
— Involve station personnel in activities that will help them to develop an understanding of the professional skills required for services supplied by external contractors. This will enable them to provide appropriate oversight of those services.

2.4. RELIABLITY OF THE EQUIPMENT

2.4.1. Background

Reliable equipment, comprising structures, systems and components, is the basis for the safe and reliable operation of nuclear power plants. A high level of equipment reliability is achieved by assigning the appropriate task, at the right time, with the required resources using well designed processes and programmes.

In the short term, one important means of ensuring equipment reliability is the prediction and discovery of incipient issues before they result in unexpected equipment unavailability. The skills of the operators, maintainers and engineers play an important role in predicting incipient problems, as discussed in Section 2.3. In addition, innovation using advanced technology can play an important complementary role by providing the capability for more intensive equipment monitoring, with longer trending intervals, using sophisticated analytical algorithms to correlate system parameters and establishing criteria to identify potentially anomalous equipment behaviour. The broader sharing of data, which could make these processes more reliable and support proper decision making, is discussed in Section 3.

It is also necessary to ensure that personnel maintain a long term view of equipment performance as opposed to seeking short term results. Expected actions include the completion of condition assessments of structures, systems and components to monitor long term ageing effects and the development of appropriate mitigation plans. Failure to perform such tasks has the potential to lead to unexpected and irreversible degradation that can adversely impact both the safety and sustainability of continued operation. Plans to mitigate ageing need to carefully consider all reasonable options, as well as the timing of their implementation, to ensure optimal costs and benefits.

2.4.2. Challenges that can lead to a decline in operational excellence

A number of challenges can have an adverse impact on the sustainability of operational excellence. These include the following:

— Avoiding first-of-a-kind implementation to preserve current results or avoid costs and risk.
— Deferring necessary initiatives. Cost pressures affecting current business results can drive business leaders to focus on the present at the expense of the future, and defer work required to economically sustain long term operation. If continued, the effect is compounding, resulting in a pattern of decline over time.

2.4.3. Possible mitigating actions

Actions to mitigate such a decline include the following:

— Collaborate with other owner/operating organizations of nuclear power plants on ways to implement robust maintenance programmes using better practices, advanced technologies, or improved surveillance shared across equipment and reactor types. A collaborative and detailed gap analysis of performance can present opportunities for improvement.
— Collaborate with other owner/operating organizations of nuclear power plants, possibly through reactor owners groups, to ‘de-risk’ first-of-a-kind projects by sharing the costs of the first implementation. For example, to improve performance and reduce implementation costs, CANDU owners shared the risks and costs of new fuel channels and fuel technology via the CANDU Owners Group.
— Collaborate, through industry associations or intergovernmental organizations, to develop a common methodology for analysing and defining thresholds for return on investment when making decisions on improvements using a graded approach [4] or when piloting implementation.

3. ENHANCING EFFICIENCY THROUGH INNOVATION, DATA SHARING AND SUPPLY CHAIN HARMONIZATION

Strategies for operating a nuclear power plant in a changing business environment were discussed and reviewed by experts from Member States at various IAEA meetings to select those most likely to result in transformative or significant improvements to performance. The following strategies were selected for plants that had been evaluated, utilizing industry programmes and standards, as already having achieved operational excellence. These strategies can also yield corresponding improvements to safety through gains in equipment and system performance, and by redirecting resources more effectively.

This section discusses the selected strategies of innovation, data sharing and supply chain harmonization. It also describes the barriers to obtaining positive outcomes and lists possible mitigating actions that can be taken by leaders.

3.1. DEVELOPING A CULTURE FOR INNOVATION

3.1.1. Background

Cultivating an organizational culture that encourages innovation can leverage ideas within the organization and use technology to improve both performance and safety. These applications of innovative ideas and new technology need to be supported by an organizational culture that values innovation and is nurtured by visionary leaders in the organization. Technological innovations applied to operating nuclear power plants, such as digital twins, robotics, Internet of Things and advanced materials, can be an important source of improved performance in terms of safety, reliability and economic competitiveness. For example, a digital twin applied to a nuclear power plant by collecting data from equipment at similar or identical plants and using machine learning will facilitate the emulation of correct plant behaviour. This use of digital information can contribute to the alleviation of unexpected failures and plant transients by providing early signs of equipment degradation or by revealing performance gaps.

