Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Authors: Nadezhda Gotcheva
Pia Oedewald

Research

2015:10

SafePhase: Safety culture challenges in design, construction, installation and commissioning phases of large nuclear power projects

Report number: 2015:10 ISSN: 2000-0456
Available at www.stralsakerhetsmyndigheten.se

SSM perspective

Background

The expectations and regulations concerning human and organisational performance and safety culture in the nuclear industry have developed during past years. However, large projects have unearthed challenges in the field of Human-Technology-Organisation which have not yet been clearly discussed in nuclear industry research. It is not always clear what a good safety culture means in practice; from a regulatory perspective this can be a problem since it is necessary to have a good understanding of what to pay attention to during supervision. The concepts and tools with which the licensees and regulators take on non-technical phenomena, such as safety culture and human performance, have proved to be challenging for operating plants to apply.

The regulator's supervisory activities are challenged as the stakeholders and their goals vary through different lifecycle phases, and as issues stemming from human and organisational factors interrelate with different national and professional cultures.

What kind of safety culture issues should the regulator and licensee prepare for in the design, construction, installation and commissioning phases of large scale nuclear projects?

Objectives

The objective of the SafePhase project was to provide a better understanding and an overall picture of the safety culture challenges in different lifecycle phases of nuclear power plant projects.

The study aims at supporting regulatory supervision and licensee project management in anticipating specific safety culture issues in the different lifecycle phases of large projects. This is done by reviewing and analysing international experiences and studies of issues stemming from human and organisational factors in the design, construction, installation and commissioning phases of new build projects and major refurbishments of nuclear installations.

Results

The study highlights challenges associated with human and organisational factors in the design, construction, installation and commissioning phases of large nuclear projects. Here, the study provides a practical contribution supporting SSM's supervisory practices and licensee activities during the different lifecycles of large nuclear power projects.

The study also provides support for adopting a proactive approach: safe and effective execution of the different phases of large nuclear projects benefits from discussions about human and organisational challenges before the challenges manifest themselves. In order for such discussions to be fruitful, the interested parties should share a common picture of the end product by defining requirements to be met regarding the design, construction and installation of components, structures and systems.

The report provides some understanding of what kind of safety culture issues could be expected in large scale nuclear power projects for the specific context of different phases and the evolvement of activities. The authors conclude that, in order to improve anticipation of human and organisational challenges in different lifecycle phases, there is a need for licensees and regulators to consider that, besides characteristics generic to large nuclear projects, each lifecycle phase also has its own intrinsic characteristics from which specific safety culture challenges emerge.

The study identifies knowledge as crucial for safety culture in practice, regardless of phase in the lifecycle of large projects; for example, knowledge about what safety culture implies in each context, how safety culture is manifested, and the points of contact for posing questions and reporting. If there are good examples to follow and emulate, it is easier for an individual to contribute to overall plant safety.

The authors conclude that an active involvement early in the *design process* could minimise the need for subsequent adaptations or changes in design. The authors also conclude that understanding the regulatory requirements is a crucial area of competence for designers. The licensees could take measures to improve the coordination and shared understanding between different stakeholders in the design process. With an understanding of the operational context, efforts could be concerted and not dispersed through thematic vagabonding. In major modernisations and new build projects, the entire design process can take years, during which staff turnover is likely; this poses challenges for maintaining a systemic view on safety, knowledge transfer, and continuity. The design of a plant or specific equipment could take place well before licensees are involved; this makes it difficult for them to influence the process of development. However, the licensees might still have to account for the quality of the design process. The licensees can therefore be proactive and make these requirements known to possible vendors.

In the *construction and installation phases* there are special challenges in ensuring high quality in manufacturing and construction work due to long supply chains, partly because economic constraints cause pressure, and partly because of insufficient specific knowledge about nuclear safety principles and risks. It is important for subcontractors involved in construction activities to understand the functionality and safety significance of their work scope because this influences their attitudes to safety and perception of deviations.

In the *commissioning phase* there are organisational challenges as the end of the project is approaching; apart from challenges due to time pressure, there are challenges regarding the clarity and transfer of roles and responsibilities. The study identifies challenges in maintaining a good safety culture throughout a plant's lifetime. Special challenges are found in maintaining knowledge through the flux of organisations before commissioning, as well as despite turnover of personnel throughout the plant's lifetime. The means to achieve and maintain a good safety culture might differ between the phases – the licensee and the regulator must keep this in mind. By having a holistic perspective and sharing the common goal of the overall safety of the plant in the earlier phases above, the complex task of putting all the pieces of the puzzle together (i.e. commissioning) can be performed effectively and efficiently.

The *decommissioning phase* of the lifecycle requires handling a wide range of human resource issues, which arise from the new situation, and the staff's feelings of uncertainty and insecurity as they might not see a future for themselves in the organisation. It is crucial for the licensee to clearly communicate its current arrangements and future prospects, ensure staff competence and motivation, and maintain a strong safety culture even if the nuclear fuel is no longer present. It is also important to strengthen the understanding of the changing faces of risks as there are new radiation hazards and contamination risks, etc. The decommissioning phase also calls for the regulator to reorient its supervision.

Need for further research

Further research could suggest appropriate tools and other facilitators for managing and maintaining such knowledge, and for supporting the shared understanding of a holistic view throughout a large project or new build.

Project information

Contact person SSM: Johan Enkvist
Reference: SSM2013-5711

Strål
säkerhets
myndigheten

Swedish Radiation Safety Authority

Authors: Nadezhda Gotcheva, Pia Oedewald
VTT Technical Research Centre of Finland

2015:10

SafePhase: Safety culture challenges in design, construction, installation and commissioning phases of large nuclear power projects

Date: February 2015
Report number: 2015:10 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Table of contents

Summary

Different lifecycle phases of a nuclear power plant present new human-technology-organization challenges to regulators and licensees. Organizational processes and practices that have evolved in one phase of development might be dysfunctional for the next phase, and the definition of "good safety culture" in practice might be unclear.

The objective of the SafePhase study is to improve the understanding of safety culture challenges facing regulators and power companies in different phases of large-scale nuclear power projects. The study utilized relevant literature and international experience on challenges in design, construction, installation and commissioning phases. Background information was provided by the interviews conducted at the Swedish Radiation Safety Authority. Some experiences concerning decommissioning were also reviewed, although this was beyond the scope of the study.

The findings indicated that organizational challenges in the design phase are related to the intangible nature of nuclear safety, which may lead to shifting the focus to paperwork and a limited sense of responsibility for the end-product and overall plant safety. Design in the nuclear industry is a slow process; designers are often involved in many projects at the same time, which hinders their capability to concentrate continuously on any of them. In major modernizations and new build projects the entire design process can take years, during which staff turnover is likely and thus knowledge transfer and continuity are also challenged.

The main issues in the construction and installation phases refer to project management in a complex multinational network and management of safety culture in a dynamic context of temporary workers, when nuclear hazards are not yet present. Special challenges in these phases are ensuring high quality in the long supply chains of the manufacturing and construction work, in which economic constraints cause pressure; also specific knowledge on nuclear safety principles and risks is insufficient.

Organizational challenges in the commissioning phase are not only related to time pressure as the end of the project is approaching; these challenges are also related to the clarity and transfer of roles and responsibilities, as well as preparedness for the unexpected and for possible emergencies with regard to the nuclear fuel loading stage.

Overall, the SafePhase project indicated the importance of understanding organizational characteristics of each nuclear lifecycle phase, which present specific safety culture challenges.

Sammanfattning (summary in Swedish)

De olika faserna under ett kärnkraftverks livscykel innebär nya utmaningar inom MTO för både myndighet och tillståndshavare. De organisatoriska processer och rutiner som har tagits fram i en fas av anläggningens livscykel kan fungera dåligt i nästa fas; dessutom kan det vara oklart på vilket sätt tillämpningen av en god säkerhetskultur skiljer sig åt mellan de olika faserna.

Syftet med studien SafePhase är att öka kunskapen om de utmaningar inom säkerhetskultur som myndighet och tillståndshavare ställs inför i olika faser av stora projekt inom kärnkraftindustrin. Studien använder sig av tillämplig litteratur och internationella erfarenheter av utmaningar inom faserna: utformning, uppförande och idrifttagning. Bakgrundsinformation samlades in via intervjuer på Strålsäkerhetsmyndigheten. Utöver faserna i syftet samlades även en del erfarenheter in rörande avveckling.

Studiens resultat antyder att de organisatoriska utmaningarna i utformning kan kopplas till att strålsäkerhet i sig inte är direkt påtaglig i denna fas. Detta kan bidra till formalism samt en minskad ansvarskänsla för slutprodukten och den övergripande säkerheten på anläggningen. Inom kärnkraftindustrin är utformning en långsam process och konstruktörer är ofta involverade i många projekt samtidigt. Detta minskar konstruktörernas möjlighet till kontinuerligt fokus på något enskilt projekt. När det gäller större moderniseringar och nybyggnation kan hela formgivningsprocessen ta flera år. Under denna tid är det troligt att personalen omsätts, vilket innebär utmaningar avseende i att upprätthålla och överföra kunskap.

De största utmaningarna i uppförandefasen rör projektledning i ett komplext internationellt nätverk; samt hantering av säkerhetskultur i ett sammanhang med tillfälliga arbetsstyrkor, innan nukleära risker finns i verksamheten. Uppförandefasen medför också särskilda utmaningar i att säkerställa hög kvalitet trots långa leveranskedjor. De långa leveranskedjorna innebär i sig ofta ekonomisk press i ett eller flera led; dessutom finns det i kedjorna kunskapsbrister avseende de risker och säkerhetsprinciper som gäller inom kärnkraften.

De organisatoriska utmaningarna vid idrifttagning härrör inte enbart från tidspress genom att projektets slut närmar sig. Utmaningar ligger också i att tydliggöra roller och ansvar, samt att överföra dessa till driftorganisationen. Dessutom finns det utmaningar i att vara förberedd på det oväntade och på möjliga händelser i samband med laddningen av kärnbränsle.

Sammantaget pekar studien på vikten av att förstå de specifika utmaningarna för säkerhetskultur som ställs i anläggningens olika faser i livscykeln.

Introduction

1.1. Traditional approaches to lifecycle management in the nuclear industry

According to the International Atomic Energy Agency (IAEA, 2007; 2012), the planning and implementation schedule of a new nuclear power plant consists of five broad phases, as depicted in Figure 1, which can be further classified into pre-operational, operational and post-operational phases. Although it is supposed that stages are developing subsequently, the boundaries are not that clear-cut and they are overlapping in reality. The discrete lifecycle stages form a continuum, and it can be assumed that activities in one stage frame the possible solutions and challenges in the next stage. For example, management decisions taken during the conceptual design phase could have a substantial impact and consequences, for example, on maintenance, waste handling and even final decommissioning costs (IAEA, 2002).

