Safety Science 158 (2023) 105965

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Situation awareness in outage work – A study of events occurring in U.S. nuclear power plants between 2016 and 2020

Elizabeth Solberg [a,*], Espen Nystad [a], Robert McDonald [b]

[a] *Department of Human-Centred Digitalization, Institute for Energy Technology, Halden, Norway*
[b] *Department of Control Room and Interaction Design, Institute for Energy Technology, Halden, Norway*

ARTICLE INFO

Keywords:
Situation awareness
Safety
Nuclear power
Planned outages
Human error

ABSTRACT

In this study, we sought to identify if human errors responsible for incidents occurring during scheduled outage periods in nuclear power plants correspond to situation awareness errors in perception, comprehension, or projection. We also sought to identify factors contributing to situation awareness errors at all levels. To do this, we analysed 58 events occurring during planned nuclear power plant outages between 2016 and 2020, as documented in U.S. Licensee Event Reports (LERs). Of the human errors analysed in these events, 14 were classified as situation awareness errors related to perception (Level 1 errors), 30 were classified as situation awareness errors related to comprehension (Level 2 errors), and an additional 14 were classified as situation awareness errors related to projection (Level 3 errors). Furthermore, we found that insufficient procedure use was identified in the LERs as a factor contributing to most errors occurring at Level 1, whereas insufficient procedures was identified to contribute to most errors occurring at Level 2 and 3.

1. Introduction

In the present study, we apply Endsley's (1988; 1995b) situation awareness concept to understand in greater detail the human errors associated with incidents occurring during planned outage periods in nuclear power plants. Planned outages are periods in which the plant is shut down and scheduled maintenance, inspection, and refuelling activities are carried out. The work environment is very different from the cockpit and control room context where the situation awareness concept is more often applied to analyse human errors. However, there is reason to believe that the concept is as relevant for understanding the human errors that occur in planned outage work as it is in other contexts.

Endsley (1988) defined situation awareness a three-level information processing process that includes (1) perceiving relevant elements in the environment, (2) comprehending their meaning, and (3) projecting their status in the near future to anticipate what could happen. To the extent that this process is successfully achieved, situation awareness results in a state of knowledge that enables better decision-making and performance in a specific situation. While originally developed in the aviation domain, the situation awareness concept is highly applicable in a range of safety–critical work contexts where it reflects the processing of relevant elements in the environment to enable the safe and effective execution of work activities (Stanton et al., 2001). On the other hand, the failure to perceive, comprehend, or project the near future status of relevant elements in the environment is held to contribute to human error and the occurrence of safety incidents. Indeed, failures to maintain situation awareness have been found to explain the human errors that result in safety incidents across a range of safety critical contexts, including aviation (Endsley, 1988, 1995a; Jones & Endsley, 1996), merchant shipping (Grech et al., 2002), offshore oil and gas drilling installations (Sneddon et al., 2006), attendant vessels servicing offshore facilities (Sandhåland et al., 2015), chemical processing (Naderpour et al., 2015), and nuclear power plant operations (Patrick & Belton, 2003). In these studies, most human errors are found to reflect situation awareness errors at the perceptual level, resulting from the failure to monitor or observe relevant elements in the environment.

While the situation awareness concept is more often applied to understand the human errors occurring during systems operations, it has long been recognized as applicable to the context of systems maintenance (Endsley & Robertson, 2000). Even in the nuclear power industry, situation awareness is held to be important for the safe and effective execution of work activities carried out during planned outages, just as it is for work activities carried out during normal operations (St Germain et al., 2017; Sun et al., 2020). This is not surprising, as planned outage

---

* Corresponding author at: Department of Human-Centred Digitalization, Institute for Energy Technology, Os Allé 5, 1777 Halden, Norway.
E-mail address: elizabeth.solberg@ife.no (E. Solberg).