Since most units of the current fleet of nuclear power plants were built in the 1970s and 1980s, many structures, systems and components were designed and manufactured using now obsolete technologies. This provides opportunities for efficiency oriented upgrades and replacement with innovative, cutting edge technologies. However, upgrades or replacement with new technologies can also

lead to challenges in terms of retrofitting existing structures, compatibility with older equipment, and workforce familiarity.

3.1.2. Potential barriers to innovation

Changing the way things are done and/or adopting new technologies in the nuclear industry require confidence building, both within the industry and the regulatory body, and regulatory acceptance. Regulatory uncertainty or reluctance to accept innovative solutions can inhibit efforts to adopt or invest in innovation.

Innovative technologies are possible only through investment in resources, both human and capital. However, over the past few decades, the nuclear community has become increasingly risk averse and has developed a fear of failure. An innovative approach to leadership is needed to change the current paradigm, as described in Section 3.1.3.

3.1.3. Possible mitigating actions

Leaders create a culture of innovation by fostering an environment in which ideas are welcomed, support to fully develop the ideas is available, and the organization is capable of implementing the ideas. Leaders can encourage ideas by managing business and technical risks and fostering an environment in which failures are anticipated and lessons are learned.

Innovation is required for the pursuit of excellence in a changing global business environment not only to remain competitive, but also to meet societal expectations such as decarbonization and assurance of safety. Leaders in the organization might consider the following actions to remove potential barriers:

— Nurture the organization’s culture for innovation and encourage new and innovative ideas for the pursuit of excellence in a changing global business environment. An essential element is to create an environment in which failure is an acceptable option (i.e. where the consequences of failure do not impact nuclear safety or have a significant effect on production).
— Engage in positive dialogue with regulators to create an avenue for early regulatory input, or increase regulatory certainty commensurate with investment. This may improve expectations for return on investment and decrease risk perception.
— Provide training and benchmarking opportunities to senior leaders on the broader aspects of operation in a competitive and changing global business

environment. Benchmark industry disrupters[1] and successful innovators. Strengthen leadership training in aspects relating to a culture of continuous improvement and innovation, collaborate with external innovator organizations, and provide corporate support for continuous improvement and innovation.

— Share information on existing or proposed organizational structures. This offers opportunities for leveraging gains made or seeking input on changes. Comparisons of the level of effort by business area, of organizational functions, or of roles across the industry or other industries may yield insights or opportunities for efficiency or collaboration. Harmonizing roles, documentation and organizational structures can improve the transfer of lessons and raise performance levels across the industry, and can also enhance the effectiveness of training.
— Share business plan objectives and organizational goals established by leaders within the nuclear industry and within comparable industries. This can challenge traditions and increase expectations.
— Identify and target necessary governance changes to facilitate adaptation and streamline business processes. Specifically, business plans might include and support innovation efforts and allow sufficient resources to manage risks or implement ideas.

3.2. DATA SHARING

3.2.1. Background

The use of digital systems in new reactors or existing system retrofits, as well as the use of business applications, has dramatically increased the quantity of technical, business and performance data collected by owner/operating organizations of nuclear power plants. To maximize opportunities for improvement, these data are ideally harvested and input into processes and programmes, rather than just collected. For example, monitoring and analysing a wide range of plant data through the use of digital technology may result in the need for less frequent maintenance, surveillance and calibration than originally recommended by the manufacturer.

[1] In this context, disruption is linked to an organization's ability to embrace potentially game changing innovation through, for example, risk management as opposed to risk avoidance, establishing innovation spaces with 'freedom to fail' cultures, and ensuring that failures are appreciated as learning opportunities.

