WORLD NUCLEAR ASSOCIATION

Lesson-learning in Nuclear Construction Projects

Title: Lesson-learning in Nuclear
Construction Projects
Produced by: World Nuclear Association
Published: April 2018
Report No. 2018/002

Cover image: Georgia Power Company

Contents

Executive summary

There are many examples from around the world of nuclear construction projects that have progressed well, especially in countries with a wealth of recent experience, knowledgeable vendors, and a pool of skilled workers. However, there have been several recent cases where lengthy hiatuses in new build have undermined the capability of the nuclear supply chain. Significant delays and project cost escalation have occurred in some well-publicized instances, threatening those projects' ultimate completion and eroding the appetite for building further nuclear power plants. The purpose of this report is to help the nuclear community take advantage of the lessons learned and contribute to the preception of nuclear power among policy-makers, regulators and civil society.

In reviewing lessons from recent projects, the World Nuclear Association's New Build Lesson-learning Task Force has concluded that vendor capability and experience, important as these are in achieving high performance, must be supplemented by excellence in project management, driven from the start by the asset owner and the project's sponsor.

One of the main lessons from the Asian experience is that nuclear power plants have been built on time and budget because the project is managed well and much of this is attributable to collaborative working relations. A collaborative or partnership approach will enable a wider set of procurement strategies to be employed and facilitate team working and knowledge sharing.

Incentives are an important contributor to ensuring the interests of key stakeholders are aligned and the project risks are allocated fairly and effectively. The right package of incentives can motivate the key stakeholders to resolve problems as they arise while discouraging obstructive behaviours that are designed primarily to limit the parties' individual liability. Standard contractual arrangements may not be sufficient to ensure this and appropriate procurement arrangements and project delivery models are needed to support such a mode of collaborative working.

Comprehensive planning within a collaborative approach will reduce the inherent uncertainties associated with complex nuclear projects. It requires the project manager to gather all relevant parties together to share their knowledge. Vendors should be brought into the planning process at an early stage. If, because institutional knowledge has been forgotten or is not available (because, for example, it is a first-of-a-kind project), then the asset owner must allow more time for the design and construction process. Lesson-learning and a commitment to continual improvement, to prevent mistakes recurring, will be bolstered by a strong culture of safety at the project.

Wider stakeholder engagement with local communities and taking an accommodative approach towards local community concerns will remove the potential of the project to generate opposition.

Participants in the new build lesson-learning task force

David SLEDZIK (Chair)	Vice President Product Management & International NPP Projects, GE Hitachi Nuclear Energy
Charles POTTER (Vice-Chair)	Director, Reactor Operations Support, UK National Nuclear Laboratory
Antônio MÜLLER	Director, Associação Brasileira para Desenvolvimento de Atividades Nucleares
João Carlos DERZI TUPINAMBÁ	Associação Brasileira para Desenvolvimento de Atividades Nucleares
Fernando HENNING	Executive Vice President, Associação Brasileira para Desenvolvimento de Atividades Nucleares
Aninda DUTTA RAY	Senior Nuclear/Mechanical Engineer, AMEC Foster Wheeler
Shengke ZHI	AMEC Foster Wheeler
Nicole DELLERO	Senior Strategic Marketing Manager, AREVA
Jean-Noel LACROIX	Vice President International Affairs, AREVA
Armand LAFERRERE	Senior Vice President, Commercial Development, AREVA
Tomás VYTISKA	ČEZ Group
Sylvain HERCBERG	Director of Technology Prospective, EDF
Xavier POUGET-ABADIE	Executive, Nuclear Engineering Division, EDF
Melanie SACHAR	HPC Project Delivery Model Lead, EDF
Maksym NEZHURA	Section Head, International Cooperation Department, Energoatom
Ioana NEAMU	Licensing Safety & Operations Manager, Engie
Barry CULLIGAN	Senior Manager, Nuclear Commercial, Koeberg, Eskom
Sadika TOUFFIE	Senior Manager, Koeberg, Eskom
David POWELL	Vice President – European region, Nuclear Plant Sales, GE Hitachi Nuclear Energy
Shailesh SETH	Vice President – Digital, Nuclear Power Projects, GE Hitachi Nuclear Energy
Yasunori SOTA	Project Manager, Hitachi Europe
Ivor SHEPPARD	Commercial Director, Horizon Nuclear Power
Rafael JIMENÉZ LOPEZ	Director, Nuclear Fleet Sustainability Program, Iberdrola Nuclear
Simon EMENY	Global Head of the Nuclear Services and Inspection Division, Lloyd's Register
King LEE	Nuclear Product Development Manager, Lloyd's Register
Hideharu ZAISHO	Engineering Manager, Nuclear Plant QA, Mitsubishi Heavy Industries
M Vann MITCHELL	Consultant, Mitsubishi Heavy Industries
Milton CAPLAN	President, MZ Consulting
Edward KEE	Nuclear Economics Consulting Group
Stephen WOODS	Overseas NEIL
Fred GATTE	Underwriter, Nuclear Risk Insurers
Elina TEPLINSKY	Partner, Pillsbury Winthrop Shaw Pittman
Richard DARTNELL	Legal Director, Pinsent Masons

Will HARRISON-CRIPPS	Assistant Director, PricewaterhouseCoopers
Alexey ALTYNOV	Chief Commercial Officer, Rusatom Overseas
Alexander BOLGAROV	Head of Licensing & Technical Regulation, Rusatom Overseas
Anton MOSKVIN	Vice President Marketing & Business Development, Rusatom Overseas
Tatiana RAKITSKAYA	Rusatom Overseas
Alexander RENEV	Chief Technology Officer VVER, Rusatom Overseas
Ilya SESYUTCHENKOV	Head of Marketing, Rosatom International Network
Oleg SIRAZETDINOV	Director, Equipment Procurement & Supply, Rusatom Overseas
Kuan-Shen CHIANG	Department of Fuels, Taiwan Power Company
Takashi AISAKA	Project Manager, Toshiba International (Europa) Ltd.
Hideki NISHIYAMA	Group Manager, Third QA Group, Toshiba Corporation
Yusuke SUZUKI	Quality Assurance Planning, Toshiba Corporation
James HARRIS	Managing Director, Turner Harris
Mika LIANG-PRICE	Development Manager Asia-Pacific, Turner Harris
Celia A SPENCE	Sustainability Director, Westinghouse Electric Company
David VARNER	Vice President & Chief Procurement Officer, Westinghouse Electric Company