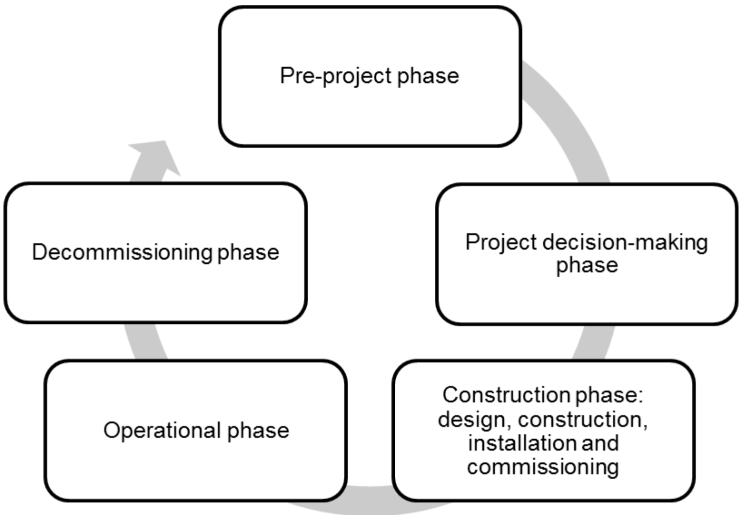

Figure 1 Nuclear power plant's lifecycle: The generic planning and implementation schedule of a new nuclear power plant (based on IAEA, 2007).

A nuclear power plant must be managed in a safe and efficient manner within each of the lifecycle phases, and also during the transition periods from one lifecycle phase to another (IAEA, 2002; Devgun, 2013). Maintaining a good safety and reliability over the entire lifetime of a nuclear plant is a challenging task due to the high complexity embedded in the industry and the long-time perspective, which may span a century and usually covers several generations of workers.

This report focuses on certain pre-operational phases, namely design, construction & installation and commissioning. These stages are relevant not only for the safety of the new builds but also for the success of major refurbishments or modernizations of units already in operation. Modernization projects refer to technical modifications, which aim at improving functionality, performance, safety and overall extension of lifetime of the plant (IAEA, 2004). Both minor and major modifications are needed and carried out in the plants; however they also bring additional technical, human and organizational factors complexity to the operating plant (OECD, 2006). Pre-operational lifecycle phases offer valuable opportunities to identify and correct possible problems, which could later be actualized in the operating phase and thereby jeopardize safety. Therefore, understanding safety culture in pre-operational phases creates technical and organizational preconditions for a good safety culture in operational and decommissioning phases.

1.2. Relevance of safety culture in large nuclear power projects

New nuclear builds are large and complex projects, which require large-scale resources, technical expertise and experienced project management (Devgun, 2013). The same is valid also for nuclear power plant modernization projects: although the scale is smaller and the timeframe is shorter as they usually concern certain systems or parts of the plant. Ruuska et al. (2009) describe large projects in general as “a dynamic network of organizations that combines the resources, capabilities and knowledge of the participating actors to fulfil the needs of the owner”. Since a vast number of large projects in various industrial domains have rather poor records in terms of schedule, cost and performance, research on governance of large projects has been recognised as important (Flyvbjerg et al., 2003; Brady and Davies, 2014). The increasing complexity of large projects has attracted the organizational research attention, which has focused on management of uncertainty and the various effects of interactions of elements (Flyvbjerg, 2014).

In nuclear power plants the complexity is not exclusive to large projects, although the magnitude of organizational complexity is substantially higher there. Technical complexity and conflicting goals are pervasive characteristics of all nuclear lifecycle phases, including the operational one. Due to the complexity of activities, nuclear power plants face various tensions and contradictions, which need to be taken into consideration because emphasizing one activity over another could result in unwanted consequences. In general, balancing between partially conflicting demands is one of the main challenges for safety critical organizations, and therefore a core issue in defining their culture (Oedewald and Reiman, 2003; Grote 2004, 2009; Hollnagel, 2009).

Some of those conflicts are the constant struggle between safety and economy, as organizations need to ensure economic profit but also operational safety (Perrow, 1984; Sagan, 1993; Kirwan et al. 2002), and the inherent contradiction between decentralization and centralization (Perrow, 1999; Woods and Branlat, 2011; Reiman and Rollenhagen, 2012). Centralized control stems from the need to have an overall understanding of different parts of the system. The justification for having decentralized control is that a single centralized unit might not identify the cause of a disturbance if it relates to interactions between sub-systems; such disturbances could be best dealt with by implementing expert solutions by personnel working directly with the sub-systems. This also relates to the need to balance between specialist and generalist roles and competences (Hoffman and Woods, 2011). Another typical conflict a nuclear power plant organization has to solve is the need to balance between acute and chronic goals and problems. Despite the complexity of the system to be managed, the context of nuclear industry brings along a tradition of hierarchical and mechanistic management models (Perin, 2005). Safety management has strong technical focus and it is based on setting and fulfilling strict quality requirements, which is then enforced by regulatory oversight.

Safety culture has been viewed in many different ways amongst practitioners and scientists. In this report the authors take a stance that safety culture can be understood as those aspects of an organization's culture that define how safety is viewed and handled daily. Culture is a phenomenon which gradually develops in the organization as it learns ways to deal with pressures, concerning external adaptation and internal integration (Schein, 1990). Therefore, the culture of an organization – and thereby safety culture – frames all activities in the organization and has widespread impacts on the performance. Safety culture affects also the way defence-in-depth is designed and executed. The principle of defence-in-depth (IAEA, 2007) has been a central safety principle in the nuclear industry for many years. It states that components and systems should be designed in such a way that if one of them breaks down, other defence layers still remain to protect the environment and population from the harmful effects of radiation. The principle should take into account human factors, organizational circumstances and technical systems alike.

To further clarify the role of safety culture, Reiman and Oedewald (2009) stated that safety culture can be seen as *organization's potential for safe activities*. The features of an organization's safety culture are not visible all the time, since certain basic beliefs and assumptions only surface when the situation requires the organization to solve a specific problem. Thus it is important for a nuclear industry organization and for the regulator to identify these underlying beliefs and assumptions, and to consider how functional they are in different types of challenges.

To describe more precisely the content of the concept of safety culture, the authors refer to previous work done at VTT Technical Research Centre of Finland. Reiman et al. (2012) have defined safety culture as an organization's *ability* and *willingness to understand* the nature of safety and hazards inherent in their activities, and the *ability and willingness to act* in a manner that the hazards are taken care of and safety is created. Safety culture is formed by a safety conscious mindset, organizational systems and structures, which create preconditions for good quality work, and understanding of the hazards and safety consequences of the work (Reiman and Oedewald, 2009; Oedewald et al., 2011). This definition tries to provide insight into those elements that are required from the organization to be able to prioritize safety in a sensible manner; that is, to understand what is safe and to provide concrete systems and structures, which allow activities to be manageable. The definition is in line with the IAEA view on good safety culture, which emphasizes that safety should receive the attention warranted by its significance.

In western countries utilities have been in operation for a long time, and there are established practices, procedures and management system, and models to measure and improve safety culture. However, traditional safety management practices and safety culture models have been developed from a single organization perspective. The models have been constructed from the viewpoint that the organization, whose safety culture should be developed and monitored, corresponds to one company or utility. This has been a sensible approach when, for instance, the safety culture concept has been used mainly in relation to operating units. In the operational phase the most activities are typically carried out by in-house personnel and performed by experienced operators. This implies that some human and organizational factors issues, which may be crucial for safety culture in large projects and their various contexts, may not be adequately taken into account in the existing safety management practices. For example, the fact that the activities in the pre- and post-operational phases rely heavily on external companies may set specific challenges for establishing a good safety culture. In the other lifecycle phases, such as design, construction or decommissioning, many activities are not carried out by the operating company itself, but by a network of actors, for example subcontractor companies. Subcontractors are also widely used in various modernizations projects.

Although IAEA (2012) has emphasized that nuclear safety begins at project conception, in new nuclear facility construction projects it is difficult to ensure that the practices of a strong safety culture are applied from the outset of the project. The relevance of the safety culture concept in pre-operational phases is challenged by the fact that the nuclear fuel and the associated hazards are not present at the site (until the initial fuel loading). The lack of possible acute consequences might lead the organization to relax their safety culture, while not fully understanding the possible consequences from decisions made in the pre-operational phase on later phases. 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, safety issues during subsequent operation of the plant, and significant economic consequences, such as cost overruns and schedule delays, which applies to both new nuclear build and big modernization projects in existing plants (Ruuska et al., 2011; IAEA, 2012).

Recent experiences indicate that achieving a good safety culture in the pre-operational phase can be challenging, especially in design and construction phases (Oedewald et. al, 2009; Oedewald et al., 2011; Gotcheva et al., 2013, 2014; Macchi et. al, 2013, 2014). According to IAEA (2012), the main challenges associated with safety culture during pre-operational phases stem from the facts that 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 relationship and communication challenges; and 4) new build nuclear power plant sites may be located in countries with no mature nuclear industry or associated nuclear knowledge and infrastructure, or in countries with a mature industry but with limited or no recent experience of nuclear design, construction and commissioning.

During the past years the expectations and regulations concerning human and organizational performance and safety culture have developed. However, large-scale nuclear projects bring out novel Human-Technology-Organization challenges, which have not been widely discussed in nuclear industry research. Different lifecycle phases pose different challenges to the regulator's oversight activities as the stakeholders and their goals vary. Also, the transition from one phase to another represents a change in the roles and responsibilities and the overall context in the project, which has potential effects on safety. In any case, the role of the licensee is to foster a strong safety culture, while the role of the regulator is to ensure that the licensee properly discharges their responsibility for safety and to "encourage the licensee to engage in safety culture" (IAEA, 2013).

From a regulatory perspective, it may be unclear what to pay attention to during the oversight, what good safety culture means in practice in different project phases, and what the unit of analysis is. Additional constrains could stem from national differences in legislation, which define the right of the regulator to oversee the activities of the subcontractors. For example, Reiman et al. (2010) indicated that there are differences in this respect between Finland and Sweden. In Sweden, although the regulator recognizes that subcontractors have a very important role in influencing safety in a nuclear power project, there are legal constraints which do not grant legitimacy to oversee the activities of subcontractors. In Finland, on the other hand, the regulator can be heavily involved as it is granted legal authority; that is, there are regulatory requirements for safety culture in nuclear power plants set in the Finnish legislation (Finnish Government, 2013; STUK, 2014).

1.3. Objective and scope of the report

The *objective* of this report is to provide a better understanding and an overall picture of the *safety culture challenges* in different lifecycle phases of nuclear power plants projects. The authors integrated and summarized the findings of relevant studies and international experiences on safety culture challenges in design, construction, installation and commissioning phases of nuclear projects and major refurbishments of nuclear installations. It is expected that the report will support the regulatory oversight and project management in the nuclear power companies in framing safety culture topics and human and organizational activities that deserve specific attention during these phases. The report takes a *proactive* approach as it aims at supporting the regulators and other relevant stakeholders in large nuclear projects in anticipating specific safety culture and human and organizational issues. The main research question is:

What kind of safety culture issues the regulator and project management should be prepared for in the design, construction, installation and commissioning phases of large-scale nuclear projects?

It should be noted that the present report does *not* cover the entire lifecycle of a nuclear power plant. Still, as in some of the interviews the topic of decommissioning was discussed, the report refers partially to safety culture issues in this phase as well.

2. Method

The following four types of material have been used in this report:

1) International reports on experiences and guidance on different lifecycle stages of large-scale nuclear projects. This data set includes, for example, IAEA reports and reports by other international institutions and organizations.