Generally, owner/operating organizations harvest the data from their own organizations to identify and improve equipment performance or business operations. Higher level plant performance data have been collected and analysed by industry associations with good results. Furthermore, the detail of the data that are now being collected, along with innovations such as artificial intelligence that analyse data across the industry, provide a significant opportunity to harmonize operations and improve cost effectiveness while enhancing safety and reliability. Data sharing across owner/operating organizations of nuclear power plants and across reactor types facilitates collaboration at all levels of the organization. For example, trends, anomalies or performance gaps with regard to supply chain, plant operating performance and equipment can be more effectively identified and analysed. Data sharing can be promoted through the effective use of advanced technologies such as big data, artificial intelligence and digitalization.

The sharing of plant performance data between owner/operating organizations is limited to high level data and has not been successful in achieving essential outcomes, except where rigorous agreements exist (e.g. INPO plant performance). Despite the enormous potential, data sharing at an industry level is difficult and numerous barriers exist, as discussed in Section 3.2.2.

3.2.2. Potential barriers to data sharing

Factors that might obstruct or slow down data sharing include the following:

— *Access.* Controls on where data are to be housed, or accessed using a cloud approach, and on data format need to be supported by agreements. Export controls may prohibit the sharing of data between countries.
— *Security.* Unauthorized data access and use, or data corruption, are a risk to owner/operating organizations. Authorized access to a broader data set through freedom of information and regulatory privileges might result in the improper public disclosure of confidential business data. Such information could affect share price and the reputational standing of businesses, for example.
— *Competition.* Competition between owner/operating organizations may prohibit the sharing of certain data or can be a disincentive to sharing. Similarly, the ownership of intellectual property held by reactor vendors and suppliers may impede data sharing.
— *Costs.* A cost sharing structure is required to support data storage and analysis, unless each owner/operating organization performs its own data mining. Liability for data and results also needs to be managed.
— *Expectations.* The direction and expectations for analysis and reporting need to be consistent and agreed to by participants involved in the data sharing.

— *Perceptions.* Although sufficient controls can be established, perception of risks and a lack of awareness of capability or potential returns on investment can deter owner/operating organizations from participating.

3.2.3. Possible mitigating actions

Actions to enhance data sharing include the following:

— Take an inventory of current efforts by owner/operating organizations to find common direction and potential and then expand the data set available for those efforts. Later, efforts can be harmonized and agreement reached to broaden the analysis by industry associations based on common interests or potential return on investment.
— Reach an early agreement on file and data formats before an agreement on sharing. This can avoid future impediments should the data be used more broadly. As the data set expands, an early agreement minimizes or eliminates costs. The increasing capability of artificial intelligence may also reduce the impact of inconsistent data storage.
— Allow owner/operating organizations to maintain control of data. Instead of submitting data, it might be better to provide access to operator data sets through a centrally controlled group, with the results published 'blind' or accessible only through secure means by the relevant owner/operating organizations. This also allows owner/operating organizations to clearly delineate costs. Agreements can be established through existing organizations, such as industry associations or intergovernmental organizations, to meet business and regulatory requirements.

3.3. SUPPLY CHAIN HARMONIZATION

3.3.1. Background

Aside from the initial financing and decommissioning reserve, the ongoing cost of nuclear power is influenced by three main components: labour, materials and services, and fuel. Materials and services account for a major portion of operating costs, and sometimes represent up to one half of operating costs depending on the lifetime and activities of the plant. During plant life extension and refurbishments, they can represent the majority of costs.

Significant efficiencies can be gained by reductions in the overall cost of materials and services. Several factors contribute to inefficiencies in the supply chain, including the following:

— *Fragmentation.* Current approaches with suppliers are fragmented and specific to individual operators. The nuclear industry does not often leverage suppliers to lower costs or to improve quality through combined purchasing and demand.
— *Capacity of supply.* In certain cases, suppliers are exiting the industry owing to insufficient product demand. This further increases costs as modifications for equivalent parts are implemented. Global supply chains need to be established here.
— *Quality*. The decline in capacity of supply is leading to additional challenges with regard to quality. This includes requiring the qualification of substitute commercial products for use in safety related applications (e.g. seismic qualification and environmental qualification) and the avoidance of non-conformity and fraudulent products.