Secretariat

Greg KASER	Staff Director – Supply Chain, World Nuclear Association
Kangjun LEE	Visiting Research Officer (seconded from KEPCO), World Nuclear Association
Shah Nawaz AHMAD	Senior Adviser, India, World Nuclear Association
Henri PELIN	Senior Adviser (seconded from EDF), World Nuclear Association

Other organizations

Richard COACKLEY CBE	Director of Energy Development, AECOM
Don WARD	Chief Executive, Constructing Excellence
Tina TAYLOR	Electric Power Research Institute
Berta PICAMAL VICENTE	Executive Advisor, FORATOM European Atomic Forum
Marco COMETTO	Analyst, Nuclear Development, OECD Nuclear Energy Agency
Geoffrey ROTHWELL	Principal Economist, Nuclear Development, OECD Nuclear Energy Agency
Nima ASHKEBOUSSI	Senior Project Manager, Nuclear Energy Institute
Suzanne PHELPS	Director of Fuel Cycle Programs, Nuclear Energy Institute
Chris SAVAGE	Vanbrugh Consulting and UK Nuclear Industry Association

1 | Introduction

The rate of at which nuclear power plants are built must be increased in order to meet the goal of a low-carbon economy – according to the World Nuclear Association's Harmony vision. The necessary investment in nuclear energy will not be forthcoming unless the expectations of project sponsors are met. This means completing the construction and commissioning of the plant on schedule and within budget.

Recent experience has shown a general shortening in the length of time for completing a nuclear power plant project, as is evident from Figure 1. There have nonetheless been a number of well-publicized cases where projects have not been completed to schedule or budget and impaired the reputation and viability of the companies concerned. As capital-intensive projects, the economics of nuclear energy may be compromised severely by schedule delays.

In North America and Europe especially, the long intervals between nuclear power plant projects meant that the supply chain lost the knowledge and experience it had acquired and needed to re-gain proficiency in the rigorous quality management that the nuclear industry demands. Suppliers also had to reinforce their safety culture in order to meet new regulatory and utility requirements and expectations. Reactor vendors were forced to raise the level of supplier oversight and review their procurement arrangements as supply issues arose, which added significantly to the costs of some recent projects.

The scale and scope of nuclear power plants have grown as a result of escalating regulatory and utility requirements, which, along with political pressures, impact the project's complexity. In a review of recent construction experience, the Nuclear Energy Agency summarized the problem as "managing complexity in a changing environment."[1] These cases are not unique to the sector and 'mega-projects' have a history of being hard to manage and expensive to complete.

A Task Force on New Build Lesson-learning was set up in 2015 by the World Nuclear Association to collate and review the issues that contributed to construction delays and cost overruns and to draw out the lessons for good project management practice. The World Nuclear Association sought examples of case studies from amongst its members and reviewed published material. The task force analyzed and discussed these findings over the course of several meetings. Good practice from other industries was also reviewed.

This report presents an analysis of these findings to obtain a better understanding why some projects can go awry and why others go well. It complements work undertaken by the UK-based Royal Academy of Engineering and by Constructing Excellence on improving productivity in design, engineering, procurement and construction of nuclear projects. Taking advantage of lessons learned will contribute to lowering the costs of construction and improving nuclear technology's reputation among policy-makers, regulators and civil society.

Figure 1. Average nuclear reactor construction times (months)

Source: World Nuclear Association, IAEA PRIS

[1] NEA, 2015, *Nuclear New Build: Insights into Financing and Project Management*, Paris: OECD-NEA: p. 11.

2 Good project management in nuclear construction

Terms highlighted in orange are defined in the Glossary

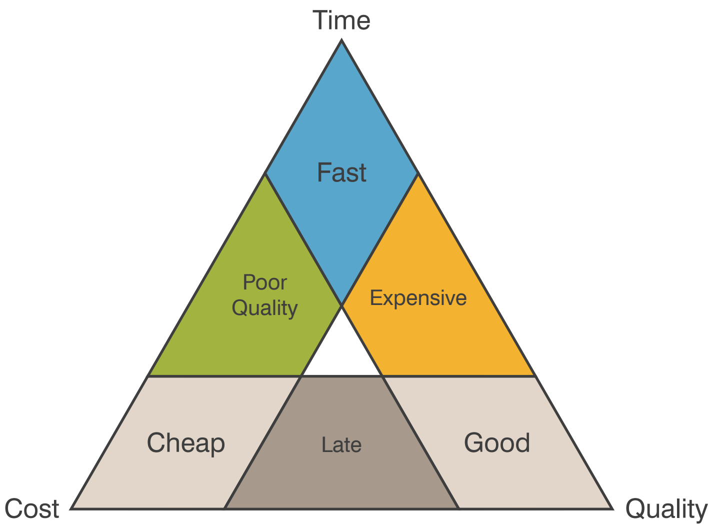
Ideally a project is completed quickly and at the lowest cost whilst ensuring the highest product quality. In practice it is commonly accepted that this is not easy to accomplish and there is a risk that one or more of these three goals may have to be sacrificed (see Figure 2).

Nuclear power plants are capital-intensive projects with a lengthy timescale for licensing, development and construction. These capital costs must be financed by the project sponsor. Projects are therefore very sensitive to any construction over-runs, as this increases the amount of interest payable before any revenue is generated. In the case of a nuclear power plant, a key consideration is safety in operation and this implies that the quality of manufacturing and construction must be of an exceptional standard.

The scope of the project must be clearly defined and should incorporate the aims of the key stakeholders, which should be identified and negotiated at an early stage in the project. Since the scope of the project has to be defined in relation to the aims of the key stakeholders, these have to be identified and negotiated at an early stage. This should limit design complexity and reduce the risk that any design inconsistencies lead to non-conformity further along the supply chain. Figure 3 illustrates how these factors – quality, scope, cost and schedule – interact and add to the project's complexity and risks to completion.

The risks of delay and budget overrun are especially significant in first-of-a-kind (FOAK) engineering projects. They have also arisen as novel techniques are employed, such as modularization. The costs can escalate exponentially as the project management organization tries to resolve multiple inconsistencies while manufacturing and construction are underway. Excellence in project management thus entails hitting the 'sweet spot' without compromising safety and quality or relaxing either the budgetary constraints or the schedule.