2) Scientific literature on safety culture and human factors issues in different lifecycle phases of large projects in high hazard industries.

3) Interviews were carried out in 2014 with seven representatives of the Swedish Radiation Safety Authority (SSM) at Stockholm, concerning the regulatory practices and requirements regarding safety culture and human and organizational factors and nuclear new builds. The duration of the interviews was between one hour - one hour and a half. The interviews were used as a background material (see the generic interview scheme in the Appendix) to provide an overview of how the Swedish Regulator identifies and handles human, organizational and cultural issues in the licensees, as well as in their own organization. The interview scheme included the following themes: safety culture regulatory oversight in Sweden; safety culture conception; warning signals of unhealthy safety culture; role of the regulator at different phases of nuclear projects; plans and preparation for nuclear new builds in Sweden; safety culture challenges in the design, construction, installation, commissioning, operation and decommissioning phases of large nuclear projects; and ideas for improvements of the regulatory practices to deal with these challenges.

Most of the interviewees had experience mainly from the plant operation phase of the nuclear lifecycle, although some have experience from big modernization/modifications projects and shutting down (preparation for decommissioning).

4) Generic lessons learned from various relevant projects, in which the researchers have been involved, complement the insights gained from the international literature to round up the understanding of safety culture challenges in the lifecycle of large projects.

Each of the nuclear lifecycle phases differs in core task, associated hazards, way of organizing and competence requirements. The concept of organizational core task refers to "the shared objective or purpose of organizational activity", influenced by the objective of the work, characteristics of the physical object of work (e.g. a certain type of power plant), and contextual factors, such as regulation, political climate, economic circumstances (Reiman and Oedewald, 2007). That is, the focus is on the boundaries and requirements of the activity in the entire sociotechnical system, as long as the different lifecycle phases of a nuclear power plant project share the ultimate goal of producing electricity safely and efficiently.

The activities during each of the lifecycle phases have certain intrinsic human, organizational and cultural characteristics, which stem from the different core tasks, different hazards and different disciplines involved. These elements set different challenges for individuals and organizations in managing the activities in a way that is good from safety point of view. Furthermore, the activities could be complicated as they are carried out in the complex environment of a large nuclear project. Essentially, if the work is outsourced, it brings certain specific challenges for managing safety, which adds to the possibility of the intrinsic challenges to actualize.

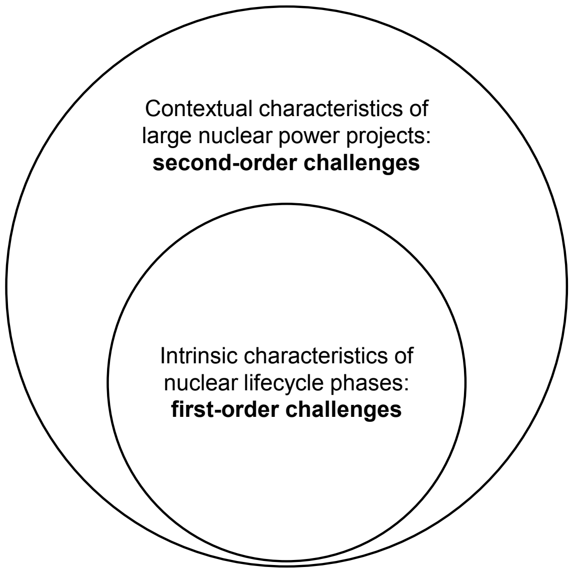

Figure 2 Integrated model for identifying safety culture challenges in different lifecycle phases in large nuclear power projects.

The authors developed an integrated model to analyze the safety culture challenges (Figure 2), in which the characteristics of the wider (project) context set a framework for second-order challenges to emerge. To varying extent, in different phases these second-order issues could refer to, for instance, outsourcing of activities and related contractual issues that could undermine safety. The first-order challenges are related to the objectives and intrinsic characteristics of each lifecycle phase. Where applicable, generic safety culture challenges, which incorporate features of the intrinsic and second-order factors, are presented. The next chapter summarizes the results.

3. Results

3.1. Safety culture challenges in design phase

Design is defined in the IAEA Glossary (2007) as *"the process and the result of developing a concept, detailed plans, supporting calculations and specifications for a facility and its parts"*. Design is a critical phase in the lifecycle because it lays the foundation for the whole nuclear plant lifecycle: manufacturing and construction is done according to the design requirements, components and equipment are installed with respect to the design specifications, commissioning tests are performed and results compared against the original design; also maintenance and decommissioning should follow design specifications. Thus from safety perspective, design stage provides the "earliest and hopefully the cheapest place to intervene and get it right" (Hale et al., 2007).

Design issues have often been found as contributing to accidents across different industrial domains: 55 percent of accidents in chemical industry and 46 percent of accidents in nuclear industry can be attributed at least partially to design errors (Taylor, 2007). Design error is defined as "a feature of a design which makes it unable to perform according to its specification" (Taylor, 2007: 62). Some examples of design-related accidents are the Turkish Airlines Flight 981 crash in 1974, the Challenger space shuttle explosion in 1986, Piper Alpha oil rig explosion in 1988, the capsize of the MS Estonia ferry in 1994, or the Wenzhou high speed train collision in 2011 (Macchi et al., 2014). In the United States nuclear industry, between 1985 and 1997, more than 3 100 licensee event reports have identified and reported design-based issues (Lloyd et al., 2000). In particular, the analysis of the Three Mile Island reactor accident (1979) revealed a basic design flaw for pressurizer relief valve (which failed open instead of closed), and design problems in the control room. Various design issues (e.g. the height of the tsunami protection wall, the location of the emergency diesel generators) emerged in the analysis of the Fukushima nuclear disaster in 2011 as well (The National Diet of Japan, 2012).

Nordic nuclear power plants have also encountered design-related issues. In 1992 in Sweden, a safety valve of the main steam system opened at Barsebäck unit 2 causing the disintegration of coverings and insulation materials from adjacent pipelines (www.analys.se, 2004). Parts of disintegrated material ended up in the reactor containment and caused clogging of the strainers for the emergency core cooling system. In 2010 in Sweden, a design flaw on four valves caused an abrupt stop of steam to the condenser leading to a short and relatively high pressure spike in the Oskarshamn 3 reactor (www.archive-se.com, 2010). Some design-related operational events in Finland include the reactor trip at Olkiluoto 1 in 2008 resulting from a design issue with the generator voltage regulator (Kainulainen, 2009); and in 2010 at Loviisa's newly built waste solidification plant low-activity rinsing water entered into the auxiliary building ventilation system during a test run (Kainulainen, 2011). Such challenges to ensure a safe design stem partially from the nature of the design process, which is an expert activity requiring abstract thinking, and aiming at developing a very practical outcome while balancing with many constraints.

The next sections will first summarize the intrinsic characteristics of the design activity and the associated challenges; then the second-order challenges, stemming from contextual characteristics of the industry and large projects will be elaborated, followed by *generic safety culture challenges*, which incorporate features of the intrinsic and second-order factors.

3.1.1. Intrinsic characteristics of design activity

The intrinsic characteristics of design work are derived from literature review (e.g. Cross 1982; Lawrence, 1988; Curtis et al., 1988; Trueman, 1998; Borja de Motoza, 2003; Aspelund, 2006; Andriopoulos and Lewis, 2010; Yang, 2009; Veland, 2010)

Design is a conceptual, visual, creative, analytical and uncertain process. In the beginning of the process, there are various possible paths to be followed to come up with a specific practical solution. This kind of *conceptual and creative activity* is difficult to standardize or support with detailed instructions. The reliability is enhanced by involving multiple individuals and performing various checks in the process, and this stage involves risks for misunderstandings. The individual "thoughts" are communicated and visualized via a collective process through "objects"; that is, physical artefacts, such as sketches and mock-ups. Despite these visualization objects, at this conceptual stage it may also be difficult to anticipate how the design components will function in reality. This anticipation challenge was also recognized in the interviews at the Swedish regulator SSM. The interviewees expressed an opinion that in design phase, *"it is hard to understand how the component will look in real life."* The regulator usually receives the documentation before the installation, which is too late, because *"lots of things have been already done or decided before we see it".*

Design is a *collective process and coordinated effort*, in which a multi-disciplinary group of actors share their knowledge and insight. One challenge related to this is the specialised expertise of designers; parties involved may not necessarily understand each other's work in detail and thus, they are not able to spot if there are errors or aspects that they should take into account and adjust for in their own responsibility area. Furthermore, integrating different technical disciplines put pressures on coordinating activities since parties involved may work according to different logics.

A profound socio-technical understanding and a systemic approach to safety is required in design work, including both *technical and non-technical* aspects, such as understanding of materials behaviour under different conditions, end user's needs and future operational context; interfaces between technical systems and their human operators. To achieve an understanding of the big picture of requirements, to take into account interdependencies and to understand who should be involved in the design process is not always easy. Understanding the context where the designed end-product will be utilized may be difficult for the designers and this may lead to dysfunctional designs.

Design could also *bring together novelty and functionality* because the final artefact in the nuclear industry should have certain features, some of which might be new.

Developing new and functional solutions to complex problems require special knowledge and expertise. However, innovativeness is not necessarily encouraged in the nuclear industry; rather, there is a tendency to rely on proven solutions which may limit the possibilities for finding new functional solutions. There may be varying opinions concerning whether proven solutions are safer solutions.

Safety is not always the first and most important guiding value in the design process (Macchi et al., 2013). The different actors involved in the design process, including the regulators, are constantly balancing between safety and economy in their work. There are commercial pressures between the organizations that may influence safety as well. For example, when making contracts with design organizations, the power companies strive to make a good deal. There is a temptation not to start the negotiation by explaining all the safety requirements, possible risks and complexities that relate to the design work. However, if this is not done already in the contract phase, it may be difficult to make demands later in the design process. The designers interviewed seem to perceive safety as integral part of their work, thus there was not much explicit discussion on their attitudes towards safety. In general, designer shared an implicit understanding that it is self-evident that designers value safety, unless schedule pressures compromise the thoroughness of their work.

3.1.2. Second-order safety culture challenges in design

The current context of large nuclear projects set some second-order challenges for safety culture in the design activities. These relate to extraordinary technical requirements in the nuclear industry, varying intensity and quality of regulatory requirements and involvement in the design process, and tendency to use external organizations for the design work.

Design is highly regulated by the nuclear safety authority in each country. Therefore, understanding the regulatory requirements is a crucial competence area for designers in nuclear industry. The design process requires varying number of approvals from the regulator, depending on the national guidelines. The “design basis” or the ability of the structures, components and systems to withstand certain range of conditions and events, needs to be thoroughly proved and documented (IAEA, 2007). Therefore, the design process is affected by the need to take into account the four main safety principles in the nuclear industry, namely *defence-in-depth, redundancy, diversification* and *physical separation* (IAEA, 2007). Also, the designers of safety-critical systems need to adopt a *long perspective* on the functionality and safety of the final artefact. Thus, nuclear power design solution should include characteristics, which may differ from those used in conventional industries, as it should operate as planned both in normal operation and in the case of an incident/accident.

