MANAGING RESILIENCE THROUGHOUT THE NUCLEAR POWER PLANT LIFECYCLE: THE SIGNIFICANCE OF PRE-OPERATIONAL PHASES

Nadezhda Gotcheva [1], Pia Oedewald [2], Kaupo Viitanen [2] and Mikael Wahlström [2]

[1] VTT Technical Research Centre of Finland, P.O. Box 1300, FI-33101 Tampere, Finland

[1] E-mail: nadezhda.gotcheva@vtt.fi, Tel. +358 40 132 6030

[2] VTT Technical Research Centre of Finland, P.O. Box 1000, FI-02044 VTT, Espoo, Finland

www.vtt.fi

Abstract

The objective of this paper is to explore how cultural challenges in the pre-operational phases of a nuclear power plant project (e.g. design, construction and commissioning) create prerequisites for development of resilience in latter phases of the project. Organizational processes and practices, beliefs, assumptions and understanding about safety developed in one lifecycle phase might not be fully relevant for the next phase. The study indicates that challenges in different phases are related to the extent of tangibility of the nuclear safety concept, magnitude of technical and organizational project complexity, extent of subcontracting, organizing of the project activities, or the priority given to nuclear-specific knowledge and understanding. Resilience management approaches should take into account the different cultural features of the lifecycle phases and how they affect safety. Accordingly, the means to support resilience should be adapted according to the specific cultural challenges in each phase. The paper highlights the significance of the pre-operational phases for making informed decisions to create and manage resilience throughout the nuclear power plant lifecycle.

1 INTRODUCTION

Many activities in contemporary large-scale nuclear energy projects are carried out by complex networks of multinational actors. Networks are seen as a dynamic set of actors who collaborate to achieve shared goals and generate value (Camarinha-Matos et al., 2009). However, the diversity of perspectives in large projects brought by multiple project partners often brings tensions, fragmentation and power issues. Although actors generally agree upon the core goals of the project, they might not share the same goals and priorities due to different roles, responsibilities and perspectives. Also, compared to single organizations, in temporary project networks it is more difficult to hold actors accountable for results and safety performance.

A general intrinsic challenge in the nuclear industry is ensuring the long lifespan of an operational nuclear power plant, which brings requirements for modernizations, maintaining mindfulness, managing the effects of aging, or preparing for internal or external turbulences. Provided that the lifetime of nuclear power plants encompass several decades and beyond, the relevance of resilience as a long-term ability to adapt and thrive in the face of changes and uncertainty is evident. The range and nature of activities in large-scale nuclear energy projects bring new challenges for creating and managing resilience. Resilience Engineering tradition sees resilience as the intrinsic ability of an organisation to adjust its functioning prior to, during, or following both expected and unexpected changes and disturbances (Hollnagel et al., 2011). The core resilience abilities to anticipate, monitor, respond and learn developed during one lifecycle phase might be dysfunctional in the next phase due to changes in the characteristics of the system. This could be referred to different organizational core task of each phase (i.e. the shared objective or purpose of organizational activity), associated hazards, ways of organizing and competence requirements (Reiman & Oedewald, 2007).

The *research question* to be addressed in this paper is how cultural challenges, identified in the pre-operational phases set conditions, which might affect the development of resilience in latter phases of the lifetime. The focus of this study is on pre-operational phases, more specifically, design, construction and commissioning, since they offer valuable opportunities to identify and correct possible issues *before* the operational phase actualizes. For example, it has been recognized that decisions taken during the design phase might have significant consequences on, e.g. maintenance, waste handling and the costs for final decommissioning of the plant (IAEA, 2002).

The paper summarizes and extends a research, which utilized international reports, scientific publications and the authors' experience from empirical projects on safety culture and organizational evaluations in different lifecycle phases in large-scale nuclear power projects (Gotcheva & Oedewald, 2015).

2 LIFECYCLE MANAGEMENT IN COMPLEX NUCLEAR POWER PLANT PROJECTS

The lifecycle of a new nuclear power plant consists of five phases (Fig. 1), such as pre-project, project decision-making, construction (including design, construction, installation and commissioning), operation and decommissioning phases, which can be grouped into pre-operational, operational and post-operational phases (IAEA, 2007; 2012).