The optimization of the supply chain through the standardization and harmonization of design requirements, market rules and regulatory requirements can yield significant economic efficiencies and consequently improve operational safety and performance and increase benchmarking opportunities.

Other industries have overcome these challenges. For example, the aviation sector has common regulatory requirements for supply, components and service. A component procured and installed on an aircraft in one jurisdiction is accepted as being airworthy in another. Aside from the practicality of the arrangement, it also reduces operating costs. In the aircraft industry, type and airworthiness certification enables mutual recognition beyond jurisdictional boundaries. Supply chains in the aerospace industry have cooperative programmes through organizations such as the International Aerospace Quality Group and Performance Review Institute to ensure the supply of quality products.

Another example is the automotive industry. Vehicle manufacturers benefit from sharing parts from component manufacturers via network exchange services (e.g. ANX (United States of America), ENX Network (Europe), JNX (Japan)).

3.3.2. Potential barriers to standardization

Barriers to supply chain harmonization through standardization can be grouped into three main areas:

(1) *Design requirements.* Owner/operating organizations of nuclear power plants or designers are creating individual specifications for components, or services for components, that are identical or marginally different and capable of meeting the same fit, form and function. This results in the use of different suppliers or different product lines from the same supplier. In addition, designers are not specifying the use of commercial components nor defining alternative specifications commensurate with the risk. In some cases, this may be driven by regulatory requirements, but the absence of alternative and consistent quality requirements for commercial applications makes regulatory changes difficult.
(2) *Market rules.* Market rules or local industrial market policies can make procurement in outside jurisdictions cost prohibitive. For example, such rules or policies might require materials or services to be sourced within the utility's borders or commercial market; require justification to procure outside those boundaries independent of cost; and/or impose the application of penalties or tariffs or bidding practices.
(3) *Regulatory requirements.* Regulatory and quality acceptance documents are often required to be produced for each jurisdiction or country in which a part or service is used, regardless of whether the part or service is identical or has already been shown to satisfy the same or equivalent regulatory and quality requirements in the country of origin. Marginally different requirements or an application for acceptance in each jurisdiction often significantly increase the final cost over the production cost or prevent suppliers from strengthening their engagement with nuclear power markets. In some cases, identical parts procured and stored at one plant, even within the same jurisdiction, cannot be used at another plant without reproducing quality acceptance documents.

3.3.3. Possible mitigating actions

Actions to mitigate the impact of barriers to standardization include the following:

— *Design requirements.* Harmonize design requirements, material specifications and modifications for obsolescence to help reduce supply chain costs. This needs to be coordinated in the first instance within reactor

owners groups to be most effective. However, participation in international collaboration to establish a compelling basis to pursue solutions to barriers (2) and (3) described in Section 3.3.2 is important. Further harmonization is also possible across reactor types for common components, which could also be coordinated by reactor owners groups. Given the scope of the work, it is important that reactor owners groups first prioritize items according to spending data to maximize return on investment.

— *Market rules.* Seek changes or concessions to market barriers in the interest of both safety and the preservation of the nuclear supply chain. This could be pursued among Member States and, at their invitation, coordinated by relevant international organizations. The barriers first need to be identified. The anticipated cost impact and benefit of the proposed changes are then needed to underpin any future discussions to relax constraints by Member States. Given the difficulty of changing market rules in a coordinated way between Member States, it is more likely that the development of coordinated and optimal strategies by suppliers and operators within existing market rules would be a more cost effective approach (e.g. developing a justification that is shared by utilities for the procurement of high volume, lower cost components from a supplier that does not normally have access to the market).