https://doi.org/10.1016/j.ssci.2022.105965
Received 28 June 2022; Received in revised form 30 September 2022; Accepted 7 October 2022

work involves many more people than in normal operations and is characterized by uncertainty, time-pressure, physical demands, and coordination challenges (Bourrier, 1996; Hinze, 2005; Hollnagel & Gauthereau, 2001; IAEA, 2005; Reiersen & Gibson, 1995). These factors could increase the demand for information processing or decrease people's ability to process important information in their environment, in ways that could impede situation awareness. Yet, to our knowledge, no attempt has been made to analyse the human errors associated with safety incidents during planned outage periods as situation awareness errors, or to identify at what level of information processing they occur and what factors might contribute to their occurrence. This is unfortunate, because having this information could enable a greater understanding of why human errors occur and inform more targeted interventions aimed at improving human performance in the complex context of nuclear power plant outage work.

Accordingly, in the present research we analyse the human errors that cause incidents occurring during planned outage periods using Endsley's (1995a; Jones & Endsley, 1996) situation awareness error taxonomy. In doing so, we extend the literature supporting the relevance of the situation awareness error taxonomy for understanding the human errors that occur in nuclear power plant operations (Patrick & Belton, 2003; Spooner & Vassie, 1999) to the context of nuclear power plant maintenance. We also contribute to the situation awareness literature more generally by demonstrating the relevance of the concept and error taxonomy for understanding human errors made in systems maintenance activities (Endsley & Robertson, 2000). However, our research also shows how situation awareness errors made in maintenance activities could differ from those made in operational contexts and thus require different interventions to address. Furthermore, our research contributes to more general knowledge of the challenges of attempting to infer errors in situation awareness from the descriptions of human errors provided in event reports, which have been identified in other research applying similar methodologies (Sandhåland et al., 2015; Sneddon et al., 2006). It also provides some practical examples for how to deal with these challenges, particularly in procedure-based work contexts.

In the paper that follows, we first review the situation awareness concept, the errors that can result in the failure to maintain situation awareness at different levels, and the personal and contextual factors that can contribute to these errors. We also explain why we believe situation awareness errors could be relevant for understanding the human errors that lead to incidents occurring during planned outage work. Next, we present an analysis of 58 events caused by human errors occurring during planned outage periods between 2016 and 2020 in U.S. nuclear power plants. In this analysis, we classify the human errors identified in each report using Endsley and colleague's (1995a; Jones & Endsley, 1996) taxonomy of situation awareness errors, taking care to be transparent about how we have dealt with the challenges of inferring errors in situation awareness from the descriptions of human errors provided in event reports. We also identify factors contributing to situation awareness errors where possible. The paper concludes with a discussion of findings, directions for future research, and implications for practice.

1.1. *The situation awareness concept*

Endsley's (1988) conceptualization of situation awareness depicts an individual's information processing process that results in accurate and activated knowledge about one's current situation and, in turn, better decision-making and performance. The first step in this process is for a person to perceive relevant elements in their environment. For example, as Endsley (1995b) describes, a military pilot might perceive different elements on their control panel (e.g., instrument readings, warning lights) and outside of the cockpit canopy (e.g., other aircraft, terrain features). However, just perceiving relevant elements is not enough to achieve a state of situation awareness. To achieve this state the person must also comprehend the situation based on the different elements perceived and be able to project the future actions of these elements. For example, a military pilot who perceives enemy aircraft flying in a certain location must comprehend certain things about their objectives and be able to correctly project how they might behave to have the knowledge needed to determine the best course of action (Endsley, 1995b).

The situation awareness concept is inherently focused on individual information processing and the knowledge states, decision-making, and outcomes that result from it. However, the concept can also be applied to collaborative work contexts. For example, in a team context, "team situation awareness" can be conceived as the degree to which every team member possesses the knowledge required to successfully execute his or her team tasks or responsibilities in a specific situation, based on his or her perception, comprehension, and projection of relevant situational elements (Endsley, 1995b). Furthermore, "shared situation awareness" refers to the extent to which knowledge about the situation, gained through individual perceptions, comprehensions, and projections of relevant situational elements, is shared among team members who are working together at a given time (Salas et al., 1995).