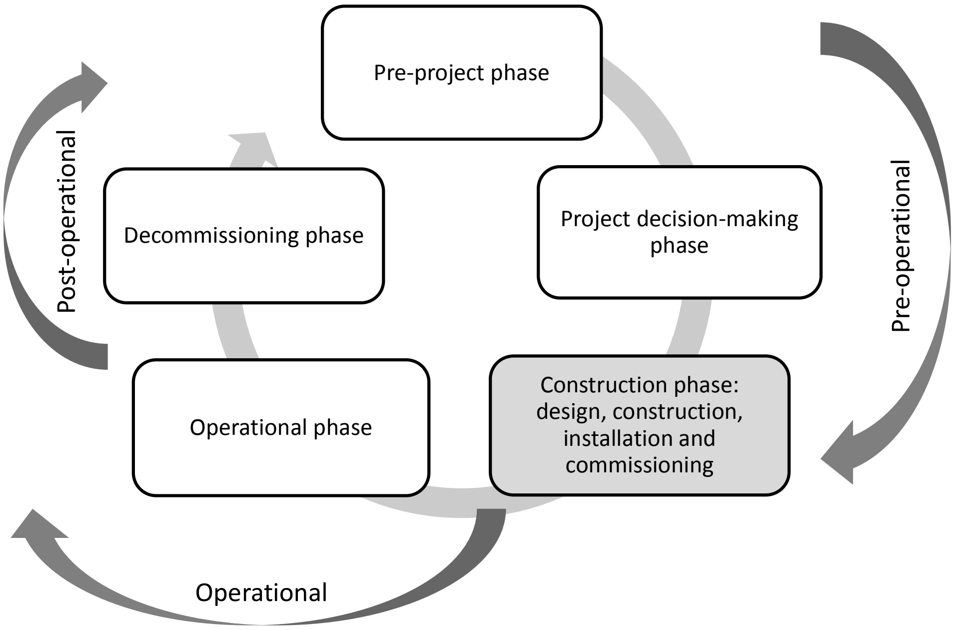

Figure 1.*Nuclear power plant's lifecycle (based on IAEA, 2007)*

This paper focuses explicitly on design, construction and commissioning activities, which are seen as a part of the construction phase in the nuclear power plant's lifecycle. In the pre-operational phases of a large nuclear project multitude of organizations from different nationalities and professional backgrounds are involved in a broad range of activities. These are usually subcontractor organizations, which might have very limited nuclear experience and insufficient knowledge of nuclear safety requirements, and often speak different languages, which create challenges for coordination, management, accountability and communication (IAEA, 2012). In the pre-operational phases the nuclear fuel and associated hazards are absent from the site until the initial fuel loading, which challenges the relevance of applying the safety culture concept.

Traditionally, the concept of safety culture in nuclear domain has been associated with nuclear hazards; therefore it may be difficult to understand its relevance in phases where nuclear fuel is not present. Safety culture is seen as an organization's potential for safety (Reiman & Oedewald 2009, Oedewald et al. 2011). If safety culture principles and practices are not adequately understood and applied from the very beginning of the project, there is a risk of latent and actualized deficiencies, project management issues, and overall safety issues during operation of the plant, which applies to both new nuclear build and big modernization projects in existing plants (Ruuska et al., 2011; IAEA, 2012). Recent research indicated that problems related to quality assurance, coordination and communication in early phases of large construction projects tend to cascade and manifest in the later construction phase (Albrechtsen & Hovden, 2014). Current experience in the Nordic nuclear industry sector points out that there are challenges associated with creating and sustaining a good safety culture during the pre-operational phases (e.g. Oedewald & Gotcheva, in press; Oedewald et al., 2011b; Gotcheva et al., 2014; Macchi et. al, 2014).

Main challenges associated with safety culture during pre-operational phases of large nuclear power projects were identified by IAEA (2012) as follows: 1) many organizations with limited direct experience and insufficient knowledge of nuclear safety requirements may be involved in various activities at the site; 2) a wide range of organizations are typically involved in pre-operational activities, which poses challenges for coordination, management and accountability; 3) projects may involve many different nationalities and cultures, which can result in communication challenges; and 4) new build nuclear power plant sites may be located in countries with no mature nuclear industry, nuclear knowledge and infrastructure, or in countries with a mature industry but with limited or no recent experience.

These issues bring complex interrelations and localized adaptations, which have the potential to aggregate and to generate emergent phenomena or system-wide patterns, which should be anticipated and managed (Eoyang & Holladay, 2013). Nuclear power plant projects can be seen as complex adaptive systems (CAS), since they represent a collection of semi-independent agents, in which inputs are not necessarily proportional to outputs, and which have the ability to learn and adapt to changes (McMillan, 2008). These systems are highly sensitive to their initial conditions: the so called "butterfly effect" implies that small differences in the initial conditions can lead to a wide range of outcomes.