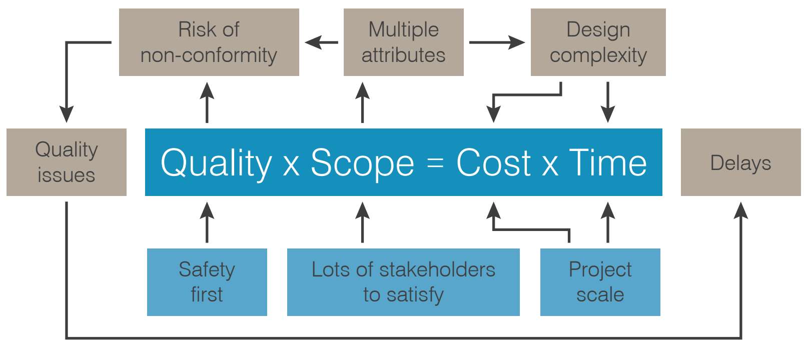
Figure 2. The triple constraints of project management[2]



[2] Adapted from Milton D Rosenau, 1984, *Project Management for Engineers*, Belmont, CA: Lifetime Learning Publications: p. 13.

[3] See IAEA, 2016, *Maintaining the Integrity of Nuclear Installations throughout their Operating Life*; A Report by the International Nuclear Safety Advisory Group, INSAG-19, Vienna: International Atomic Energy Agency: paras. 5, 10 and 12; World Nuclear Association, 2015, *Design knowledge and design change management in the operation of nuclear fleets*, London: World Nuclear Association: pp. 3-4; and World Nuclear Association, 2017, *Implementation of the Design Authority within a Nuclear Operating Organization*, London: World Nuclear Association: pp. 6-8 and 15-17.

Figure 3. Drivers of project cost overrun and delay



Adopt a collaborative approach

The regulatory environment under which a nuclear power plant is designed, built and operated imposes a relatively unusual distribution of responsibilities among the organizations undertaking the project. The sponsor of a nuclear power plant project is often a utility, which contracts with the reactor technology vendor and other key suppliers to undertake construction, and then takes over the plant at its commissioning. However, this is not always the case, and the investors can establish a special purpose entity, in which the utility may have a stake, to act as the project's sponsor and manage the construction and commissioning.

Utilities are understandably reluctant to take on the risks associated with design approval and construction but they will become, nonetheless, the operators and often assume ownership of the asset on the project's completion. The utility will have usually specified particular requirements that the design must meet for operation. Moreover, as an 'intelligent customer' the sponsor must supervise the project management organization, even if this is contracted to an engineering, procurement and construction (EPC) company. In addition, by the time the plant is handed over for operation, the operator must have the capability to act as the design authority to maintain design integrity and preserve design knowledge over the lifetime of the plant.[3] The utility, as the licensee for operation, often assumes design authority in a staged process as the works are completed. In doing so, the utility takes over the as built design and accepts the plant as ready for operation.

Although the reactor vendor is responsible for the design of the nuclear reactor itself, once it is under contract to the project sponsor, the reactor vendor is simply considered by the regulatory authority to be a 'responsible designer'. The project sponsor's architect-engineer, who is usually the designer for architectural, structural, mechanical and electrical, and landscaping elements of the project, is also deemed to be a responsible designer. The formal separation of asset owner, the project sponsor, its contractors, and the licensed operator introduces a series of interfaces between organizations which must be managed in order to ensure that the design knowledge is ultimately taken over by the plant's operator. It implies that the operator needs to understand the whole project design process, including any changes made during construction, well in advance of assuming design authority for the plant's operation.

The relationship between the project sponsor, the technology vendors, the architect-engineer and the future operator is therefore a partnership where risks are managed through collaboration. The contracts between these top tiers must reflect their interconnected responsibilities and mutual reliance upon each other for navigating the regulatory hurdles to project completion.

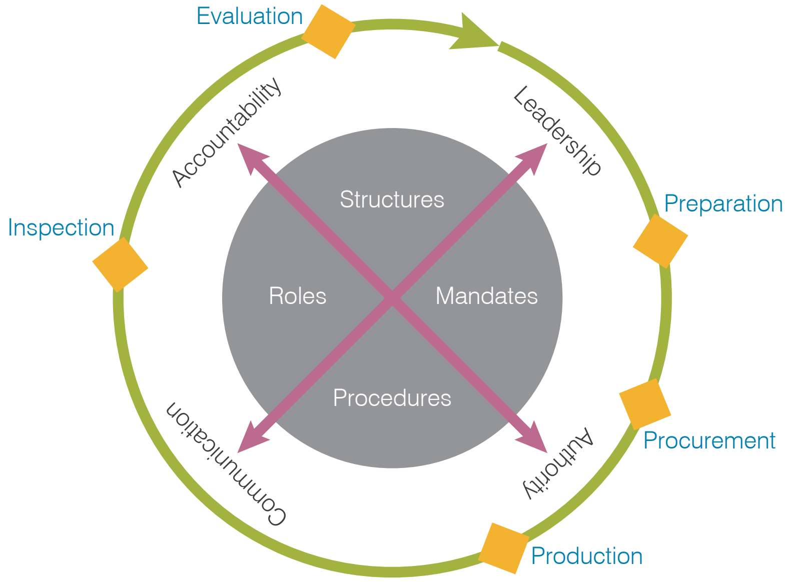
Organize the project to secure resources at the time they are needed

Good project governance provides well-founded, clear and timely decisions and accountability to stakeholders, and will help secure the sponsor's objectives. It demonstrates compliance with laws, regulations and other requirements, and respects basic rights and ethical principles. Processes for ensuring leadership, delegating authority and securing accountability, and for communication must be supported by institutional arrangements, including mandates, organizational structures, roles and responsibilities, and procedures (see Figure 4).

Among the procedures are standards and controls, which ensure that the requisite level of performance is achieved. A common set of tools and methodologies will ensure that activities can be tracked and accountability is maintained.