Design is sometimes developed by in-house personnel of the power company but often designers work for an engineering company, to which the licensee has outsourced the work. Such engineering firms serve multiple customers in various industrial domains and it is reasonable to assume that they might not necessarily be fully familiar with the nuclear industry context and its specific requirements.

The interviews with the Swedish regulator indicated that challenges in design phase are related to the fact that SSM does not have the legal authority to review and oversee the vendors’ and contractors’ design activities early in the process. Design, testing, and mock-up are seldom done in Sweden; they are usually outsourced. It was recognized that the licensees need to have competences and tools for leading, managing and supervising the contractors, involved in design activities:

> *In the licensee organization there needs to be competence to evaluate the work of the contractor, and they should be able to lead, manage and supervise the contractor – we have been looking at that and we have seen a lot of problems – they are very much relying on the contractors, they don't like to interfere – we want to see that they can read a report, understand it and interpret it.*

Recent studies on safety culture in design in the Nordic nuclear industry, based on case studies and interviews with representatives of power plant organizations, design organizations and regulators, indicated a range of second-order and generic challenges presented below (Macchi et al., 2013, 2014; Gotcheva et al., 2014).

Organizations do not always share safety philosophies and understand safety requirements in the same way, which poses challenges to coordination

Safety philosophies and understandings of the safety requirements may differ between operating organizations and design organizations, thus posing challenges for coordination. For example, the Finnish regulator emphasises the principle of continuous improvement much more than the regulators in some other countries (Reiman et al., 2010). If the designers do not understand this principle, they may not design enough buffers for the designed components.

Distributing roles and responsibilities between different stakeholders in design is challenging

If the design activities are purchased from several subcontractors, it is sometimes unclear who is responsible for the interfaces. This relates to the role of the regulator as well: if the regulatory strategy is very prescriptive and the regulator is involved in reviewing the design from the early stages, it may be perceived as the regulator would be responsible for consulting the process and coordinating the solutions.

The slowness of nuclear design process challenges the systemic view on safety, knowledge transfer and continuity

Design in the nuclear industry is a slow process. This may cause thematic vagabonding (Reason, 1990), that is, switching from one subproject to another without concentrating continuously on any of them, which may endanger the designers' capacity to develop a holistic overview of the system. The length of a modification or modernization project in the nuclear industry can vary from a few months to years. In one of the studied cases, the process of documentation writing for an adjuster modification took ten months, which was considered too long time by the interviewees. In major modernizations and new build projects the entire design process can take years, during which staff turnover is likely, which poses challenges to knowledge transfer and continuity.

3.1.3. Generic safety culture challenges in nuclear power plant design

Understanding the end-product context may be difficult for designers, which may lead to dysfunctional design

It was mentioned by the interviewees that some of the I&C designers have never worked at an operating power plant and thus they might not think of some relevant issues in their design work. Also, the interviewees pointed out that since in some countries the nuclear domain has been developed and in others recessed, the level of designers' nuclear power specific expertise may vary depending on the country. It was considered important by the interviewees that the power company's personnel who guide the design work have solid understanding on the functioning of the plant and can communicate it to the designers.

Challenges associated with understanding and management of requirements

Design activities in the nuclear domain are closely related to collecting, reading, analysing and interpreting requirements, and respectively producing extensive written documentation. Regulator's strict requirements and the documentation verification process impose the assumption that the nuclear design process is linear. However, the process requires many iterations of the written documentation. Carrying out comprehensive research to understand the regulatory requirements, related to separate components, structures and systems could contribute to losing the big picture. Catching up with the ever expanding set of requirements is a challenge as well. This research aspect of designers' work is insufficiently supported as designers need to find and implement various types of requirements and specifications in different regulatory guides and other documents. Designers need to understand not only the requirements per se but also the intent of the requirements, their underlying assumptions. This causes frustration as some designers indicated that dealing with requirements could be done in a mechanical manner. Still, many designers indicated the need to understand requirements' premises in order to interpret them correctly and not to apply them blindly.

The challenge of dealing with complexity and uncertainty in design work

The intrinsic uncertainty of designing future end-products plays a role in the way design projects are performed. Designers are to create an artefact that does not exist yet, and they are required to prove and verify that it will work, and to describe its function. For a complex design task it is challenging, if not impossible, to foresee how the process will proceed in practice and how long it will take. To manage the complexity and uncertainty, design activities are decomposed into more manageable smaller projects, which set clear goals. Designers prefer to work with familiar people from the industry via regular face-to-face informal contacts, meetings and discussions, which increases their feelings of stability and control. However, the interviews indicated a possible downside of over-reliance on familiar and well-established contacts; for example, in one of the cases a device delivered by a familiar manufacturer did not work as expected and did not meet the requirements; as it turned out, that the "trusted" supplier had not tested the system comprehensively beforehand.

Conceptions on the scope of designers' responsibility

The majority of the designers felt responsible for the overall design process and its outcome, acknowledging that design makes a difference when it comes to safety. Still, some designers believed that they are only responsible for some part of the project and that the overall responsibility lies somewhere else, outside their scope. Clear distribution of roles and responsibilities was considered critical by the designers. In a major project where a prototype of a safety relevant system was designed, the project was considered quite successful by the interviewees, even though the systems had features that lead to an incident in the test run. When the designers judged the success of the project, they emphasised keeping the schedule and budget, and seemed to think that the incident in the test run had more to do with the end-users than the design. Besides, the fact that the system was a prototype seemed to make the technical challenges more acceptable for designers.

3.2. Safety culture challenges in construction phase

The IAEA Glossary (2007) defines *construction* as the *"process of manufacturing and assembling the components of a facility, the carrying out of civil works, the installation of components and equipment, and the performance of associated tests."* In the IAEA Glossary there is no separate definition for "installation".

Oedewald et al. (2009) discussed the significance of nuclear power plant construction phase for nuclear safety. The technical and organizational prerequisites for safe operation of a nuclear power plant are created during the construction stage. The quality of construction and installation work affects the technical quality of structures, components and systems, and thus the overall reliability and safety of the plant, which relates to the principle of *defence-in-depth* (IAEA, 1996). Good quality of the components affects the first level of safety defence; that is, disturbance-free operation of the plant; and the second level, as it affects the functioning of the safety system and further the mitigation phase. Structures and devices in a nuclear power plant have to be constructed and installed in such a way that the plant operates as planned both in normal operation and in case of an incident. Some components, structures and systems have nuclear safety significance only in the case of a reactor accident. For instance, they could prevent the spreading of harmful radiation, and hence they have different characteristics compared to those used in conventional power plants, which poses certain challenges for the construction and installation. Additional issues could be brought on if there are novel features in the technology and if some components are designed and/or manufactured in an unconventional manner.

The next sections summarize the intrinsic characteristics of construction activities and the associated challenges, the second-order challenges, related to contextual characteristics of large projects, and generic challenges, which incorporate features of the intrinsic and second-order factors.

3.2.1. Intrinsic characteristics of construction activities

Construction is inherently a site-specific project-based activity (Cox and Thompson, 1997), which brings two features: a) focus on individual projects and component-by-component activity, which favours a narrow time and scope perspective, and b) the need for local adjustment at the construction site due to lack of complete specification and an unpredictable environment. Related to the narrow focus is the expectation that the manufacturing organizations and civil construction companies should take only their own area of responsibility into account. Competitive tendering in construction typically results in subcontracting, which in turn tends to be carried out at the lowest possible cost (Cox and Thompson, ibid.).

Dubois and Gadde (2002) indicated that the construction industry has features of a "loosely coupled system" (Weick, 1976). They analysed the couplings among activities, resources and actors, and indicated that the pattern of couplings seemed to favour short term productivity while hampering innovation and learning. The focus on project efficiency in construction, the short time perspective and the lack of systemic view could jeopardize safety.

The construction industry as characterised by high labour intensity and mobility, and high entrepreneurial risk. As it is typically composed of small businesses, the small size of the average firm and mutual competition, resulting in narrow profit margins, do not allow the great majority of firms to invest in research and development activities (Zantanidis and Tsiotras, 1998). Construction personnel are composed predominantly of labour workers and technicians (e.g. plumbers, carpenters, welders, etc.), that are not necessarily experts in the nuclear industry as for example the personnel in the design phase. Usually, construction workers perform their tasks according to specifications and requirements defined by another party, such as designers. The hierarchy management model, typically utilized in construction industry, emphasises bilateral interactions and information flow, which is problematic because it hides the complexity of the interdependencies in the project network (Kornelius and Warmelink, 1998; Oedewald and Gotcheva, submitted). In construction activities there is a focus on occupational safety issues rather than on system safety. Also scientific research concerning subcontractors and safety is largely focused on occupational safety, with few exceptions (e.g. Dahl, 2013; Quinlan et al., 2013; Nesheim and Gressgård, 2014). In studies concerning occupational safety in construction projects and the occupational safety of subcontractors, awareness of safety issues, management style of immediate supervisors and financial pressures have been found to be factors explaining the individual safety-related behaviour (Choudhry and Fang, 2008; Jaselskis et al., 2008; Larsson et al., 2008; Mayhew et al., 1997). Construction workers have their traditional occupational culture and practices, which they bring along to the nuclear industry.

In a summary of nuclear safety culture lessons learned during construction phase, the Royal Academy of Engineering (2012) emphasized that in the construction phase of a nuclear new build, an open culture should be encouraged to ensure that individuals feel able to speak up about organizational issues, such as an observed lack of competence, excessive pressure to accomplish a task, or to make decisions.

3.2.2. Second-order safety culture challenges in construction

Albrechtsen and Hovden (2014) discussed how problems related to quality assurance, coordination and communication in early phases of a large project cascaded and manifested in the construction phase of the project. The authors discussed the problematic *fragmentation of tasks and responsibilities in large projects* (e.g. outsourcing and multinational workforce speaking different languages), and indicated that the emerging accident risks were largely attributed to deficiencies and deviations from other organizational units; different units were blaming each other, top management and the builder. Recent studies on the governance of Olkiluoto 3(OL3) nuclear power plant construction project in Finland indicated how the *responsibility and risk were transferred to project actors, who were not capable of carrying them properly* (Ruuska et al., 2009; 2011)

Oedewald and Gotcheva (submitted) studied safety culture and subcontractor network governance in a complex safety critical project. The study identified a set of practical and theoretical challenges in applying the concept of safety culture in a complex, dynamic network of subcontractors involved in the construction of a new nuclear power plant in Finland.

The challenge of understanding in practice what is safe and what is unsafe

In large nuclear projects, there are hundreds and even thousands of workers from different countries with little knowledge of the nuclear industry context and understanding of the nuclear specific hazards. Without sufficient prior knowledge and experience in the nuclear industry, hazards may be difficult to understand. Complex systems pose countless opportunities for things to go wrong. Some of the mechanisms involved are easy to perceive, some involve rare phenomena that only few experts master (Grøtan et al., 2011). If workers have an insufficient understanding of quality requirements and their role for nuclear safety due to, for example, lack of experience or language barriers, they might not fully comprehend the need to follow the procedures and requirements, which could compromise safety.