In that sense, what works in one lifecycle phase cannot be simply replicated in another phase because each one has distinct characteristics. Crosby (2012) studied building resilience in large high-technology projects and indicated that early adoption of certain approaches and launch conditions have the capacity to position a project for resilience in its later phases of the lifecycle. For example, paying attention to "front-end shaping", which builds resilience by alignment of all parties with a common objective and setting launch conditions, such as a clearly defined mission, clear reporting and decision structures, preparation for unexpected risks and awareness of the external environment, as well as establishing deliberate support for collaborative relationships and structures, including contractors. This implies that we need to better understand the initial characteristics and typical human, organizational and cultural challenges, experienced in the pre-operational phases of the lifecycle in order to create potential for creating and managing resilience throughout the whole lifecycle.

3 CULTURAL CHALLENGES DURING PRE-OPERATIONAL PHASES OF NUCLEAR POWER PROJECTS

The following sections summarize the main results; that is, the cultural and organizational challenges that arise in the different lifecycle phases of a nuclear power plant project (for a more detailed report on safety culture challenges in large nuclear projects see Gotcheva & Oedewald, 2015).

3.1 Design phase

Design in the nuclear industry is a *collective process and coordinated effort between multiple parties*, such as the licensee, the regulator, the vendor and a large network of design organisations, which sets demands on collaboration activities, sharing of responsibilities and communication concerning safety requirements and priorities. Distributing roles and responsibilities between different stakeholders in design is challenging, especially in the beginning of a project when relationships and organisational structures are still establishing. Design involves effective *requirements management*: identifying, finding, understanding and implementing various requirements. In addition, national regulatory requirements should be thoroughly understood by foreign designers. When multiple organizations are involved, designers' sense of responsibility for safety and functioning of the end-product may be challenged due to their physical or psychological distance from the end-users and their local context, which poses a risk for suboptimal solutions. This implies that to develop resilient design, a culture which encourage open reporting of safety or quality concerns should be developed. Besides, designers' knowledge on the broader context and use of the systems in the plant should be enhanced. It is difficult to standardize the conceptual stage of design with detailed instructions and requirements. There is a large amount of requirements and their interpretations among designers might differ. There is a need to *manage tensions and to develop a systemic view* in design, including technical and non-technical understanding such as materials behaviour, end user's needs and future operational context. Psychologically, in this phase nuclear safety is a distant concept, which may contribute to a limited sense of responsibility for the end-product and the overall plant safety.

3.2 Construction phase

In the construction phase it is challenging to ensure that the large number of actors, e.g. subcontractors, in a complex temporary multinational network have a sufficient safety understanding. Provided that the majority of the construction subcontractors usually work in non-nuclear domain, where the requirements and vocabulary are different, it is not easy to understand what is safe and what is unsafe, especially when immediate nuclear hazards are not yet present at the site. Also, when multinational workforce in involved in the construction field, language and cultural barriers could complicate understanding of the need to follow procedures and nuclear specific requirements, which could compromise safety. Therefore, collaborative relationships with contractors need to be supported and developed, especially since the construction context is highly dynamic: the constant flux of companies and workers disturbs the process of shared learning through training and knowledge transfer. Another challenge is that traditionally, construction industry is focused on occupational safety rather than on system safety. Construction industry utilizes hierarchical management model, which emphasises bilateral interactions and information exchange and focus on efficiency, which might have undesirable effects on safety.

3.3 Commissioning phase

Commissioning is a critical phase in the nuclear power plant lifecycle because it aims at demonstrating and verifying that the constructed components, systems and structures are operational and done in accordance with the design specifications (IAEA, 2014). Unidentified deficiencies in this nuclear safety critical phase could remain major latent failures for a long time after the reactor starts operation (Zerger and Noël, 2011). Dealing with possible deficiencies during the commissioning phase requires deep knowledge, prompt and prudent judgement and managerial excellence (Cagno et al., 2002).

Commissioning involves more tangible safety risks compared to design and construction insofar as loading of nuclear fuel is part of commissioning. After the fuel loading, the commissioning tests require the same attention to nuclear safety as during the operational phase. In this phase, fragmented problem solving process might impede communication and coordination, and cloud the big picture. Hence, integration of activities and management of the unexpected are required during the commissioning process because of the increased organizational and technical complexity. Commissioning activities require a deep understanding of the nuclear specific quality requirements, which makes it different from construction work since the hazards of the nuclear fuel are present at the site after the fuel loading, and the systems are actually used, not only constructed or designed; the empirical findings stemming from using the systems need to interpreted against the design basis.In addition, the increased organizational and technical complexity requires a systemic view for dealing with expected and unexpected conditions.