"Distributed situation awareness" (DSA) is another situation awareness concept developed for collaborative work contexts. Like team situation awareness, the DSA concept acknowledges that different team members will have different knowledge about the current situation, based on their individual processing of situational information. However, research on DSA is more concerned with the exchanges of different, but compatible, knowledge between agents in a distributed system and how to facilitate these exchanges such that the right knowledge is passed between the right people at the right time to enable better decision making (Salmon et al., 2015; Stanton et al., 2006; Stanton et al., 2014). A point raised by scholars studying DSA is that a system can have the situation awareness needed to make a good decision, even if individual agents in that system do not. This is because it is possible that different agents can contribute to perceiving, comprehending, and projecting the future state of a situation. What is important is that this knowledge is passed between and used by agents in the system.

As is evident, situation awareness concepts derived at the team and system levels offer unique and relevant perspectives for research on the phenomenon. For example, the DSA concept could be used to study how failures in the exchange of situational knowledge could have contributed to human errors made in the context of outage work. Yet, we believe that Endsley's (1988) conceptualization of situation awareness as a three-level information processing process is most appropriate in the present study, as our intention is to better understand the human errors occurring during planned outage periods and at what level of information processing they occur. However, knowing that our research takes place in a collaborative work context, we assume that it could be difficult to tease apart individual situation awareness from the situation awareness of a work group in the event report data we analyse.

1.2. *Errors contributing to the failure to maintain situation awareness*

While having situation awareness in a safety–critical context should contribute to the safe execution of work activities, the failure to maintain situation awareness could contribute to unsafe work performance and the occurrence of safety incidents (Stanton et al., 2001). Endsley (1995a) (see also Jones & Endsley, 1996) identified a number of "situation awareness errors" that can result in the failure to maintain situation awareness at each level of information processing in aviation. Subsequent research has shown these errors to be applicable in a range of safety critical contexts (e.g., Patrick & Belton, 2003; Sandhåland et al., 2015; Sneddon et al., 2006). Accordingly, in the paragraphs that follow, we draw on Endsley et al.'s research and other studies applying their error taxonomy, outlined in Table 1, to describe errors that can result in the failure to maintain situation awareness at each level.

Table 1
A taxonomy of situation awareness errors according to (Endsley, 1995a) **and** Jones and Endsley (1996).

- Level 1: Failure to perceive the situation
  - Data not available
  - Data difficult to detect or discriminate
  - Failure to monitor or observe data
  - Misperception of data
  - Memory loss/failure
- Level 2: Failure to comprehend the situation
  - Lack of or poor (incomplete) mental model
  - Use of incorrect mental model
  - Over-reliance on default values
- Level 3: Failure to project situation into the future
  - Lack of or poor (incomplete) mental model
  - Over projection of current trends

1.2.1. *Errors contributing to the failure to perceive the situation*

At the perceptual level, the failure to maintain situation awareness occurs when people fail to perceive relevant elements (i.e., “data”) in their environment. According to Endsley’s (1995a) taxonomy, one reason for failure at this level could be because relevant data is not perceptible (available) in the immediate environment. This can occur when relevant data is not signalled or communicated to the people involved, perhaps because of a lack of available system indicators (e.g., failure warnings) or interpersonal communication failures (Jones & Endsley, 1996; Sandhåland et al., 2015). Failures of this type can also occur when equipment or apparatus that would signal relevant data are located in a place where they cannot be observed (e.g., in a well shaft or within pipes; Sneddon et al., 2006).

Failures at the perceptual level can also occur when relevant data is difficult to detect or discriminate, often due to poor physical conditions (e.g., poor visibility, obscured line of sight, high noise levels; Naderpour et al., 2015; Sandhåland et al., 2015; Sneddon et al., 2006). It could also be that relevant data is available and readily perceptible, but people simply fail to observe or monitor it. The failure to observe or monitor data in one’s environment could occur for many reasons, including omission, but also because of distraction, stress due to high task load, or being too narrowly focused on a given task (Endsley, 1995a). Furthermore, failures at the perceptual level may also occur when relevant data is misperceived, which could be due to disorientation or communication distortion (Sneddon et al., 2006). Failures can also occur when relevant information is initially perceived, but then forgotten, often because of a disruption or other distraction (Endsley, 1995a).