Nowadays, the construction of a nuclear power plant is carried out by a complex and often multinational network of subcontractors. The same applies to manufacturing and installation activities in major modernizations. The construction and installation activities are usually performed by several tiers of international subcontractors, which form long supply chains. Although overall quality and safety falls within the work scope, contractual arrangements often direct the focus to economic aspects, such as faster accomplishment of the assignment at the site, and pressure to move to the next construction site. Such economic pressures, paired with insufficient understanding of safety consequences of the work, could jeopardize safety. In the case of OL3 construction project, many subcontractor companies and their workers had little prior experience of the nuclear power industry. Thus, expectations on nuclear specific working practices were not always understood even if they were communicated via project specifications or formal contracts. The subcontractor companies were not prepared for the precise nature of quality requirements in the Finnish nuclear community culture.

The challenge of dynamic project network with temporary workforce

Related to the contractual arrangements is the challenge of temporary workers; usually subcontractors have a short-term contract, related to performing certain assignments at the nuclear site, after which they are leaving, and other subcontractors are coming to continue the process; there is a constant flux of personnel. Due to the dynamic changes in the personnel, training results are relatively short-lived and cannot be sufficiently shared in the organization. The dynamic nature of the project and temporary contracts may reduce motivation of different parties to invest in joint development of activities and culture. The feelings of job insecurity and stress among workers could affect the openness and questioning attitude. In such a fast-changing networked context, the shared time spend with various partners is short and fragmented, which sets constraints for accumulation of lessons learned through informal interactions.

The interviews with representatives of the Swedish regulator SSM indicated that when there are subcontractors involved in construction and installation projects, as well as in big modernizations projects, it is difficult both for the regulator and the licensees to understand the contractors' impact on safety:

> *If it's a big modification and many subcontractors, it is really hard to get the safety culture for all the people involved, especially if there are people involved for just a few weeks, what impact they have on the safety?*

In another study, Gotcheva et al. (2013) indicated that in the construction phase of a large-scale nuclear project nuclear safety comes near to promoting technical quality of components and systems, that is, the focus is on ensuring safety through case-by-case fixes of deviations, problems and deficiencies. However, the size and complexity of a large nuclear new build project challenges the ability to follow the big picture and handle technical, human and social phenomena at the same time. Also the regulator's possibility to gain a good overview of safety culture related issues in the construction phase is challenged by issues that traditionally have not been part of the regulatory inspections' scope, such as relations in informal social networks.

The global management consultancy Arthur D. Little (2010) examined the management and technology issues facing new nuclear build projects, and concludes that besides the technical complexity, the management issues are underestimated. Thus the authors emphasized the importance of professional project management in large nuclear projects. It was stated that *new nuclear build projects are not managed from a holistic perspective* and the *complex interdependencies between project activities are often underestimated*. They identified the following key management challenges:

- Start of construction before design completion (including changes imposed by owner);
- Insufficient incorporation of regulatory requirements into design and lack of reliability of licensing process;
- Insufficient schedule integration and communication between suppliers and owner;
- Lack of strategic and operational planning by the owner (processes, activities, milestones);
- Insufficient control and progression of the new build project (time, costs, quality);
- Poor interface definition and management between involved parties (including language handling);
- Hesitant implementation of countermeasures for identified risks and constraints;
- Lack of timely provision of suitably qualified and experienced staff (owner and suppliers)

The UK Parliament recently issued a report "Building new nuclear: the challenges ahead", which summarizes the lessons learned in new nuclear projects worldwide, including the design, construction and commissioning phases (House of Commons, 2013). The report noted that *adopting best practices from other countries should be implemented with caution,* and that lessons learned cannot be easily transferred because of "differences in working cultures, geography and regulatory regimes between countries" (p. 12), meaning that every new nuclear build project should be considered a "first of a kind" initiative.

3.3. Safety culture challenges in commissioning phase

Commissioning is defined in the IAEA Glossary (2007) as *"the process by means of which systems and components of facilities and activities, having been constructed, are made operational and verified to be in accordance with the design and to have met the required performance criteria. Commissioning may include both non-nuclear and/or non-radioactive and nuclear and/or radioactive testing."*

Commissioning is a critical phase in the lifecycle from the nuclear safety point of view because it aims at noticing and fixing all deficiencies and possible errors before the nuclear fuel is loaded and the plant is taken to operation. After fuel loading, mistakes could have significant safety consequences, just as in plants already in operation. In modernization projects, performing the safe commissioning of a new system is challenging as well due to the need to test new features within the multitude of existing systems in an operational plant.

3.3.1. Intrinsic characteristics of commissioning activities

Commissioning is more final and functional than construction: the end point of the project is more visible, and there is the challenge of dealing with time pressure and "tunnel vision"; that is, emphasis on failures and issues that are specified in the test programmes and less focus on more vague problems. In such a context, there might be a lack of conservative decision-making. Since the hazards of the nuclear fuel are more tangible in commissioning than in construction, there are higher safety risks. Nuclear safety should be a very tangible topic in the organization, as commissioning activities also involve the loading of nuclear fuel and the associated hazards and radiation protection challenges.

During commissioning, the personnel on site are more educated and experienced on nuclear technology; therefore, the knowledge base is different from the construction phase. It can be assumed that in commissioning it should be clearer what is safe and what is not safe, and the nuclear specific quality requirements should be understood. However, such experienced personnel are somewhat limited in numbers and is often fully involved in the existing plants. Provided that there are many new builds and modernization projects worldwide, the nuclear industry is facing the challenge of bringing many newcomers, sometimes "straight from the university", and training them to gain experience and contribute to the activities in a meaningful way.

There are fewer companies present at the site compared to construction phase during commissioning but there are still multiple parties and external subcontractors involved, for example, suppliers who have manufactured or installed certain components or sub-systems might be involved in testing their functionality. More integration of activities is required because of the organizational and technical interfaces: understanding of the big picture actualizes in commissioning phase especially because there is a need to take a stance and confirm that the systems are safe and that they can proceed further towards operating the plant. Thus in a context of increased social and technical complexity, management of the unexpected is a topical challenge in commissioning.

Cagno et al. (2002) studied the commissioning process from the perspective of risk analysis and management of chemical process plants, and indicated that there are four main challenges in the commissioning phase:

1) *Uncertainty in events*: Provided that process plant commissioning relates to extremely complicated systems, commissioning always faces deviations from the expected plant performance, which are at times new and unpredictable, particularly when a new technology is implemented;
2) *Pressure of time*: The project schedule is often complicated by the accumulated delays from previous phases, which means that the time available to complete start-up is often very short;
3) *Technological complexity*: Commissioning is a critical phase from a technical point of view and demands collaboration of a large number of people from different technical disciplines. Operators should be able to address problems and critical issues connected to areas other than their own area of competence;

4) *Managerial complexity*: Commissioning of a complex plant requires preparation and separate start-up of many systems and their correct interfacing, which implies the importance of coordination and good project management in the commissioning phase.

Zerger and Noël (2011) analysed events related to the commissioning of new nuclear power plants as reported to the IAEA International Reporting System database. After the initial screening of the database, they have analysed in detail 34 events to highlight the lessons learned specific to different components and to raise the general recommendations related to the commissioning. They found out that almost half of the events were related to I&C deficiencies, one in four events was related to mechanical components (e.g. pipes, valves, pumps) and the remaining events were related to fire protection, electrical components and the emergency diesel generator. The authors summarized the main generic challenges as follows:

- Time of testing: Long period of inactivity and the construction of other equipment during this period challenge the test results.
- Scope of the tests: It is challenging to test the system under representative conditions and to understand how simultaneous tests may have an influence on each other's results.
- Documentation of the tests: Refer to the original design drawings and requirements, and understanding where they are coming from is a challenge regarding the acceptance of commissioning tests.
- Test acceptance criteria: The challenge is that the criteria should be able to verify not only the functionality of a system or component but also its level of performance.
- The systems reconfiguration after commissioning tests: The proper reconfiguration of the systems after the commissioning tests should be checked.
- The management of the temporary devices: Understanding what is temporary and what is not is challenging. Temporary devices used at the commissioning phase should be properly documented to ensure that all the temporary devices are removed after their use.

3.3.2. Second-order safety culture challenges in commissioning

The possible lack of experience due to long time without new nuclear power plant construction logically sets challenges for commissioning as well. Some of the plants soon to be commissioned are first-of-a-kind plants, such as the EPRs (European Pressurised Reactors). Due to the uncertainty and the technical and social complexity of such megaprojects, commissioning poses challenges for utilizing conservative decision-making; that is, prompt and prudent consideration of safety impacts of solutions, and handling the transfer of responsibility and related nuclear safety responsibility in the case of a turn-key contract.

Recently, there were some studies and media attention focused on the controversial experience of megaprojects in Europe, which involve innovative technology and complex supply networks. Some human and organizational challenges from two cases are briefly summarized here, namely London Heathrow Terminal 5 and Boeing Dreamliner 787.

London Heathrow Terminal 5 (T5) was designed to be the most technologically advanced airport terminal in the world by speeding passengers through the airport as quickly and comfortably as possible. The baggage handling system at T5 is the largest in Europe, and was a first-of-a-kind in the sense that it was one of the airline industry's first attempts to "combine customer information from across the complete booking-to-fulfilment lifecycle in a single unified data layer" (Krigsman, 2008). The work has involved over 180 IT suppliers. The project was completed on time and within budget. The planning for the commissioning phase was extensive as "training and familiarization procedures were carried out for a year so that staff could test the new IT systems in place throughout the building" (*Computing*, 2008).

Nevertheless, the very opening of T5 was a customer and public relations disaster. On the first day in operation, the baggage handling system at T5 failed: there were long queues and delays at the terminal; four days after opening, more than 28 000 bags were missing, and more than 500 flights were cancelled (Baker, 2008). The Chief Executive of British Airways publicly acknowledged that the importance of the commissioning phase of the project, including testing and training, was underestimated (House of Commons, 2008):

> *We compromised on the testing of the building as a result of delays in the building programme. If I was to pick on one issue that I would do differently...it is that particular issue.*

There have been emerging warnings from other similar large scale projects: for example, Denver and Hong Kong airports had significant baggage handling problems as well (Krigsman, 2008). Besides, a seemingly unconnected issue on the opening day played a role as well; a majority of the staff at T5 was unable to reach their workplace on time because there were not enough parking places available. Reports indicated that T5 problems were caused by two main factors: insufficient communication between owner and operator, and poor staff training and system testing (House of Commons, 2008). Even though T5 was a success in terms of schedule and budget, its senior management was not able to demonstrate a systemic understanding on how a variety of issues can combine and affect the core process.

Another recent case comes from the airline industry. The Dreamliner 787 was designed to be Boeing's new flagship large commercial aircraft; the most fuel-efficient airliner and the world's first major airliner to use composite materials as primary material in its airframe. Other innovative features included multiple new electrical systems, power and distribution panels. Boeing used an unconventional subcontracting strategy as well: about 70 per cent of the 787 was outsourced to tier-1 suppliers around the globe, a portion of which was then outsourced to additional tiers (Gates, 2013; Tang and Zimmerman, 2009). However, there were quality issues in design and construction phases related to extensive outsourcing and the challenges for managing the supply chain (Kotha and Srikanth, 2013). The commissioning phase of the 787 lasted around four years and involved two stages of testing and verification activities: pre-flight ground testing (2007-2009) and flight testing (2009-2011) (Wikipedia). Although the 787 Dreamliner project used relatively unproven battery systems, the supervisory authority US Federal Aviation Administration (FAA) had left the testing and certification to the manufacturer Boeing.