Project execution relies upon the sufficient and timely availability of resources: human, financial, technical

Figure 4. Project governance architecture



and natural. But resources enter the project as 'pre-packaged' goods and services (Figure 5). The human resources inputs arrive as labour services, as already trained and qualified workers under contract as direct employees or through a service providing organization. Financial resources are procured under covenants with banks, or as internal funding secured from the issue of corporate bonds, and so on. The different forms that resources come in mean that they are not fungible. This means that they cannot be substituted for one another but must be managed as distinct contributors to a portfolio of capability. There are limits to the extent that workers from different trades can be used flexibly for a range of tasks, for example, and this has important implications for productivity.

It is generally recognized that productivity in construction tends to be lower than manufacturing productivity. Construction projects present greater diversity than a manufactured product that has come off a production line. Usually a factory has a stable workforce who can learn and develop to do things better. The drive to achieve higher productivity through multi-skilling, standardization, lean production, just-in-time delivery, modularization and rigorous quality control is more advanced in manufacturing although its application to construction has been demonstrated in Japan in particular.[4] Enhancing productivity in nuclear construction has been recognized as essential and the World Nuclear Association has joined with Constructing Excellence, a UK-based industry body, to promote the concepts and tools needed.[5]

Involve key suppliers in comprehensive planning

The complexity of project management can be lessened by improving the quality of knowledge, thereby reducing uncertainty, and by broadening the areas of stakeholder agreement. Acquiring and applying knowledge is an important factor in the effective management of all mega-projects. Involving key stakeholders in a comprehensive planning exercise brings in the knowledge which they possess and

[4] See World Nuclear Association, 2014, *The World Nuclear Supply Chain: Outlook 2030*, London: World Nuclear Association: pp. 149-150 and 165-166.

[5] Constructing Excellence, 2017 (forthcoming), *Construction Factory Thinking: Ideas for responding to the productivity challenge*, London: Constructing Excellence.

[6] Constructing Excellence and Nuclear Industry Association, 2011, *Japan's Nuclear Construction Industry: Report of the UK Study Tour in March 2011*, Watford: Constructing Excellence: p. 18.

[7] See Engineering the Future, 2010, *Nuclear Lessons Learned*, London: Royal Academy of Engineering.

Figure 5. Sequence for product realization

will help the project management organization address the inherent complexity of the project.

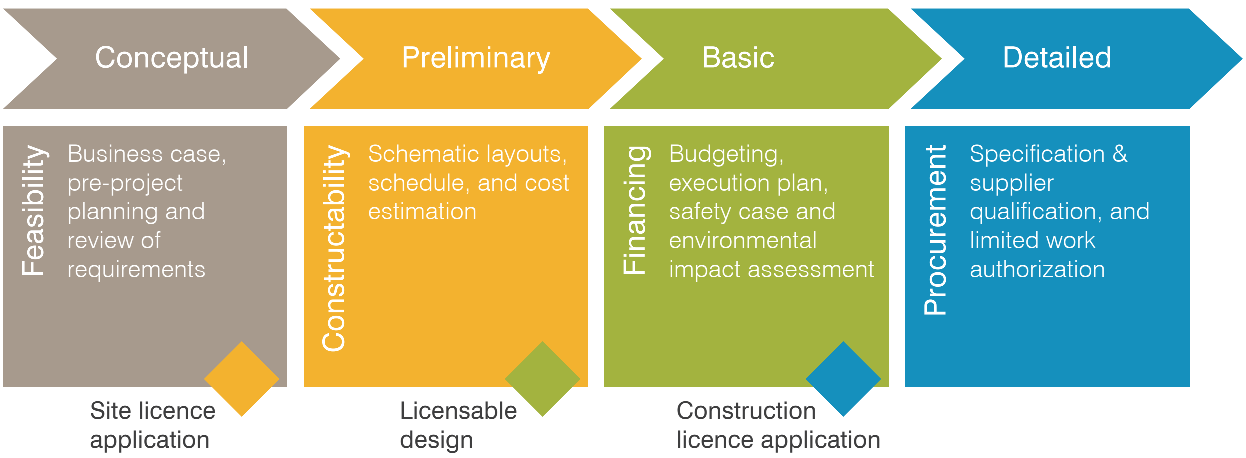
The comprehensive planning involving key stakeholders that is undertaken in the Japanese construction sector has resulted in some of the fastest build times for nuclear power plants in the world. About one year is spent in construction planning before construction starts in collaboration with the supply chain.[6]

The benefits of thorough and detailed planning apply particularly to the phasing of design, engineering and procurement. The phase-gate model has proved useful in the engineering construction industries generally, whereby the project is divided into stages with clear criteria established at each 'gate' to allow review before progressing to the next stage. An illustration of how this can be applied to nuclear power plant projects is shown in Figure 6.

Initially a utility must review the reactor vendor's conceptual design and assess whether this meets regulatory and its own requirements. If it is not an already licensable design, the utility will need to agree with the reactor vendor on any design changes needed. Some safety regulators provide an early design assessment process to give the project sponsor greater assurance that the design can be licensed, as is the case in Canada and the UK for instance. The sponsor's final investment decision will usually be taken on receipt of the construction licence, by which time the detailed design should already have been completed. Project delays have arisen when the sponsoring utility has submitted a preliminary design to the safety regulator that has not been sufficiently worked out to provide the basis for the safety case needed to obtain a construction license. Delays have also been caused when the sponsor has authorized construction to commence without finishing the detail design.[7]

Some of these difficulties arose because the reactor vendor was constrained financially and could not undertake the design work fully until receipt of the design and build contract from its customer, the utility, who, in turn, sought a fixed price for the project. As a result the utility embarked upon a project with an immature design and inadequately specified scope of work. In theory the fixed price insulated the project sponsor from bearing the additional cost of unforeseen work. In practice the contractual arrangements shifted responsibility for project completion onto the technology vendors without providing a means through which the project risks could be addressed.

Figure 6. Stages in the design and engineering of a nuclear power plant project



Allocate project risks through appropriate procurement strategies

Contracting creates relationships between the key stakeholders and thus provides a framework to manage the disruptions that are inevitable along the critical path. But contracts may also create obstacles to project management if incentives are misaligned and an inappropriate project structure is adopted. A standard engineering and construction contract, like those issued by FIDIC[8] or the International Chamber of Commerce, assumes that variations can be managed by negotiation or third party arbitration and that penalties in the form of liquidated damages – which are capped at a fraction of the contract price – will exert sufficient pressure on the main contractor and its suppliers to maintain the schedule. These are suitable where the risks can be defined and allocated between the parties. However, where the parties are operating in a complex environment these assumptions may be invalidated. The tendency for claims and counter-claims to escalate in value well beyond the contracted price creates an untenable situation in which the relationship between the parties may break down and there is a risk that one or other side will abandon the project altogether. Alternative forms of contract have been adopted for mega-projects in the UK (including a nuclear project) to allow project partners to share risks and rewards.