— *Regulatory requirements.* Consider developing common regulatory standards, or accepting materials produced in another jurisdiction that meet a common standard, in order to reduce suppliers' costs. Currently, regulatory requirements are viewed as the individual responsibility of Member State regulatory agencies. Reactor owners groups can facilitate this by placing components that meet an accepted standard in a virtual warehouse that can be accessed by owner/operating organizations to purchase those components. Similarly, components that meet commercial or military quality requirements and that are installed in nuclear facilities can also be identified in a virtual warehouse for and across reactor types.

— *Learning from other industries.* Take opportunities to find practical solutions in these three areas by learning from other industries. In contrast to the fragmentation in the nuclear industry, networking, mutual recognition and cooperation in quality assurance take place in other industries, as described in Section 3.3.1.

4. ENGAGING POLICY MAKERS TO SUSTAIN AND EXPAND THE FLEET OF OPERATING REACTORS

4.1. BACKGROUND

According to the IAEA publication Climate Change and Nuclear Power 2020 [18]:

> "Global emissions of greenhouse gases (GHGs) have been increasing almost continuously since the start of the industrial revolution and have nearly doubled since 1970. The production and use of energy currently accounts for around two thirds of total GHG emissions, and electricity generation in turn accounts for one third of these energy related emissions. Emissions from the electricity sector are growing rapidly and have more than tripled since 1970."

In addition:

> "Low carbon electricity generation technologies have helped to avoid the use of significant quantities of fossil fuels. These technologies are estimated to have reduced direct power sector carbon dioxide (CO_2) emissions by up to one third over the period 1971–2018. After expanding rapidly from the early 1970s onwards, nuclear power has contributed substantially to reducing emissions, supplying close to 50% of low carbon electricity in the 1990s. Annual emissions would have been around 2 gigatonnes (Gt) of CO_2 higher over the past decade if electricity from nuclear power plants (NPPs) had instead been supplied using the average global fossil fuel generation mix. The IAEA estimates that over the period 1971–2018, nuclear power avoided a total of 74 Gt CO_2, equivalent to the cumulative emissions from the entire power sector for the six years from 2013 to 2018."

Considering the above, and with the prospect of an increase in the electrification of transportation, nuclear power can play an important role by supplying affordable, reliable and dispatchable low carbon electricity, complementing and supporting the deployment of other low carbon sources such as variable renewable energy technologies. The importance of including nuclear energy in an energy portfolio has become evident in recent years as it provides reliability and diversity to energy supply systems, strengthening their resilience to various events or system stresses.

Furthermore, future nuclear energy applications have the potential to support further fossil fuel substitution and decarbonization by providing low carbon high temperature heat (more than 500°C) to manufacture hydrogen.

The P3 scenario in the special report on global warming, issued by the Intergovernmental Panel on Climate Change (IPCC), projects global final energy demand to increase by 21% and electricity generation to increase threefold from 2010 to 2050, with nuclear electricity generation representing 25% of total generation of 62,400 TWh in 2050 [19]. This means investing in the long term operation of existing plants and initiating a major nuclear new build effort.

4.2. BARRIERS TO PROGRESS

Although the case for long term operation and nuclear new build is compelling, several factors are impeding progress, including the following:

— *Cost and schedule uncertainties*. Major nuclear projects, whether long term operation or nuclear new build, have often exceeded their initial schedule and cost estimates. On a positive note, lessons are being learned and many projects are now being completed on time and within budget. Important actions that contribute to this success include the following:
  - Reduce the scope and risks of the long term operation project by executing the project over many shorter outages;
  - Commence planning and preparation many years in advance of the scheduled start;
  - Ensure that the engineering for implementing long term operation or nuclear new build is fully completed before finalizing project plans and costs;
  - Secure all regulatory approvals and assurances early enough in advance of the scheduled start to provide regulatory certainty during execution.

— *Insufficient appreciation of nuclear baseload generation.* Recent weather events in various regions of the world have demonstrated the vulnerability of energy supply systems reliant largely on a single energy source or renewables. In contrast, nuclear power plants have continued to operate reliably despite significant weather events. The importance of ensuring energy security and system resilience through supply diversity is being increasingly acknowledged.