1.2.2. *Errors contributing to the failure to comprehend the situation*

At the comprehension level, the failure to maintain situation awareness occurs when people fail to understand the significance or meaning of the data they perceive in their immediate environment and how it relates to pertinent goals. Endsley (1995a) suggests that this could be because people lack a mental model, or internal representation of how something is and how it works, to be able to integrate and make sense of the data available in the situation. It is important to specify here that a mental model represents a person’s generic knowledge about how something is/how something works. Situation awareness, by comparison, is concerned with generating accurate knowledge about the present state of a system or system component (Endsley, 2000). Research on situation awareness specifies that mental models can facilitate situation awareness by helping a person to determine what information to attend to in their immediate environment, and how to interpret that information. When people lack a mental model relevant for their situation, they may not know to attend to certain information in their environment, or they may not know how to interpret the information that they do attend to (Endsley, 1995b, 2000).

Similarly, the failure to comprehend the situation could also occur because a person has a poor (incomplete) mental model. Just as when people lack a mental model, people who have a poor mental model about the equipment they work with or the tasks they are engaged in may overlook the need to attend to certain elements in the environment because they do not understand that they are important. For example, Sneddon et al. (2006) describe an error they attributed to a poor mental model where a worker injured himself by catching his foot on the side of a machine. This error occurred, they argue, because the worker was unfamiliar with a piece of machinery and therefore was unaware of what areas on the machine to observe. Having a poor mental model may also make it difficult to interpret the situational information that a person does perceive. For example, having a poor mental model could lead to the failure to understand that the data a person perceives in the environment are not favourable for performing a specific operation (Naderpour et al., 2015; Sandhåland et al., 2015).

The failure to comprehend the situation could also occur when people use an incorrect mental model in a particular situation. For example, when they rely on a mental model for a task that worked well in another situation that is not well-suited for the situation it is applied to, because they have not recognized that key parameters relevant for the safe execution of the task have changed (Sneddon et al., 2006). Failure at this stage could also occur because a person relies on defaults in the mental model used, or general expectations of how things work that are not evidence-based. This error could occur, for example, when a person follows informal routines instead of prescribed, correct procedures (Sneddon et al., 2006).

1.2.3. *Errors contributing to the failure to project situation into the future*

Finally, at the projection level, the failure to maintain situation awareness occurs when people are unable to project the future implications of the information they perceive in the situation. The reasons why people fail to correctly project a situation can be more difficult to assess than failures at other levels. However, as with errors made in comprehension, it could be because they lack a mental model or apply an incorrect model. In either case, failures at this level lead to the inability to project the safety consequences of a decision or action taken in the environment (Sandhåland et al., 2015; Sneddon et al., 2006). Failures at this level may also result from over-projecting current trends instead of projecting how the situation will actually develop (Endsley, 1995b).

1.3. *Personal and contextual factors that influence situation awareness errors*

Maintaining situation awareness requires significant cognitive resources. When cognitive resources are not sufficient for the information processing demands present in a given situation, situation awareness errors can occur. Several personal factors influence the cognitive resources necessary for maintaining situation awareness. Notably, research indicates that people who have the knowledge and skills to correctly perceive, comprehend, or project the near future status of relevant elements in the environment are expected to maintain situation awareness more than people who do not have the necessary knowledge and skills (Endsley, 1995b; Simons, 2000; Wickens & Carswell, 2021). These factors can be influenced by a person’s innate ability as well as the experience and training they have received in a particular domain. Accordingly, not having the knowledge and skills to correctly perceive, comprehend, and project relevant elements in the environment will increase the likelihood of situation awareness errors occurring.

Characteristics of the work environment will also influence the ability people have to maintain situation awareness, either by influencing information processing demands in the situation or by influencing a person’s information processing abilities. For example, work environments characterized by greater task uncertainty and task complexity should have greater information processing demands, and thus make maintaining situation awareness more challenging (Endsley, 1995b). Furthermore, non-optimal work conditions related to noise, temperature, lighting, physical demands, work load, time pressure, or other factors can also reduce a person's capacity to process relevant information in a situation, either directly or through mechanisms like fatigue, stress, or boredom (Endsley, 1995b). As such, these factors could also increase the occurrence of situational awareness errors.