A collaborative or partnership approach should allow the sponsor's project management organization to access the knowledge held by key stakeholders during the design and planning processes. It will enable a wider set of procurement strategies to be employed and facilitate team working on the project through an integrated project management structure. Adequately resourcing the project management organization and ensuring good communication across interfaces are also necessary.

Uncertainty about the future cannot be eliminated altogether so there exist residual risks that are by their nature not amenable to estimation but must nevertheless be managed by the sponsor.[9] Risks that can be estimated are priceable and thus financeable so it is in the sponsor's interests to reduce the degree of uncertainty by as much as possible.

Align the interests of key stakeholders

Complexity reduces when the interests of key stakeholders are aligned. Key stakeholders include the owners, the investors and bankers, the operator (the licensee), the regulators, the staff and contractors, and the customers. Ensuring that suppliers fulfil the expectations of the licensee and the regulators without intrusive (and expensive) supervision will be assisted if interests are aligned properly. Such close supervision of suppliers can be time-consuming and will tie up the resources of the quality management and engineering staff.

Aligning the interests of key stakeholders can be achieved in many ways. In some countries the utility and the reactor vendor are members of the same corporate group. In others, a project sponsor may establish a special-purpose entity in which the reactor vendor is a shareholder along with the intended long-term asset owner. Governments could also take a shareholding in the special-purpose entity to secure long-term investments in reliable energy supplies to the country. Once the plant is operating, the reactor

[8] International Federation of Consulting Engineers (Fédération Internationale des Ingénieurs-Conseils).

[9] World Nuclear Association, 2017, *Nuclear Power Economics and Project Structuring*, London: World Nuclear Association: pp. 29-30 and 34.

[10] World Nuclear Association, 2017, *Nuclear Power Economics and Project Structuring*, London: World Nuclear Association: p. 40.

[11] World Nuclear Association, 2014, *The World Nuclear Supply Chain: Outlook 2030*, London: pp. 150-151.

[12] McKinsey & Company; 2016, *Imagining construction's digital future*, Singapore: McKinsey & Company.

operator and the government can sell their shares in the special-purpose entity. No nuclear power plants have yet been built as stand-alone merchant plants through a project finance model because the regulatory and construction risks have proved to be so hard to control.[10]

In the first instance, nuclear power plant projects must meet challenging regulatory requirements and sometimes inconsistent expectations from decision-makers and communities. These factors will impact on the scope of the project's design and the quality of manufacturing and construction to be achieved. They in turn will drive up the complexity and risks associated with the project. To manage a project effectively asset owners must build relationships with key stakeholders to limit uncertainty, and thus be in a position to control the risks.

Incentivize contractors

Key stakeholders require incentives to ensure a high level of performance is maintained but contractual arrangements may not be sufficient and adopting a collaborative way of working will bolster these relationships. Lower tier suppliers can be incentivized through early completion bonus payments or targeted cost saving clauses (and penalized through the imposition of liquidated damages in case of delays). Nonetheless, and depending upon the criticality of their inputs, some suppliers may also need to be brought into the project management team and a stable relationship with the project sponsor/EPC company will help ensure this.

Collaboration will give critical suppliers a voice in project planning; it also implies that they will share in the project's construction risk.[11] If the technology vendor or the EPC company places too much emphasis on an externalized procurement strategy, especially if this is combined with a threat to buy elsewhere if the supplier does not reduce its prices sufficiently, then, inevitably, the supplier will not be motivated to become a project partner. Identifying just who are the critical suppliers and choosing the appropriate procurement strategy is therefore of great importance.

Communicate expectations along the supply chain

Some projects have encountered technical and managerial interface issues. Technical interface issues arose during project execution as a result of design inconsistency or ambiguity. Managing interfaces between organizations and between activities could also be disruptive. FOAK projects are especially vulnerable to technical interface problems but the complexity of the project means that this will remain a source of disruption to the critical path and the necessity for re-work is difficult to eliminate altogether. Interoperability can be improved if the design is accessible to all key stakeholders and there are clear and workable procedures to introduce design changes well before project execution begins. Common procedures for work execution will also reduce the risk of interface issues arising and these must be negotiated and prepared in advance.

The risk analysis should categorize the activities carrying the largest risks to project fulfilment. The procurement strategy should then form part of the risk mitigation plan. Processes where a fixed price can be agreed may be identified, while contracts permitting the supplier supplementary resources on a basis of reimbursement of time and materials (subject to a cap and by agreement with the project management organization) if difficulties arise can be used where the riskiness of the activities warrant it. Well-defined expectations regarding performance need to be set by the project management organization and the lines of accountability and communication must also be clear.

The licence conditions appertaining to a nuclear project require the project sponsor to demonstrate that the plant's structures, systems and components will function under potentially extreme conditions and therefore suppliers must show they have adhered to strict quality standards during manufacture and construction. The stringency of the quality control measures applied by suppliers to critical processes should be commensurate with the risk to safety posed by the product according to a graded approach. It is important that the sponsor and the top tier vendors provide suppliers with sufficient information on the safety significance of their product so that resources are used effectively and to avoid unnecessary cost escalation.

Deploy digital tools and establish a controlled construction environment

Digital tools such as Building Information Modelling and open system platforms allow teams to collaborate more easily and preserve information. Project management has moved from using spreadsheets and stand-alone software tools towards integrated platforms that provide real-time information spanning design, planning, procurement, manufacturing, construction, commissioning, operation, maintenance, and decommissioning.[12] These tools will assist the utility to take on its role as the design authority.

Pre-assembly of components in the factory has helped avoid unexpected problems arising on site later. Modular construction techniques are used and temporary structures shelter site and installation works at the nuclear island.[13] There is general acceptance within the industry that performance and conformity are improved if work is undertaken in a controlled sheltered environment.