3 DISCUSSION

To enhance the overall resilience of the future plant, it is important to understand how the pre-operational lifecycle phases of a nuclear power plant project create prerequisites for developing resilience in the next phases. Hence, the discussion focuses on the lifecycle phase interactions and the possible relations to the resilience cornerstones.

The *design* phase sets some of the key preconditions for self-organising later in the project. If this effect is not considered, e.g. by means of including end-users who actually operate the plant in design activities, the designers may not understand or anticipate correctly how the system will evolve and self-organise when it is taken into operation. Design is also incorporating lessons learned from previous experiences concerning the nuclear power plants. Active involvement of the licensee and the regulator early in the design process is critical for anticipating the risks for costly and time-consuming design changes, which might have effects on safety in the later phases. The design solutions are crucial for the capability for monitoring and responding as well, yet the designers need to understand how these activities should be carried out and integrated in the design process. Organizational systems and structures should support the coordination and shared learning between different stakeholders in the design process, such as the licensee, the regulator, design organizations, external consultants, subcontractors, etc. Safety should be made a more tangible concept for designers, and thus improving their sense of responsibility for the final outcome and the overall plant safety.

In the *construction* phase there are multiple interactions between a large number of actors in the project, which creates preconditions for patterns of coordination to arise out of the local interactions in a highly dynamic context. Construction provides opportunities to monitor if there are needs for modifications in case of weak or dysfunctional design solutions, which could jeopardize safety of the future power plant. The resilience development approaches should take into account the challenge of prioritizing quality and safety in a context of multitude of international construction workers, who are typically involved in non-nuclear industries. Thus subcontractors need to be involved and supported in understanding the nuclear specific hazards, since otherwise their ability to anticipate potential risks and react adequately to disruptions could be diminished.

In the nuclear industry, *commissioning* refers to proving the resilience of a safety-critical system before it is put in operation. In a way, the commissioning phase "acquire" the conditions of the plant, shaped by the developments during the design and construction. The activities are focused on noticing and fixing possible deficiencies from the previous phases, and testing the components and systems against design and safety requirements. Anticipating the potential safety impacts of specific actions or decisions during commissioning requires solid knowledge in technical characteristics, hazards and system behavior. This cornerstone of resilience may be challenging to achieve when utilizing subcontractors in safety critical activities. Learning from past experiences and understanding of the big picture actualizes in commissioning phase because there is a need to verify that the systems are safe. The safety risks related to the nuclear fuel loading stage bring pressure for dealing with the unexpected, just like in operational plants. The increased social and technical complexity in this phase requires effective coordination and clear roles and responsibilities. From resilience cornerstones perspective it can be stated that during commissioning there is a need to create an ability to anticipate how the plant will function in the future, develop organisational capabilities for monitoring and responding to expected and unexpected plant behaviors. Overall, this process can be seen as a learning journey, which is documented carefully and often under time pressure.

Organisations evolve dynamically throughout their lifetime and are often characterised as being sensitive to initial conditions. This notion could be applied also to complex nuclear power plant projects. The resilience abilities developed during one lifecycle phase might prove to be dysfunctional if applied directly in the next phase. For instance, organizations might have developed practices to respond to certain conditions during the construction phase, such as the huge number of subcontractors from different nationalities, which might be dysfunctional for the commissioning phase, where there are typically less staff and less foreign subcontractors involved. Learning from past events can be problematic in project-based organizations since there might be not sufficient time to reflect, to communicate and to share experiences among different actors due to the temporal context and changes of personnel. It can be argued that although each of the lifecycle phases affects the overall resilience of the future power plant, the pre-operational phases set conditions, which influence significantly the long-term ability of the actors in a project network to continuously adjust to or recover from changes and disturbances.

4 CONCLUSION

This paper highlighted the significance of pre-operational phases for developing resilience throughout the nuclear power plant lifecycle by pointing to the need to capture the dynamics of the pre-operational phases and develop an understanding on the cultural challenges that might have an effect on safety. Organisations evolve dynamically throughout their lifetime and are often characterised as being sensitive to their initial conditions. Understanding the characteristics, behaviour of the system and the challenges organizations face early in the lifetime allow making informed decisions to create and manage resilience in latter phases. This understanding supports the timely and sufficient development of system capabilities for safety and coping with varying conditions throughout the lifecycle. In other words, this enhances the ability of organizations to recognize outdated practices and to develop flexibility to revise the relevance of communications, decision processes, procedures and systems during each lifecycle phase. In this paper we argue that the culture, which steers the way workers think and behave in latter phases of the lifecycle, is set in the pre-operational phases, and it includes the formation of structures and practices, values, attitudes, knowledge and understanding. Changing this interlocking set of cultural features is a large-scale and long-time undertaking. Therefore, if from the beginning an organization is developed in a dysfunctional way, it might be more difficult to manage resilience in the later phases. Since organizational challenges differ between the phases, the means to support and sustain resilience might need to adapt accordingly.