1.4. Factors that could contribute to situation awareness errors in outage work

Planned outages refer to the period when a nuclear power plant shuts down for scheduled maintenance, inspections, and refuelling. The work conducted during planned outages is very different from work conducted during normal operations where a limited number of control room operators, who typically have extensive training and long experience performing the same tasks in the same environment, carry out a range of responsibilities, many of which are monitoring tasks. By comparison, planned outage work involves much more personnel than in normal operations, including large numbers of contract workers and newer, less experienced staff (IAEA, 2005). These personnel may not have sufficient knowledge or skills to perceive or comprehend important elements in their environment or project the safety implications of their actions. Furthermore, the environment for carrying out outage work is characterized by uncertainty, time-pressure, physical demands, and coordination challenges (Bourrier, 1996; Hinze, 2005; Hollnagel & Gauthereau, 2001; IAEA, 2005; Reiersen & Gibson, 1995). High workload and heightened stress have also been observed as contextual factors affecting the performance of plant personnel during outage (Haber et al., 1992). These factors may increase the demand for information processing, or overload outage personnel's cognitive resources, decreasing their ability to correctly perceive, comprehend, and project the near future status of relevant elements in the environment.

While the factors described above could be unique to outage work, we expect that they will influence outage workers' situation awareness in the same way that personal and contextual factors are found to influence situation awareness more generally. That is, we expect they could negatively influence outage workers' perception or comprehension of relevant information in their environment or hinder their ability to understand the future implications of the information available in ways that could result in safety incidents. Accordingly, we expect that the situation awareness errors taxonomy described in Section 1.1 should provide a relevant lens through which to explain the human errors that result in safety incidents during outage periods.

2. Method

2.1. Sample

Data for this study was collected from U.S. Licensee Event Reports (LERs) relating to events occurring during planned outages. We selected U.S. LERs for our study as they are publicly available through the LER database.[1] This means the data is easy to obtain, both for the present study and for any future study seeking to replicate our results. A search of the LER database was conducted in October 2021 for events occurring between January 1, 2016 to December 31, 2020 during all operating modes encompassed in the definition of an outage. This includes planned refuelling outage periods as well as standby, hot shutdown, cold shutdown, and start-up operating modes.

Our search of the LER database generated 148 reports ($N_{\text{standby}} = 2$; $N_{\text{hot shutdown}} = 8$; $N_{\text{cold shutdown}} = 31$; $N_{\text{refuelling}} = 91$; $N_{\text{startup}} = 16$). Several duplicates were removed. Additionally, several event reports were discarded because they related to technical failures (e.g., corrosion, wear, faulty componentry) or to external environmental factors (e.g., weather related events) and did not have any element of human error. As a result, only 58 LERs were included in the final analysis. Table 2 reports LER exclusion and final sample size by operating mode.

Table 2
LER exclusion resulting in final sample size, per operating mode.

Operating Mode	2	3	4	5	7	Totals
Event reports available	16	2	8	31	91	148
Duplicate event reports	1	1	1	1	12	16
Events with no human errors	3	0	3	12	56	74
Final sample size	12	1	4	18	23	58
% of total sample	20.6	1.7	6.9	31.0	39.7	100

Note. Mode 2 = Start-up; Mode 3 = Hot Standby; Mode 4 = Hot shutdown; Mode 5 = Cold shutdown; Mode 7 = Refuelling. No LERs corresponded to Mode 6 = Cold Shutdown.

2.2. Procedure

LERs are made using NRC Form 366.[2] This form requires plants to provide an event description that includes an overview of systems affected, actuations and their initiating signals, causes, effects of the event on plant, actions taken or planned, or other relevant information. The standardized format of the LER made it relatively easy to identify the key information necessary for conducting our analysis, notably information about the human errors that caused the event. This information was typically outlined in the causal analysis section of the report.