Engage with stakeholders in the community

International experience indicates that concerned citizen groups target specific sites and investments in order to mobilize support for their point of view and make an impact on the national political scene. Such tactics exploit the tendency within a local community to worry about risks that they feel are being imposed upon them without consultation or compensation. Organized citizen groups can become the main source of information on a project or incident and as the news media is duty-bound to report all sides of the story, distortions may spread widely and exacerbate fears. Gaining public confidence, then, involves tackling the local anxieties first and foremost, and realizing that concern over 'safety' is the sign of dissent, not necessarily its cause. The main driver of opposition may well be locally-rooted opposition to the impact of the development itself, rather than generalized fears over the safety of the facility.

Extensive stakeholder engagement with local communities and taking a genuinely accommodative approach towards local community concerns will reduce the potential for the project to generate opposition.

A collaborative or partnership approach should allow the sponsor's project management organization to access the knowledge held by key stakeholders during the design and planning processes. It will enable a wider set of procurement strategies to be employed and facilitate team working on the project through an integrated project management structure. Good interface management and internal project communication; the establishment of enduring collaboration with key stakeholders; quality control and supplier oversight; and human performance improvement will enrich the relationships between key stakeholders. Adequately resourcing the project management organization is also necessary.

[13] Constructing Excellence and Nuclear Industry Association, 2011, *Japan's Nuclear Construction Industry: Report of the UK Study Tour in March 2011*, Watford: Constructing Excellence: pp. 8 and 18-19.

3 Capturing lessons

Information is not the same as knowledge. It must be processed and codified by the knowledge management system to be used intelligently in an organization. An organization's knowledge management system must be able to create, share and use the information and experience gained from its activities and that of others.[14]

A key success factor is therefore the quality of knowledge, as already mentioned. Planning at the start of a project may be impaired if, for example, there is a lack of knowledge about how the supply chain operates in practice or about the aims and interests of external stakeholders (i.e. the local political representatives or sections of the community).

If the client side of the project (investors, sponsor, operator) is poorly informed it may not be able to act as an intelligent customer. Close collaboration and a trusting relationship between the project sponsor and the Tier 1 partners are essential to unlocking the knowledge and capabilities of lower tier contractors. On the contractor/vendor side, lack of knowledge due to inexperience in working outside of its 'comfort zone' or usual 'domestic' arena can hamper performance, especially on an international project where teams have been drawn from a wide range of backgrounds.

Fostering a culture where established practices and thinking can be questioned has been recognized as important for safety. A questioning attitude and openness are not necessarily disruptive since learning can reinforce good practices. An organization can learn from its successes that it is doing things right just as much as from incidents which indicate something has gone wrong. Celebrating good performance is as important as correcting problems for ensuring that there is continual improvement. A project culture (including safety culture) that spans the many organizations involved should be promoted by the project sponsor.

While the nuclear industry has gone a long way towards establishing mechanisms for capturing and sharing knowledge through the promotion of a culture of safety and learning, this has for the most part involved operational experience rather than construction experience. Other industries have already pioneered the application of digital technologies to assist in design and engineering and the nuclear industry is now taking strides in this direction. Digital platforms for managing construction and manufacturing are developing rapidly. For many nuclear service companies, those good operational practices are already embedded in their management systems and are available for deployment in managing project complexity. The industry must transfer this good knowledge and management practice to the nuclear supply chain in order to achieve exceptional performance in manufacturing and construction.

Regarding the regulatory authorities, the construction experience (ConEx) program at the Nuclear Energy Agency offers regulators some guidance on the scope of their oversight and the sort of checks they should undertake during a project. At this point, the NEA ConEx database is the only platform where construction experience is gathered systematically.

High performance depends upon organizational and individual capability, but also on a willingness to improve, in order to prevent mistakes recurring. Lesson-learning is part of this process and will be bolstered by a strong culture of safety.

[14] See Harry Scarbrough, J Preston and Jacky Swan, 1999, *Knowledge management: A literature review*, London: Institute of Personnel and Development: p.1; and Shan L Pan and Harry Scarborough, 1999, Knowledge management in practice: An exploratory case study, *Technology Analysis and Strategic Management*, 11, 3: p. 360.

4 Benchmarks for successful project delivery

Taking account of the best performers and when organized correctly, it should be possible to complete projects within 120 months or less (see Figure 7). A construction period of 50 months from the pouring of the concrete for the nuclear island base mat until grid connection may be achievable with n^{th}-of-a-kind (NOAK) designs and uninterrupted experience as a result of repeat ordering. In Figure 7 it is assumed that construction takes 70 months, which approximates to the average construction period for 90 percent of the 600 reactor units built over the past 60 years: 71.8 months.[15]

These targets are achievable and learning the lessons from recent construction project experience will help developers bring forward new projects with a high degree of confidence that the project will remain within its budget and schedule.

A collaborative approach will permit key stakeholders to put in the requisite effort to plan the project down to its last detail. But it takes time and has to be paid for up-front. If, because institutional knowledge has been forgotten or is not available (because it is a first-of-a-kind project), then the project sponsor must be realistic and allow more time for the design and construction process.

Conceptually, collaboration and sharing knowledge can be combined with what management consultants PwC has suggested are the critical success factors for project execution:

- Planning and governance;
- Standards and controls;
- Human resource management;
- Project funding.[16]

These 'building blocks' can be combined into a table that summarizes the lessons learned (Table 1). The complexity of nuclear construction projects calls for a team whose interests are aligned (relationships), who understand what has to be done (knowledge), and who can draw upon the necessary technical, human and financial resources.