— *'Clean energy equality'*. In some energy markets, policy and market design do not reflect a technology neutral approach to valuing and remunerating different low carbon energy options. This has resulted in the premature

removal from service of top-performing nuclear power plants. Key to achieving that equality is a high level declaration that nuclear power is a low emission energy source.

— *A holistic energy policy.* The transition to a sustainable low carbon energy supply system requires a holistic energy policy and planning that fully recognizes the economic, social and environmental value of nuclear power and other low carbon technologies in the energy system, and that avoids expenditures that will not deliver climate and market pricing goals.

— *Decreased public recognition or confidence.* Gaining public acceptance of nuclear energy is becoming increasingly difficult:
    - The general public lacks an appreciation for the existing planning and financing of legacy issues for decommissioning, waste and spent fuel. Solutions for the safe storage of fuel have been in use for decades, and longer term storage facilities have already been constructed in some jurisdictions.
    - The general public has misperceptions regarding the significant positive impact of nuclear energy on the environment, especially with regard to its low carbon intensity ($gCO_2/kW{\cdot}h$) and its safety record relative to other forms of electricity generation.

— *Financing projects.* Financial modelling does not favour investment in nuclear power plants for the following reasons:
    - Although nuclear power plants might operate for a longer period of time, financial models are effective for periods shorter than actual life spans, after which revenue streams are discounted to zero.
    - Concepts such as energy security, intensity, density and diversity are not factored into financial modelling.
    - Excluding carbon pricing or capacity payment, the emissions free aspect is not priced.

  Considering these three reasons, as well as additional factors such as expected revenues from the price of electricity in a deregulated market and evolving regulatory requirements, it is becoming more difficult to secure financing for major nuclear projects.

4.3. POTENTIAL ACTIONS

While owner/operating organizations of nuclear power plants have a key role to play in addressing the predictability of project costs associated with long term operation and nuclear new build, other factors are influenced largely by government policy makers. A dialogue between policy makers, intergovernmental organizations and nuclear industry executives may help to identify actions to

resolve the current impasse over some of the issues discussed in Section 4.2. Industry associations could collaborate to align messaging and focus efforts on engaging key policy decision makers or influencers. Also, collaborative efforts to ensure that major projects across the industry are successful (and that these successes are publicized) will address many of the concerns associated with the reluctance to secure financing.

5. CONCLUSIONS

The need for collaboration and action to ensure that nuclear power plants that have achieved operational excellence respond to market conditions was recognized by the members and observers of the IAEA's TWG-NPPOPS. There are three main courses of action that leaders can pursue in response to the challenges faced by nuclear power plants:

(1) Prevent a decline in performance by ensuring that key principles for operational excellence are preserved. The principles selected in this publication are actual principles observed in nuclear power plants that have experienced a decline in performance from an excellent level or have received remedial measures. This is a symptom based strategy that responds to early indications of decline within the plant regardless of external causes. Taking action to ensure that these principles remain robust, and applying the measures described in INPO, IAEA and industry publications [1–12, 16], can guard proactively against external pressures and performance declines.
(2) Increase collaboration between owner/operating organizations and in the nuclear industry to implement the changes necessary for improving the efficiency and cost effectiveness of nuclear power plants. Potential areas of focus for the further improvement of plants that have already achieved operational excellence include supply chain harmonization; sharing and mining of plant performance data; and developing a culture of innovation. Collaboration among industry leaders is needed to improve performance beyond the levels that individual owner/operating organizations of nuclear power plants achieve if they leverage these areas alone. Establishing links between reactor owners groups or other industry groups and focusing on selected high leverage areas will provide early returns on investment by delivering benefits or avoiding pitfalls.
(3) Inform policy makers of the reliability and contributions to energy diversity that nuclear power plants offer and the resilience that they deliver to an

energy supply system. Convince them that nuclear energy is a low emission energy source within the context of climate change goals. This will require a coordinated and collaborative effort by industry leaders to develop and deliver consistent and clear messaging to key influencers, policy makers and regulators. Efforts are needed to support the future development of nuclear power plants, to secure investment for long term operation and to avoid scenarios in which nuclear power plants — despite achieving operational excellence or improving cost effectiveness — are no longer viable and have to be shut down.