In our dataset, there were six event reports where multiple people or groups involved in a single event were indicated to have performed erroneously. In five cases, multiple errors were indicated for the same person or group. In line with other research (e.g., Sandhåland et al., 2015), we included only one human error per event in our analysis, the human error most proximal to the event.

We replicated the approaches taken in other research (e.g., Patrick & Belton, 2003; Sandhåland et al., 2015; Sneddon et al., 2006) to classify the human errors included in our analysis against Endsley's (1995a) situation awareness error taxonomy. However, as in other research, we acknowledge that this process was not straightforward, as LERs did not generally describe human errors in terms of situation awareness errors (and when they did, they did not specify the level or type of error). Accordingly, the coding process required making subjective judgements about the correspondence between the human error described in the LER and the situation awareness errors described in Section 1.1. In the Appendix we provide several sample event descriptions and event causes extracted from the LERs together with the situation awareness error assigned in our analysis and our rationale for this assignment.

Outage work is guided by specific and detailed work procedures (Bourrier, 1996), and insufficient procedures and procedure use have been identified as common high level causes of human error-related events in outage (St. Germain et al., 2017). After an initial processing of the LERs, we found that considering if and how procedures contributed to the event could help when classifying human errors against the taxonomy and make more transparent our coding approach. Specifically, if the LER indicated that personnel did not follow work procedures and this contributed to the human error that caused the event, we categorized the error as a Level 1 error related to the failure to monitor or observe relevant information in the situation – i.e., information that was specified in work procedures. Moreover, if the LER indicated that insufficient work procedures (e.g., procedures that did not specify a safety–critical step in the work process, contained an error, or were missing) contributed to the human error, we categorized this as a Level 2 or Level 3 error related to the lack of or poor (incomplete) mental model. This is because we believed that work procedures should contribute to the mental model outage personnel have about their work tasks and how to conduct them – i.e., a mental representation of the task around which

---

[1] https://lersearch.inl.gov/LERSearchCriteria.aspx.

[2] https://www.nrc.gov/reading-rm/doc-collections/forms/nrc366info.html.

situational elements perceived in the work environment could be integrated. If an LER indicated that an error occurred because a work procedure was misinterpreted, this was also categorized as a Level 2 or Level 3 error related to the lack of or poor (incomplete) or incorrect mental model. Finally, if an LER indicated that an error occurred because a work procedure was incorrectly applied, this was categorized as a Level 2 or Level 3 error related to having an incorrect mental model. In all cases, this coding was applied unless other information was provided in the LER that would indicate classification as a different error type.

To increase reliability, two of the study's authors completed the error classification. Each first worked independently to classify each event. We then met to review and compare the codes assigned. Where coding was different (approximately 10 percent of cases), we reached an agreement by clarifying and explaining our positions. In all cases, an agreement about the classifications was reached without the need for a third rater to intervene.

In addition to classifying each human error using the taxonomy of situation awareness errors, we also coded each error as being latent (an error committed prior to the event, for example, in a previous outage, whose effects are not discovered until an event occurs in the present outage) or active (an error occurring in the same timing, i.e., outage period, as the event itself) (Gertman et al., 2002), as both types of human errors contributed to events and could be relevant for interpreting findings. Where possible, factors identified as causing or contributing to the human errors made (beyond insufficient procedures or procedure use) were also noted.

3. Results

Table 3 summarizes the situation awareness errors identified in our analysis by operating mode. As indicated in this table, 14 events (approximately 24 percent) were classified as being caused by Level 1 situation awareness errors, one of which was a latent error. A further 30 events (approximately 52 percent) were classified as being caused by Level 2 situation awareness errors, six which were latent errors. Finally, 14 events (approximately 24 percent) were classified as being caused by Level 3 situation awareness errors, nine of which were latent errors. In the following sections, we review findings relating each level in more detail.

Table 3
Types of situation awareness errors identified, by operating mode investigated.