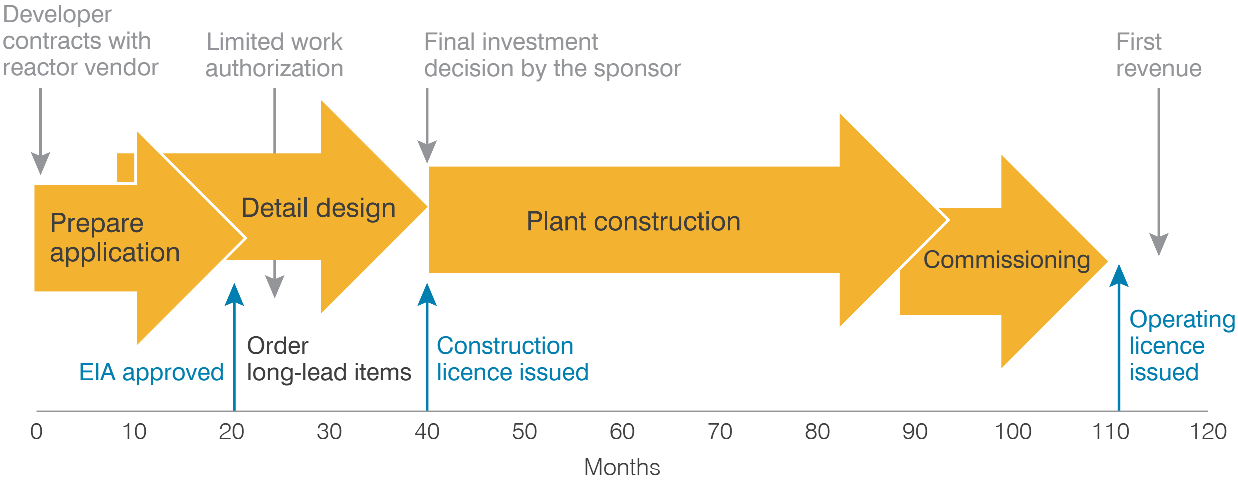
Lastly, it has to be recognized that project risks cannot be eliminated altogether. The time-quality-cost trilemma is not entirely under the project sponsor's control since the quality goal is determined ultimately by the regulatory bodies. The risks associated with nuclear power plant projects – including regulatory, project delivery, operational and market risks – can be mitigated through good project management, planning and partnership. All such risks must be allocated to the appropriate stakeholder in the best position to take on and manage that risk, and often this will be the project sponsor through insurance and contingency provisions. Given the intractable nature of uncertainty, it may be desirable, in some situations, for the government or the energy market regulator to permit cost-recovery arrangements or provide loan guarantees in order to attain national energy security through a diverse portfolio of energy technologies, which includes nuclear.

This wider picture is important. Competitive pricing of electricity offers consumer benefits but customers expect an uninterrupted power supply and not simply cheap supply. Market authorities need to take notice of this in establishing energy markets. Unfortunately the

[15] Excludes the 10 percent of exceptionally delayed projects due to political factors; see World Nuclear Association, 2016, *World Nuclear Performance Report*, London: World Nuclear Association: p. 19.

[16] PwC, 2012, *Projects without Borders: It's all about execution*, London: PricewaterhouseCoopers: p. 21.

Figure 7. Typical project completion schedule



EIA: Environmental Impact Assessment

market design in some countries has created a potentially unreliable electricity supply system. Short-term wholesale energy markets have had to be fixed by setting up additional markets for spare stand-by capacity and other grid stability services. Capital-intensive projects find it difficult to recover their investment unless season-ahead markets or other long-term electricity pricing arrangements exist. Such arrangements will enable the project sponsor to obtain financing at commercial rates. Leadership on the client side by the project sponsor to assemble a coalition of public, private and civil society partners to argue for an appropriate energy market design is thus crucial to underpin the successful completion of nuclear power plant projects.

Table 1. Main lessons for nuclear power plant projects

Dimensions of complexity	Governance, design and planning	Standards and controls	Human resource management	Financial resource management
Management of relationships with key stakeholders	• Licensee possesses capability to independently verify that licence requirements are being met • Integrated management system (including active interface management) • Common vision • Empowerment of project management organization • Collaborative contractual relationships • Commitment to resolving social and environmental issues	• Licensee ensures that the scope of the project is well-defined at the outset • Effective and timely communication in quality control processes • Phase-gate process with well-defined milestones • The flow-down of requirements to suppliers should follow a graded approach and be properly supervised	• Attention to conflicting priorities • Open reporting of non-conformances and risks • High level of employee engagement • Celebration of good performance	• Project preparation needs to be funded by the project sponsor • Contingencies should be allocated in line with the responsibilities for managing risks • Graded approach to supplier oversight will focus resources on critical processes
Quality of knowledge (reducing uncertainty)	• Design and engineering apply a proven technology • Front-end planning, engineering and design • Basic design to incorporate stakeholder knowledge • Risk assessment • Cautious localization	• Regulations and guidance are understood • Project design is licensable • Well understood quality management system • Proven methods of working	• Wide understanding of the importance of safety culture • High and sustained level of human performance encouraged	• Project preparation needs to be funded by the project sponsor

5 Recommendations

By applying lessons learned the nuclear industry can meet the expectations of asset owners, other investors and vendors to prepare and deliver nuclear power plant projects effectively and avoid the pitfalls. The main recommendations from this review of lessons learned may be summarised as follows:

- **The asset owner is ultimately responsible** for managing the project. The asset owner sponsors the project and should supervise all stages of the project. The sponsor must act as the 'intelligent customer' and oversee the transfer of design authority to the licensed operator.
- **Comprehensive planning** to reduce the inherent uncertainties and broaden the area for stakeholder agreement will help the project management organization address project complexity. The project sponsor should engage with customers, project partners and local community representatives in defining (and controlling) the project's scope and in preparing a practical and comprehensive project execution plan.
- **A collaborative or partnership approach** should allow the project management organization to access the knowledge held by key stakeholders during the design and planning processes. Vendors should be brought into the planning process at an early stage.
- **A well-organized project will secure resources** at the time they are needed. Project execution relies upon the sufficient availability of resources: human, financial, technical and natural. Good project governance provides well-founded, clear and timely decisions so that resources can be procured and deployed on time.
- **An appropriate set of procurement strategies** should be employed to facilitate integrated team working on the project, help ensure collaboration in execution, and address the risks inherent in mega-projects. Risks should be allocated to the parties in the best position to take on and manage them.
- **Incentivize** key stakeholders, including project partners and vendors, to ensure a high level of performance is maintained.
- **Wide and multi-stage stakeholder engagement** with local communities and taking a genuinely accommodative approach towards local community concerns will reduce the potential of the project to generate opposition.
- **Deploy digital tools** to design and plan the project comprehensively in advance of execution.
- **Controlled construction environments** will help achieve high levels of quality as will off-site pre-assembly of modules and raise productivity.
- **Communicate high expectations** according to a graded approach for quality along the supply chain. The project sponsor should encourage the transfer of good practice, including knowledge management, along the supply chain in order to achieve exceptional performance throughout nuclear manufacturing and construction.
- High performance depends upon on a willingness to improve, in order to prevent mistakes recurring. Lesson-learning is part of this process and will be **bolstered by a strong culture of safety**.