Boeing's 787 project was over budget and over schedule. The first planes were delivered over three years late. There were several electrical failures and incidents, related to malfunctions of the lithium-ion batteries. The FAA-Boeing review team concluded that the 787's testing procedures relied on assumptions that no longer worked with the aircraft's advanced electrical systems; that is, the certification and safety analysis applied for the 787 were the same as for a less complex aircraft, which did not rely heavily on a globalised supply chain (Trimble, 2014). In January

2013, after a battery fire erupted on a parked Japan Airlines 787 at Boston Logan airport, all Boeing 787 Dreamliners worldwide were grounded, based on safety concerns (Williard et al., 2013).

Both cases are illustrative for the complexity of commissioning in large projects, especially when there is a first-of-a-kind innovative technology and a huge scope of work, involving a multicultural network of subcontractors. These examples indicate that extensive commissioning activities can ensure valid results provided they are based on correct assumptions, relevant to the specific project context. The critical role of the supervisory authority was also highlighted by the Dreamliner 787 case, as well the importance of assessing and managing cultural differences within the project network. These cases demonstrate the multi-dimensional nature of challenges, which could be experienced during commissioning of large complex projects, and open avenues for organizational learning.

3.4. Safety culture challenges in decommissioning phase

In this chapter the authors review only partially some experiences concerning decommissioning, because the theme emerged in the SSM interviews; however, this phase was beyond the scope of the study.

According to IAEA (2007), *decommissioning phase* includes "*administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility, except for a repository or for certain nuclear facilities used for the disposal of residues from the mining and processing of radioactive material, which are 'closed' and not 'decommissioned'.[...] The actions will need to be such as to ensure the long term protection of the public and the environment, and typically include reducing the levels of residual radionuclides in the materials and on the site of the facility so that the materials can be safely recycled, reused or disposed of as exempt waste or as radioactive waste and the site can be released for unrestricted use or otherwise reused.*"

IAEA (2002) indicated that strategic decisions about the way the transition from operation to decommissioning occurs will directly influence the human resource strategy, as there will be increased pressure to reduce staff costs and hence numbers. When a nuclear power plant reaches the decommissioning phase in its lifecycle, this will bring feelings of uncertainty and insecurity for the staff, as they might not see any future in the organization. Clear management communication is important to reduce insecurity and to clarify future prospects. Potential human and organizational challenges are the affected motivation of the personnel, psychological stress and the importance of human resources management before and after shutting down. The dismantling stage pose challenges related to knowledge of the changing faces of risks, as the plant, radiation hazards, and contamination risks are changing. That is, compared with radiation protection in operating units, decommissioning and dismantling activities pose different risks; thus nuclear safety knowledge in the organization needs to adapt to these changes.

In the SSM interviews, shutting down of Barsebäck plant in Sweden was also recognized as a new activity, which involves different risks and changes quickly, hence it poses challenges to continue to work safely. Besides, the need for radiation protection varies due to the physical changes of the facility:

> *In decommissioning, also radiation protection work changes a lot because all of a sudden you have radiation in places where you are not used to, and to have a consistent awareness of the safety issues. Maybe it's not as dangerous as when the fuel was there but it is dangerous in a different manner – it changes so quickly in the different phases in the decommissioning – how does that change the individual's' work and what they need to think about.*
>
> *The biggest thing is to understand that it is still important to work in a safe manner, to understand where the hazards are. Also, they look at it as a big project, they think about the risk in the main project, they are so much in the project mode (time and money mainly), they forget about the actual risk the workers have to deal with.*
>
> *Decommissioning is hard – it is really hard to understand that the requirements need to be there because you are doing something that you haven't done before*

It was identified as a challenge for the licensee that during decommissioning *"good care of people is important"*. This refers to maintenance of motivation and open discussion about the future, also practical care was taken for workers as the licensee was supporting them financially for one year, and helping them with relocation and finding new job. The regulator recognized the need for additional personnel during decommissioning activities.

Slavcheva et al. (2005) studied safety culture and organizational challenges during the transition period from operation to decommissioning. The study emphasized that pre-shutdown is an important period in the lifetime of a nuclear power plant due to the changes and challenges to be faced by the management, which include issues related to safety culture, plant safety and nuclear waste. The key human and organizational challenges to be timely faced were identified as: preservation of staff competence and moral, management and organizational capability, preservation of knowledge and corporate memory, preservation of safety culture, surveillance and permanent control to maintain adequate level of nuclear and radiation safety, development of appropriate solutions for the new incoming issues such as the future of the site and the future of the workers.

4. Discussion

The literature review and the researchers' experience indicate that the possible safety culture challenges in different nuclear plant lifecycle phases are partly the same and partly different from those of operating organizations. Prioritizing safety when the schedule is pressing and economic constraints are tight for example, are challenges shared by the all the lifecycle phases. Conservative decision making is expected from actors in all phases of large projects as well. However, *the situations*, in which the organization's tendency to prioritise other-than-safety goals would surface, and the *reasons why* the organization ends up acting that way may differ. Therefore the means to support good safety culture might have to be diverse.

In the design phase the organizations are challenged by the conceptual features of design work, which are difficult to standardize by detailed instructions, and which hinders the ability to anticipate how the design components will function in reality. The likelihood for design error is reduced by involving many individuals with various competences and continual iterative checks in the process. On the one hand, the regulator and the licensees are not always actively involved early in this process, often due to legal constraints, which could contribute to latent issues. On the other hand, there is the challenge that the regulator, licensee and different parties are so heavily involved, that the design process becomes lengthy and bureaucratic. This could hinder designers' opportunity to concentrate on and take responsibility for the actual design work and keep focus on the big picture instead of mechanically focusing on the paperwork. At this phase, the tendency in the nuclear industry to rely on proven solutions could limit the possibilities for finding novel functional solutions.

Design errors have received increased attention in the field of safety science, and strategies for preventing their occurrence have been proposed (Hatamura, 2009). From safety point of view, it is not only the design errors that are relevant. The delay of a design process may also become a significant safety issue, since operating units may then face pressures to continue operations with less reliable old technology or with systems where the availability of spare parts is limited. Human factors and ergonomics are usually considered in the design of tools, interfaces and systems to provide end-users with artefacts satisfying usability criteria, such as context of use, easiness of use, learnability, and satisfaction. Still, the design organizations and design processes have seldom been the subject of human factors or safety culture studies.

In the *construction* and *installation phases*, the challenge is to prioritize safety in a context of thousands of international workers involved in various activities, who are only temporary at the site, speak different languages and have little knowledge of nuclear industry context and understanding of the nuclear specific hazards. It might be difficult for workers to follow the quality requirements when they do not fully comprehend their role in nuclear safety. The long supply chains are not a danger to safety as such, but they challenge the balance between safety and economy because of the pressure for efficiency and the difficulties of communicating safety culture relevant information throughout the supply chain.

In the *commissioning phase* the end point of the project is approaching, which brings challenges of prioritizing safety in a context of time pressure and "tunnel vision", which could hinder the ability for conservative decision-making. Although commissioning involves more highly educated and experienced personnel, the higher safety risks, related to the nuclear fuel loading stage, bring additional pressure to train newcomers in understanding and dealing with specific nuclear hazards; for example, subcontractors might be experts in commissioning certain system but do not necessarily know nuclear industry. In this context of increased social and technical complexity, management of the unexpected becomes a topical challenge.

The decommissioning phase brings challenges related to human resources management and the changing context in the plant from a nuclear safety, organizational and technical perspective. From a human resources management perspective, safety should be prioritized in a situation where staff is reduced, strong feelings of uncertainty and insecurity are shared, and motivation is affected. The dismantling stage poses challenges for safety insofar as the physical layout of the plant is changing, along with the radiation hazards and contamination risks.

However, the safety culture model, or the normative ideal model of good safety culture, can be the same in all lifecycle phases. Still, the knowledge aspect, which proves to be crucial especially when dealing with subcontractors, is fairly subtle in some safety culture models; for example, the IAEA model. The same is also valid for the systemic approach to safety. The safety culture discussions do not usually put much attention to how safety is understood, and the organizations may have a predominantly technical and mechanistic view on how safety is created and ensured. The need for systemic safety view, which was also recognized after Fukushima accident, should be incorporated into the safety culture models to avoid a situation where safety is developed in a simplistic or fragmented manner. Besides, the means to achieve safety culture might differ since the work processes and people's knowledge base vary in different phases.

Koivula (2012) explored challenges related to safety culture in a nuclear power plant new build organization. She identified four specific difficulties, facing a new licensee without previous experience in operating a nuclear power plant: 1) nuclear safety is an abstract concept before operation; 2) there is a lack of understanding how one's activities relate to the safety of the new plant; 3) it is difficult to realize that dealing with nuclear power plant sets special expectations regarding the quality of the work; 4) development of routine practices from carrying out similar work with different specifications could affect people's willingness and ability to follow procedures. Hence, the rationale behind the different kind of expectations in the nuclear industry should be explained to the personnel. Accordingly, it might be difficult for experienced personnel in the nuclear industry to appreciate that newcomers have quite much to learn about nuclear safety. The special expectations and requirements regarding the quality of the work are not easy to understand and internalize, since many of the participants of a new build project are newcomers to the industry, or people who have learned practices, gained under different conditions and specifications. This implies that the nuclear safety requirements and their implementation may not be familiar beforehand.

Overall, generic safety culture challenges stem from the fact that activities performed in the design, construction & installation, and commissioning phases of the nuclear lifecycle evolve in a complex socio-technical system operating under uncertainties, with multiple interdisciplinary international stakeholders that have conflicting goals, under time and financial pressures. Although safety is critically important, the *unit of analysis* in complex multinational projects might still be *unclear.* Whose culture should be analysed/monitored/improved at the nuclear construction site, which represents a complex multinational network? In the nuclear industry, the responsibility for nuclear safety usually lies within the licensee, and the regulator's requirements and oversight activities primarily focus on the licensee organization. In some projects, the licensee might have a limited role in the construction activities if they are outsourced to the vendor.

The Finnish Government decree on Safety of Nuclear Power Plants (2013), section 28, indicates that *all organizations* involved in the nuclear project, not only the licensee, are expected to engage in processes and behaviours that are believed to exemplify good safety culture. In practice, it is impossible to approach safety culture of a complex networked activity by assessing, monitoring or developing culture of each of the companies case by case. Instead, it is the *network as a whole* whose dynamics should be understood and the network should be taken as a unit of analysis.

However, the culture which emerges in a complex network may not be homogeneous and distinct because many of its members develop multiple identifications: the project, own company, or professional group (e.g. welder, concrete manufacturer, electrician, quality control engineer), ethnic group, etc. Still, culture does not necessarily need to be uniform and strong to be characterised as a good safety culture. The competing interests, diverse competencies and conflicting viewpoints that heterogeneous groups bring into the activities are opportunities to continually reflect on the process of creating safety (Silbey, 2009). Nevertheless, certain aspects need to be shared, especially the conception that safety is an important goal.