Operating Mode Situation awareness error	2	3	4	5	7	Totals
Level 1: Failure to perceive the situation						
1 - Data not available						
2 - Data difficult to detect or discriminate						
3 - Failure to monitor or observe data	4			1 (1)	7	13
4 - Misperception of data				1		1
5 - Memory loss/failure						
Level 2: Failure to comprehend the situation						
6 - Lack of or poor (incomplete) mental model	2	1	4	1 (2)	4 (4)	18
7 - Use of incorrect mental model	2			7	3	12
8 - Over-reliance on default values						
Level 3: Failure to project situation into the future						
9 - Lack of or poor (incomplete) mental model	(3) 1			(4) 1	3 (2)	14
10 - Over projection of current trends						

Note. Mode 2 = Startup; Mode 3 = Hot Standby; Mode 4 = Hot shutdown; Mode 5 = Cold shutdown; Mode 7 = Refuelling. Numbers shown in parentheses indicate the number of latent errors identified for each situation awareness failure type by operating mode. Numbers not in parentheses indicate active errors.

3.1. *Level 1 situation awareness errors*

Fourteen of the 58 events we analysed were classified as being caused by Level 1 situation awareness errors. The most common situation awareness error at the perceptual level was the failure to monitor or observe safety information in the situation, accounting for 13 of the 14 errors identified at this level (92.9 percent). Only one event was found to relate to another Level 1 situation awareness error. This case was associated with the misperception of safety information in the situation. A brief interpretation of all Level 1 situation awareness errors that we identified in our analysis are provided in Table 4. (In the Appendix we provide several examples of how the interpretive text provided in the results tables have been extracted from the LERs analysed.).

Ten of the 13 events classified as the failure to monitor or observe data in the environment (76.9 percent) were associated with the failure to follow work procedures. For example, the LER for the event ensuing from control room personnel's failure to track primary containment inoperability in preparation for eventual plant model change and start-up, stated that this error could have been prevented if control room personnel had followed work procedures. Similarly, the event that

Table 4
Failures to perceive the situation.

Mode	Failure	Error	Situation awareness error made
2	Active	3	Control room personnel failed to track primary containment inoperability in preparation for eventual plant model change and start-up
2	Active	3	Operations personnel failed to notice that the turbine control system pressure setpoint was incorrectly set to 1 psig, instead of 100 psig
2	Active	3	Shift team failed to observe gaps in the preparation and execution of the plant's start-up procedure
2	Active	3	A work control supervisor failed to follow the plant barrier impairment process after authorization was granted to prop open pump room doors (a secondary containment boundary) to facilitate welding activities
5	Active	3	Operators failed to observe the need to return plant service water supply isolation valves for the alternative decay heat removal system to the normal "open" position after heat exchanger cleaning
5	Latent	3	Manufacturer failed to notice that one of the fuse elements to fuse ferrule connections had flux applied but no solder
7	Active	3	An employee being followed by several others failed to observe that not every-one was in the airlock and the entry door was not closed before opening the exit door
7	Active	3	A group of individuals did not observe the airlock indication light prior to entry, which indicated that the airlock was currently in use and could not be entered
7	Active	3	A technician failed to notice the work crew entering the airlock behind him, and that the outer door was not closed, prior to opening the inner door of an airlock
7	Active	3	Vendor failed to observe that a cotter pin was missing from the assembly of a fan breaker, preventing it from closing and remaining closed
7	Active	3	Technicians failed to observe the need to apply adequate force to properly seat a transmitter manifold valve, such that it would function
7	Active	3	Technicians failed to notice that they were opening the low-pressure isolation valve instead of the equalization valve
7	Active	3	Technicians failed to notice that they were opening the wrong fuse drawer
5	Active	4	An engineer incorrectly perceived the need to key-card through the inner door of an error

Notes. Mode 2 = Startup; Mode 3 = Hot Standby; Mode 4 = Hot shutdown; Mode 5 = Cold shutdown; Mode 7 = Refuelling. Error code 3 = Failure to monitor or observe data; Error code 4 = Misperception of data. Descriptive text in the table indicates our interpretation of the situation awareness error made and is not a direct quote from the LERs analysed.

ensued from giving the authorization to prop open pump room doors (a secondary containment boundary) to allow welding cables to extend through was indicated as having been preventable had the work control supervisor utilized the plant barrier impairment process, per plant procedures. This way, operations would have known that this boundary was inoperable before entering Mode 2 (Start-up). In other events, it was indicated that technicians could have avoided failures such as opening outer airlock doors before inner doors were closed and opening wrong valves or fuse drawers if they had followed work procedures.