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REFERENCES

Albrechtsen, E. & Hovden, J. (2014). Management of emerging accident risks in the building and construction industry, In Proceedings of Workingonsafety.net, 7th international conference, 30 September-03 October 2014, Scotland, UK.

Cagno, E., Caron, F. & M. Mancini (2002). Risk analysis in plant commissioning: the Multilevel Hazop. *Reliability Engineering & System Safety*, *77*(3), 309-323.

Camarinha-Matos, L.; Afsarmanesh, H; Galeano, N. & Molina, A. (2009). Collaborative Networked Organizations, *Computers and Industrial Engineering*, *57*(1), 46-60.

Crosby, P. (2012). Building resilience in large high-technology projects: front end conditioning for success, *International Journal of Information Technology Project Management, 3*(4), 21-40.

Eoyang, G. & Holladay, R. (2013). *Adaptive action. Leveraging uncertainty in your organization*. Stanford University Press, Stanford.

Gotcheva, N. & Oedewald, P. (2015). SafePhase: Safety culture challenges in design, construction, installation and commissioning phases of large nuclear power projects, February, 2015:10, ISSN 2000-0456, Swedish Radiation Safety Authority (SSM).

Gotcheva, N., Oedewald, P., Macchi, L., Alm, H., Osvalder, A.-L. & Wahlström, M. (2014). Managing safety culture in design activities: Evidence from the Nordic nuclear power domain; presented at the WOSNET 2014, 7th international conference, 30 September - 03 October 2014, Glasgow, Scotland, UK.

Hollnagel, E., Paries, J., Woods, D. & Wreathall, J. (Eds.) (2011). *Resilience Engineering in Practice: A Guidebook*. Ashgate.

IAEA (2002). *Safe and Effective Nuclear Power Plant Life Cycle Management towards Decommissioning*, IAEA, Vienna, IAEA-TECDOC-1305.

IAEA (2007). *Managing the First Nuclear Power Plant Project*, IAEA-TECDOC-1555. Vienna: International Atomic Energy Agency.

IAEA (2012). *Safety Culture in Pre-Operational Phases of Nuclear Power Plant Projects*. Safety Reports Series No. 74. Vienna: International Atomic Energy Agency.

IAEA (2014). *Commissioning for Nuclear Power Plants*, Specific Safety Guide, No. SSG-28. Vienna: International Atomic Energy Agency.

Macchi, L., Gotcheva, N., Alm, H., Osvalder, A.-L., Pietikäinen, E., Oedewald, P., Wahlström, M., Liinasuo, M. & Savioja, P. (2014). Improving design processes in the nuclear domain. Insights on organizational challenges from safety culture and resilience engineering perspectives, Final report, Nordic Nuclear Safety Research, NKS-301.

McMillan, E. (2008). *Complexity, Management and the Dynamics of Change*. London: Routledge.

Oedewald, P. & Gotcheva, N. (in press) Safety culture and subcontractor network governance in a complex safety critical project, Reliability Engineering and System Safety, Special Issue "Resilience Engineering".

Oedewald, P., Gotcheva, N., Reiman, T., Pietikäinen, E. & Macchi, L. (2011b). Managing safety in subcontractor networks: The case of Olkiluoto3 nuclear power plant construction project. 4th Resilience Engineering International Symposium, Sophia-Antipolis, France, 8-10 June.

Oedewald, P., Pietikäinen, E. & Reiman, T. (2011a). *A guidebook for evaluating organizations in the nuclear industry – an example of safety culture evaluation*, SSM: The Swedish Radiation Safety Authority, 2011: 20.

Reiman, T. & Oedewald, P. (2007). Assessment of complex sociotechnical systems: theoretical issues concerning the use of organizational culture and organizational core task concepts. *Safety Science, 45*(7), 745-768.

Reiman, T. & Oedewald, P. (2009). Evaluating safety critical organizations: focus on the nuclear industry. Swedish Radiation Safety Authority, Research Report 2009:12.

Ruuska, I., Ahola, T., Artto, K., Locatelli, G. & Mancini, M. (2011). A new governance approach from multi-firm projects: lessons learned from Olkiluoto 3 and Flamanville 3 nuclear power plant projects. *International Journal of Project Management*, *29*, 647-660.

Zerger, B. & Noël, M. (2011). Nuclear power plant commissioning experience. *Progress in Nuclear Energy*, *53*(6), 668-672.