National cultural differences with regard to safety culture have recently been perceived as a topical issue. In 2014 the IAEA organized a workshop on global safety culture and national factors relevant to safety culture, in which the importance and role of cultural differences have been recognized, and the role of each nation involved in nuclear power for gaining insights about its own culture was highlighted. It should be acknowledged that certain safety culture characteristics (such as a questioning attitude) may manifest in various ways in different national cultural contexts.

The Institute of Nuclear Power Operations (INPO, 2010) developed principles for successful new nuclear plant construction, focused on a culture of excellence and high quality standards, based on lessons learned from past problematic nuclear projects, as follows:

- Key managers have relevant nuclear experience;
- Complete and correct design;
- Well qualified personnel and trade;
- Strong first-line supervision to ensure quality during the progression of the work (not afterwards, when the work is already done);
- Realistic, accurate, well-developed and well-communicated schedule;
- All project personnel is aware of the specific nuclear requirements for construction;
- Adherence to the design documents, and well planned handover to owner.

The conception of a well-functioning organization in the nuclear domain can be described as mechanistic and hierarchical, as it emphasises clear requirements, control and supervision (Perin, 2004). However*, the traditional hierarchical management is insufficient and sometimes inadequate.* The “culture of control” in nuclear industry and the generic governance mode play a role in the development of management models. The management culture of current large new nuclear build projects can be characterised as top-down hierarchy: the regulators set the overall requirements, which the licensee needs to comply with. The licensee requires the vendor to take the requirements into account, who in turn translates these into applicable requirements for the contractors and subcontractors. However, the assumption of bilateral interactions and information flows underestimates the fact that parties in a nuclear project network might act differently than expected because their work processes are also affected by other factors than those imposed by the hierarchical structure. In the traditional hierarchical management communication and decision making, structure is rigid and slow, especially if the work does not proceed according to plans and local adaptations are needed.

5. Conclusions and recommendations

The objective of the study was to provide a better understanding of safety culture challenges in different lifecycle phases of large nuclear power plants projects by summarizing and integrating the findings of relevant studies and international experiences. In addition, interviews conducted at the Swedish Radiation Safety

Authority were utilized as background information. Although decommissioning is beyond the scope of the study, some experiences related to this phase were also reviewed.

Regarding the *design phase*, licensees and the regulator should be actively involved early in the design process through frequent personal communication and coordination with the design organizations, which work is often outsourced. This approach could minimize the need for the licensee to adapt to already developed and manufactured design solutions, or possible delays related to a need to re-design the solution. However, in some countries, for instance Sweden, there are legal limitations for such a proactive approach, which might require some political decisions in favour of this approach to be made. Licensees and the regulator should acknowledge that understanding the regulatory requirements is a crucial competence area for designers in the nuclear industry, which should be supported by different tools. Designers' energy and focus should be steered towards the development of the final artefact and understanding the operational context, and not dispersed through thematic vagabonding. It should be noted that the intangible nature of nuclear safety in this lifecycle phase may lead to shifting the focus to paperwork and a limited sense of responsibility for the end-product and overall plant safety. In major modernizations and new build projects the entire design process can take years, during which staff turnover is likely, which poses challenges for preserving knowledge and continuity. The licensees should take measures to improve the coordination and shared understanding between different stakeholders in the design process. The role of the regulator should be clearly communicated in the design process: for example, if the regulatory strategy is very prescriptive and the regulator is involved in reviewing the design from the early stages, the licensee may perceive that the regulator would be responsible for consulting the process and coordinating the solutions.

In the *construction & installation phases* achieving a good safety culture is facing the practical difficulties of facilitating shared cultural features in a dynamic project setting with multiple changing actors and not yet present nuclear hazards. The dynamic nature of these phases means that the network and the contracts of the employers are often temporary. The complexity and size of the network of international subcontractors requires various activities, such as coordination, training, foreign language interpretation, and sufficient attention for developing shared cultural characteristics and practices at the very beginning of the construction phase. Special challenges are ensuring the focus on safety and quality of the manufacturing and construction work in long supply chains, in which economic constraints cause pressure, and specific knowledge on nuclear safety principles and hazards is insufficient. Subcontractors involved in construction activities should understand the functionality and safety significance of their work scope because this influences their safety attitudes and perception of deviations, and facilitates reporting and following rules and procedures. To this end, they should actively engage in direct and frequent interaction with the vendor. However, language barriers and cultural differences could be a challenge in this process. Knowledge of local requirements and practices as well as understanding of the impact of national culture differences on safety should be emphasized.

Organizational challenges in the *commissioning phase* are related to time pressure, as the end of the project is approaching, as well as to the clarity and transfer of roles and responsibilities, and preparations for dealing with the unexpected with regard to the nuclear fuel loading stage. In this phase conservative decision-making should be supported, and higher safety risks associated with the fuel loading stage should be clearly communicated to all parties involved: nuclear safety and the associated hazards should become tangible topics for discussion. The holistic understanding actualizes in commissioning because there is a need to make many prompt and prudent decisions regarding the safety of the tested components, structures and systems. Another safety culture challenge is the allocation of responsibilities between parties, for example, manufacturer, vendor, licensee, operator, in case of test problems. Furthermore, in case of emergencies it might be difficult for the operating organisation to maintain the vigilance and clarity of roles. In a context of increased social and technical complexity, management of uncertainty is a topical challenge as well, which requires the various actors to gain a better knowledge and understanding on new phenomena, related to the systems behaviour.

The *decommissioning phase* of the lifecycle requires handling a wide range of human resources issues, which arise from the new situation and the feelings of uncertainty and insecurity for the staff, as they might not see a future in the organization. The licensee should clearly communicate the current arrangements and future prospects, preserve staff competence and motivation, and maintain a high relevance of safety culture even though nuclear fuel might not be present anymore. Understanding of the changing faces of risks should be strengthened as there are new radiation hazards and contamination risks. The regulator should reorient its supervision accordingly, allocate sufficient staff to keep adequate presence onsite, and maintain an open communication with the licensee.

Finally, it is concluded that to improve anticipation of human and organizational challenges in different lifecycle phases, licensees and regulators need to take into consideration that each lifecycle phase has its own intrinsic characteristics, from which specific safety culture challenges emerge, yet all lifecycle phases share certain generic characteristics. The present study contributes to a better understanding of constrains and characteristics, provided by the specific context, in which design, construction, installation, commissioning and decommissioning activities evolve.

References

Albrechtsen, E., Hovden, J. (2014). Management of emerging accident risks in the building and construction industry. In Proceedings of WOSNET 2014, 7th international conference "Learning from the past to help shape the future", 30 September - 03 October 2014, Glasgow, Scotland, UK.

Andriopoulos, C. and Lewis, M. (2010). Managing innovation paradoxes: Ambidexterity lessons from leading product design companies, Long Range Planning, 43, pp. 104-122.

Arthur D. Little (2010). Is nuclear new build more a management than a technology challenge? Energy & Utilities. Available at http://www.adlittle.com/downloads/tx_adlreports/ADL_Nuclear_New_Build_Unveiled.pdf

Aspelund, K. (2006). The design process. Fairchild publications: USA.

Borja de Motoza, B. (2003). Design management: using design to build brand value and corporate innovation. Canada, Alworth Press.

Brady, T. and Davies, A. (2014). Managing structural and dynamic complexity: A tale of two projects. Project Management Journal, 45, 21-38.

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

Choudhry, R. M. and Fang, D. P. (2008). Why Operatives Engage in Unsafe Work Behavior: Investigating Factors on Construction Sites. Safety Science, 46(4), pp. 566-584.

Computing (2008). Staff at T5 equipped to use new IT system, available at http://www.computing.co.uk/ctg/analysis/1855325/staff-t5-equipped-it

Cox, A. and Thompson, I. (1997). 'Fit for purpose' contractual relations: determining a theoretical framework for construction projects. European Journal of Purchasing and Supply Management, 3, pp. 127-135.

Cross, N. (1982). Designerly Ways of Knowing. Design Studies 3 (4): 221-27.

Curtis, B., Krasner, H. and Iscoe, N. (1988). A field study of the software design process for large systems. Communications of the ACM, 31, 1268-1287.

Dahl, O. (2013). Safety compliance in a highly regulated environment: A case study of workers' knowledge of rules and procedures within the petroleum industry. Safety Science 60, pp.185-195.

Devgun, J. (Ed.) (2013). Managing Nuclear Projects: A Comprehensive Management Resource. Woodhead Publishing series in energy; no. 60.

Dubois, A. and Gadde, L.-E. (2002). The construction industry as a loosely coupled system: implications for productivity and innovation, Construction Management and Economics, 20(7), pp. 621-631.

Finnish Government (2013). Government Decree on the safety of nuclear power plants (717/2013).

Flyvbjerg, B. (2014). What you should know about megaprojects and why: an overview, Project Management Journal, April/May, 45(2), pp. 6-19.

Flyvbjerg, B., Bruzelius, N. and Rothengatter, W. (2003). Megaprojects and risk: An anatomy of ambition. Cambridge University Press.

Gates, D. (2013). Boeing 787's Problems Blamed on Outsourcing, Lack of Oversight. The Seattle Times Business/Technology, 2 February 2013. Available at: http://seattletimes.com/html/business technology/2020275838_boeingoutsourcingxml.html

Gotcheva, N., Oedewald, P., Macchi, L., Alm, H., Osvalder, A.-L. and Wahlström, M. (2014). Managing safety culture in design activities: Evidence from the Nordic nuclear power domain. In Proceedings of WOSNET 2014, 7th international conference "Learning from the past to help shape the future", 30 September - 03 October 2014, Glasgow, Scotland, UK.

Gotcheva, N., Reiman, T. and Oedewald, P. (2013). Follow-up evaluation of safety culture at Olkiluoto 3 nuclear power plant construction site. Confidential customer report.VTT-CR-04386-13.

Grøtan, T. O., Størseth, F. and Albrechtsen, E. (2011). Scientific foundations of addressing risk in complex and dynamic environments. Reliability Engineering & System Safety. 96 (6), pp. 706-712.

Grote, G. (2004). Uncertainty management in the core of system design. Annual Reviews of Control, 28, 267-274.

Grote, G. (2009). Management of Uncertainty: Theory and Application in the Design of Systems and Organizations. Springer.

Hale A., Kirwan B. and Kjellén U. (2007). Safe by design: where are we now? Safety Science, 45, 1-2, pp. 305-327.

Hatamura, Y. (2009). Learning from Design Failures. Springer.

Hoffman, R. and Woods, D. (2011). Simon's Slice: Five Fundamental Trade-offs that Bound the Performance of Human Work Systems. The 10th International Conference on Naturalistic Decision Making, Orlando FL.

Hollnagel, E. (2009). The ETTO Principle: Efficiency-Thoroughness Trade-Off. Burlington, VT: Ashgate.

House of Commons (2008). The Opening of Heathrow Terminal 5: Twelfth Report of Session 2007-08; Report, Together with Formal Minutes, Oral and Written Evidence. Great Britain: Parliament: House of Commons: Transport Committee.

House of Commons (2013). Building New Nuclear: The Challenges Ahead, Sixth Report of Session 2012–13, Volume I. London: The Energy and Climate Change Committee.