Ultimately it is the project sponsor who must guide the project to its completion.

Glossary

The following terms are used in this report:[17]

Activity: A unit of work with four characteristics: 1) defined duration; 2) logical relationship with other activities; 3) transformation of inputs into outputs; 4) a measurable cost in terms of resources consumed and money. It is an alternative term for a task.

Collaboration: A collaborative or partnership approach to working can take different forms but must be based upon a shared culture to be successful in a commercial environment. The vision and values of the project sponsor should shape the project's culture and governance, guide partner selection and thus frame the contractual relationships between the key stakeholders. Clear rules should be established for resolving issues and for disengagement in the event of a breakdown of relations.

Complexity: The complexity of a project varies according to the number of interconnections between the activities necessary to deliver the project's goals which are undertaken by autonomous agents who are accountable to different authorities for their performance.

Critical path: The longest sequence of activities that must be finished on time for the project to be completed by its due date. An activity on the critical path cannot be started until its predecessor activity is finished and if it is delayed the project is delayed (unless the subsequent activity is completed faster than planned).

Design authority: The licensed operator of a nuclear power plant has the responsibility and authority for approving and maintaining the licensing basis of the plant, including design changes, and for ensuring that the requisite knowledge is established, preserved and extended with operating experience. The licensed operator is responsible for any changes to the plant's design and licensing bases throughout the plant's lifetime. The reactor vendor normally retains proprietary design information and is known as the responsible designer.

Goal: The goals of the project are its desired results. Goals are normally specific, measurable, achievable, relevant and time-bound (SMART). The interests of the key stakeholders in the project will normally determine the goals set for the project.

Graded approach: A regulatory approach to controlling a process under which the stringency of the control measures applied is commensurate with the risk to safety.

Interoperability permits the exchange of information at interfaces between systems, between activities or between stakeholders.

Knowledge differs from information in that it is contextual, that is to say, it exists in relation to a field (or family) of ideas that are related to one another. This field is sometimes called a paradigm, that is, a set of theories that guide a person or an organization's actions. New knowledge must fit into an existing paradigm of knowledge to be useful. From time to time, in science, new knowledge leads to a 'paradigm shift' and a novel way of looking at the world emerges.

[17] Adapted from the Business Dictionary (http://www.businessdictionary.com/definition/) and IAEA, 2007, *IAEA Safety Glossary: Terminology used in Nuclear Safety and Radiation Protection*, Vienna: International Atomic Energy Agency at <http://www-pub.iaea.org/MTCD/publications/PDF/Pub1290_web.pdf>.

Knowledge management is the process of creating, acquiring, capturing, organizing, preserving, sharing and utilizing knowledge to enhance learning and performance in organizations. An organization has both tacit and explicit knowledge at its disposal, but in order to be a learning organization it must be able to communicate its reserves of tacit knowledge to people joining it or to external organizations.

Learning is the process of acquiring knowledge or modifying existing knowledge from observations and experience. Learning is a key attribute of an organization that can adapt and manage change.

Licence: An authorization from a regulatory body to perform specified activities. The holder of a license is a licensee. The project's 'social licence' is granted if the project's stakeholders give their consent to the specified activities.

Mega-project: A large and complex infrastructure project.

Outcome: The results from putting the product into use. The electricity generated by an operating nuclear power plant is an outcome of the construction project.

Performance: Performance describes the extent to which the planned activities are accomplished and/or the goals of the project are achieved.

Productivity: While often used interchangeably with efficiency, productivity may be considered as the ratio of an output to the inputs used in an activity related to the production process.

Project: A project comprises an interrelated set of activities that result in a product. A nuclear power plant is the product from the design, manufacturing and construction activities.

Project sponsor: The project sponsor is responsible for identifying the business case for the investment, maintains the project's alignment with the investor's business strategy and risk appetite, and for ensuring that anticipated benefits are realized. The project manager is responsible for planning, controlling, monitoring and delivering the project with delegated authority from the project sponsor.

Resources: A factor of production required to deliver an activity. The project will draw upon the resources furnished by the key stakeholders in order to realize the project's goals. Resources are always limited and are thus a potential constraint upon the project as much as they are necessary for its completion.

Risk: The combination of exposure to an undesirable event (uncertainty) and the severity of the impact of such an event (loss).

Scope: The scope of a project defines the goals to be achieved. It is usually broken down into a set of activities, each of which delivers one or more of the goals.

Special-purpose entity: A legal entity established to fulfil a specific or temporary objective, such as a capital expenditure project. A special-purpose entity may be owned by several organizations and is aimed at isolating the financial risk attached to the project.

Stakeholder: A stakeholder is a person or organization with an interest in the outcome of a project. A key stakeholder is a stakeholder whose cooperation is critical to the achievement of the project's goals, since these agents furnish the necessary resources. Among the key stakeholders in a nuclear power plant construction project are the owners, the investors and bankers, the operator, the regulators, the staff and contractors, and the customers. Other stakeholders include the plant's neighbours, the wider community and their political representatives. All may have some influence, in that the local community may pressure the political authorities to authorize the regulators to issue instructions to the plant's operator – in this case, the community and its representatives have an indirect influence on the operator, while the regulator has a direct influence.

Uncertainty: A situation where, in the current state of knowledge, events are unpredictable and credible probabilities for outcomes cannot be assigned.

World Nuclear Association
Tower House
10 Southampton Street
London WC2E 7HA
United Kingdom

+44 (0)20 7451 1520
www.world-nuclear.org
info@world-nuclear.org

The World Nuclear Association is the international organization supporting the people, technology and enterprises that comprise the global nuclear energy industry.

Our membership encompasses uranium mining, conversion, enrichment and fuel fabrication; reactor vendors; major nuclear engineering, construction, and waste management companies; and the majority of world's nuclear generation. Other members provide international services in nuclear transport, law, insurance, brokerage, industry analysis and finance.

Lesson-learning in nuclear construction projects reports on the work of the World Nuclear Association's New Build Lesson-learning Task Force. The report reviews and analyzes recent nuclear power plant construction projects to identify good practice and lessons learnt.