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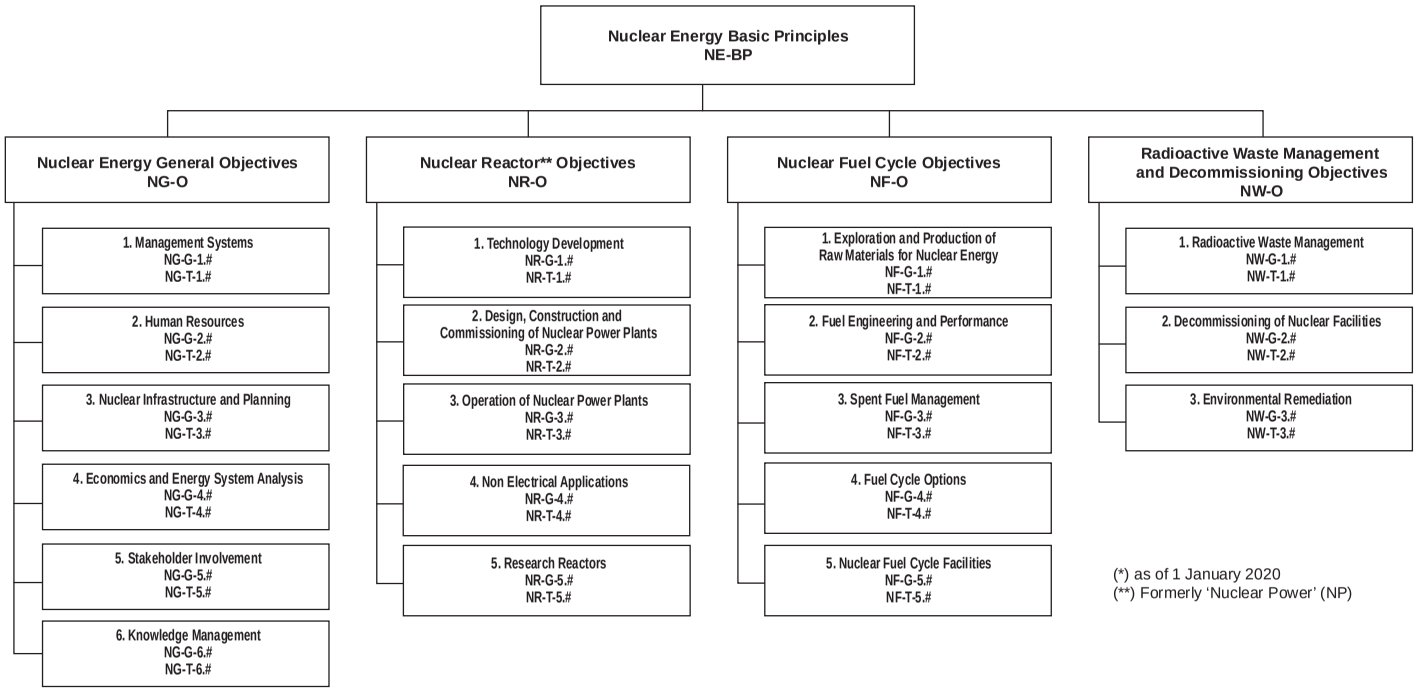

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Complementing existing standards and guides on the operational excellence of nuclear power plants, this publication supports leaders of owner/operating organizations by providing strategic responses to current business challenges and effective measures to sustain high performance levels. The publication considers activities that are under the control of the owner/operating organization as well as those that involve interaction with other stakeholders such as regulatory bodies, industry peers, international organizations, policy makers and academia.

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