IAEA (1996). Defence in depth in nuclear safety: INSAG-10. Vienna: International Atomic Energy Agency.

IAEA (2002). Safe and effective nuclear power plant life cycle management towards decommissioning, IAEA, Vienna, IAEA-TECDOC-1305.

IAEA (2004). Managing modernization of nuclear power plant instrumentation and control systems. Vienna: International Atomic Energy Agency.

IAEA (2007). IAEA Safety Glossary: Terminology used in nuclear safety and radiation protection. Vienna: International Atomic Energy Agency.

IAEA (2012). Safety Culture in Pre-operational Phases of Nuclear Power Plant Projects. 2012; Safety Reports Series 74. Vienna: International Atomic Energy Agency.

IAEA (2013). Regulatory oversight of safety culture in nuclear installations. Vienna: International Atomic Energy Agency.

INPO (2010). Principles for Excellence in Nuclear Project Construction. Institute of Nuclear Power Operations, INPO, 09-007, Revision 0, May 2010.

Jaselskis, E., Strong, K, Aveiga, F., Canale, A. and Jahren, C. (2008). Successful multi-national workforce integration program to improve construction site performance. Safety Science, 46, pp. 603-618.

Kainulainen, E. (Ed.) (2009). Regulatory control of nuclear safety in Finland. Annual report 2008. STUK-B 105. Säteilyturvakeskus, Helsinki.

Kainulainen, E. (Ed.) (2011). Regulatory oversight of nuclear safety in Finland. Annual report 2010. Edita Prima Oy, Helsinki.

Kirwan, B., Hale, A. R. and Hopkins, A. (2002). Insights into safety regulation. In: Kirwan, B., Hale, A. R. & Hopkins, A. (Eds.), Changing Regulation Controlling Risks in Society. Oxford: Pergamon.

Koivula, N. (2012). Safety culture in a new build organization - challenges and methods. Presented at the Technical Meeting on Safety Culture in Pre-operational Phases, IAEA, South Africa 26-30 November, 2012.

Kornelius, L. and Warmelink, J. W. F. (1998) The virtual corporation: learning from construction. Supply Chain Management, 3(4), pp. 193-202.

Kotha, S. and Srikanth, K. (2013). Managing a Global Partnership Model: Lessons from the Boeing 787 'Dreamliner' Program. Global Strategy Journal, 3, pp. 41-66.

Krigsman, M. (2008). IT failure at Heathrow T5: What really happened, available at http://www.zdnet.com/blog/projectfailures/it-failure-at-heathrow-t5-what-really-happened/681

Larsson S., Pousette A. and Törner M. (2008). Psychological climate and safety in the construction industry-mediated influence on safety behaviour. Safety Science, 46(3) pp. 405-412.

Lawrence, P. (1988). The Design Asset, The Corporate Board, July/August.

Lloyd R., Boardman, J. and Pullani S. (2000). Causes and Significance of Design-Basis Issues at U.S. Nuclear Power Plants. NUREG-1275. U.S. Nuclear Regulatory Commission, Washington, D.C.

Macchi, L., Gotcheva, N., Alm, H., Osvalder, A.-L., Pietikäinen, E., Oedewald, P., Wahlström, M., Liinasuo, M., and 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.

Macchi, L., Pietikäinen, E., Liinasuo, M., Savioja, P., Reiman, T., Wahlström, M., Kahlbom, U. and Rollenhagen, C. (2013). Safety culture in design. Final report. Nordisk Kernesikkerhedsforskning, Roskilde, Denmark.

Mayhew, C., Quintan, M., Ferris, R. (1997). The effects of subcontracting/ outsourcing on occupational health and safety: Survey evidence from four Australian industries. Safety Science, 25, pp. 163-178.

Nesheim, T. and Gressgård, L.J. (2014). Knowledge sharing in a complex organization: Antecedents and safety effects. Safety Science 62, pp. 28-36.

OECD (2006). Nuclear power plant operating experiences from the IAEA/NEA Incident Reporting System, 2002-2005. Organization for Economic Co-operation and Development.

Oedewald, P. and Gotcheva, N. (submitted) Safety culture and subcontractor network governance in a complex safety critical project. Safety Science.

Oedewald, P. and Reiman, T. (2003). Core task modelling in cultural assessment: a case study in nuclear power plant maintenance. Cognition, Technology & Work 5, pp. 283-293.

Oedewald, P., Gotcheva, N., Reiman, T., Pietikäinen, E. and Macchi, L. (2011). 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. and Reiman, T. (2011). A Guidebook for Evaluating Organizations in the Nuclear Industry – an example of safety culture evaluation, SSM: The Swedish Radiation Safety Authority, 2011: 20.

Oedewald, P., Reiman, T. and Talja, H. (2009). Safety culture: Understanding the safety significance of the job in the construction of the OL3 nuclear power plant. Confidential Research Report, VTT-R-01593-09.

Perin, C. (2005). Shouldering Risks: The Culture of Control in the Nuclear Power Industry. Princeton University Press.

Perrow, C. (1984). Normal accidents: Living with high-risk technologies. New York: Basic Books.

Perrow, C. (1999). Normal accidents: Living with high-risk technologies. Updated edition. Princeton, NJ: Princeton University Press.

Quinlan, M., Hampson, I. and Gregson, S. (2013). Outsourcing and offshoring aircraft maintenance in the US: Implications for safety. Safety Science, 5, pp. 283-292.

Reason, J. (1990). Human Error. Cambridge: University Press, Cambridge.

Reiman, T. and 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), pp. 745-768

Reiman, T. and Oedewald, P. (2009). Evaluating safety-critical organizations – emphasis on the nuclear industry. SSM: Swedish Radiation Safety Authority, Research Report 2009:12.

Reiman, T., Pietikäinen, E., Kahlbom, U. and Rollenhagen, C. (2010). Safety Culture in the Finnish and Swedish Nuclear Industries - History and present. Nordic nuclear safety research, NKS-213. ISBN 978-87-7893-282-2.

Reiman, T. and Rollenhagen, C. (2012). Competing values, tensions and trade-offs in management of nuclear power plants, Work, 41, pp. 722-729.

Reiman, T., Pietikäinen, E., Kahlbom, U. and Rollenhagen, C. (2010). Safety Culture in the Finnish and Swedish Nuclear Industries – History and Present. NKS-213. Roskilde: Nordisk kärnsäkerhetsforskning.

Reiman, T., Pietikäinen, E., Oedewald, P. and Gotcheva, N. (2012). System modeling with the DISC framework: Evidence from safety-critical domains, Work. IOS Press. 41, pp. 3018-3025.

Ruuska, I., Ahola, T., Artto, K., Locatelli, G. and 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, pp. 647-660.

Ruuska, I., Artto, K., Aaltonen, K. and Lehtonen, P. (2009). Dimensions of distance in a project network: Exploring Olkiluoto 3 nuclear power plant project. International Journal of Project Management 27, pp. 142-153.

Sagan, S. D. (1993). The Limits of Safety. Organizations, Accidents, and Nuclear Weapons. New Jersey: Princeton University Press.

Schein, E. H. (1990). Organizational culture. American Psychologist, 43 (2), 109-119.

Silbey, S. (2009). Taming Prometheus: Talk About Safety and Culture. Annual Review of Sociology, 35, pp. 341-369.

Slavcheva, K., Mori, M., D'Amico, N. and Sollima, C. (2005). Safety culture and organizational issues during transition from operation to decommissioning of NPPs, in Proceedings of the International Conference Nuclear Energy for New Europe.

STUK (2014). Management system for a nuclear facility, Guide YVL A.3, Helsinki: The Radiation and Nuclear Safety Authority.

Tang, C. and Zimmerman, J. (2009). Managing New Product Development and Supply Chain Risks: The Boeing 787 Case. Supply Chain Forum: An International Journal. 10, pp.74-86.

Taylor, J. R. (2007). Statistics of design error in the process industries. Safety Science, 45(1), pp. 61-73.

The National Diet of Japan (2012). The official report of the Fukushima nuclear accident independent investigation Commission.The National Diet of Japan, Tokyo, Japan.

The Royal Academy of Engineering (2012). Nuclear constructions lessons learned. Guidance on best practice: Nuclear safety culture. The Royal Academy of Engineering, London, UK.

Trimble, S. (2014). Boeing, FAA share blame for 787 reliability issues, available at http://www.flightglobal.com/news/articles/boeing-faa-share-blame-for-787-reliability-issues-397213/

Trueman, M. (1998). Managing innovation by design - how a new design typology may facilitate the product development process in industrial companies and provide a competitive advantage, European Journal of Innovation Management, 1(1), pp. 44-56.

Veland, O. (2010). Design patterns in the nuclear domain: theoretical background and further research opportunities. OECD Halden reactor project. HWR-932.

Weick, K. E. (1976). Educational organizations as loosely coupled systems. Administrative Science Quarterly, 21, pp. 1-19.

Wikipedia: http://en.wikipedia.org/wiki/Boeing_787_Dreamliner

Williard, N., He, W., Hendricks, C. and Pecht, M. (2013). Lessons Learned from the 787 Dreamliner Issue on Lithium-Ion Battery Reliability, Energies, 6, pp. 4682-4695.

Woods, D. and Branlat, M. (2011). How human adaptive systems balance fundamental trade-offs: implications for polycentric governance architectures. 4th Resilience Engineering International Symposium, Sophia-Antipolis, France, 8-10 June 2011.

www.analys.se (2004). Analysgruppen Bakgrund [Online, in Swedish] Available from: http://www.analys.se/lankar/Bakgrunder/2004/Bkg%201-04.pdf.

www.archive-se.com (2010). [Online, in Swedish] Available from: http://archive-se.com/page/147799/2012-07-18/http://www.okg.se/templates/NewsPage____993.aspx

Yang, M. (2009). Observations on concept generation and sketching in engineering design. Research in Engineering Design; 20(1): 1-11.

Zantanidis, S. and Tsiotras, G. (1998). Quality management: A new challenge for the Greek construction industry, Total Quality Management, 9(7), pp. 619-632.

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

Appendix

Generic interview scheme

1. Background: could you tell about your job, what is the content of your work? In which of the nuclear power plant lifecycle phases you have had experience?
2. Could you describe the organization oversight in Sweden? How it is organized and what issues do you pay attention to?
3. What is safety culture in your opinion, how can you describe it?
4. What are some warning signals of unhealthy safety culture?
5. How do you see the role of the regulator at different phases of a nuclear project?
6. Plans and preparation for new builds in Sweden: Have you been discussing what kind of safety culture challenges there could be in the beginning of the nuclear project?
7. What are the emerging safety culture challenges in the design phase of large nuclear projects?
8. How about the construction and installation phases: what kind of new safety culture challenges do they pose?
9. How do you perceive the main safety culture challenges in the commissioning phase?
10. What are the emerging safety culture challenges in the decommissioning phase? How have you been preparing for the decommissioning of the operating units?
11. What improvements in regulatory practices could be made to deal with these challenges?
12. Would you like to add something?

2015:10

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 315 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

Tel: +46 8 799 40 00
Fax: +46 8 799 40 10

E-mail: registrator@ssm.se
Web: stralsakerhetsmyndigheten.se