However, the reason why work procedures were not followed was only specified in three of these events. Having a too narrow focus on a particular task was identified as an issue in the case where a shift team failed to observe gaps in the preparation and execution of the plant's start-up procedure and in the case where a work control supervisor failed to utilize the plant barrier impairment process. Perceived time pressure was provided as an explanation for an employee who failed to observe that not every-one who was following was in the airlock and that the entry door was closed before opening the exit door. Accordingly, while not many explanations were provided, those that were aligned with the factors identified by Endsley (1995a) to cause the failure to monitor or observe information in the situation. (Of note, in two events, both associated with opening airlock doors erroneously, less than adequate situational awareness was cited as the cause of the event. However, factors that could have contributed to less than adequate situation awareness in this context were not provided.).

The remaining three events relating to the failure to monitor or observe information in the situation that did not correspond to the failure to follow work procedures, did not give an indication of the factors contributing to this failure. Furthermore, no contributing factor was specified for the event associated with the misperception of safety information in the situation.

3.2. Level 2 situation awareness errors

As indicated in Table 3, most situation awareness errors that we identified in our analysis were at Level 2, indicating the failure to comprehend the situation. Of these, the most common error was associated with the lack of or poor (incomplete) mental model, which led to the failure to know that some action was necessary to prevent an incident from occurring. These types of situation awareness errors accounted for 18 of the 30 Level 2 errors identified (60 percent). Furthermore, 12 events were determined to be associated with the use of an incorrect mental model. A brief interpretation of all Level 2 situation awareness errors that we identified in our analysis are provided in Table 5.

Of note, lacking or insufficient work procedures were identified in the LERs as a factor contributing to human error in 15 of the 18 events classified as having failures associated with the lack of or poor (incomplete) mental model (83.3 percent). For example, in one case, procedures that did not include the visual inspections of stabs and contacts were stated as having contributed to technicians not knowing that secondary connection stabs feeding an auxiliary oil pump needed to make contact in the motor control centre for a pump to start. In another case, it was stated that installing washers in the cut-out switch assembly of electromatic relief valves was not clearly specified as a critical step in the assembly process. Therefore, maintenance personnel did not understand the need to install washers in the switch assembly of five electromatic relief valves. This resulted in the switches not functioning properly. As another example, technicians did not know to identify the correct adjustment of a breaker actuator arm. This was because post-maintenance testing of switch contacts did not exist as step in the work procedures, having been removed in an earlier procedural change. Failure to ensure correct adjustment of the breaker actuator arm led to the failure of a switch connected to the auto-start function of a residual heat removal service water pump.

Other factors identified as contributing to failures associated with the lack of or poor (incomplete) mental model included inadequate plant

Table 5
Failures to comprehend the situation.

Mode	Failure	Error	Situation awareness error made
2	Active	6	Technicians did not know to check that secondary connection stabs feeding an auxiliary oil pump made contact in the motor control centre
2	Active	6	Operations personnel did not know about performing electromagnetic and radio-frequency interference noise testing to detect abnormalities in nuclear instrumentation
3	Active	6	Maintenance workers did not know to verify that switch alignment was adequate in relation to final travel of a breaker actuating arm
4	Active	6	Operators did not know that the guidance needed for dealing with an issue they were facing was available in another operating procedure
4	Active	6	Operations personnel did not know what conditions needed to be verified prior to a scram reset
4	Active	6	Operators did not know that shutting down a reactor feedwater pump would result in no flow path for the condensate pumps to supply water to the vessel
4	Active	6	Operators did not know that equalizing pressure above a certain psid was necessary to avoid a main steam line high flow signal when the valves were opened
5	Active	6	Maintenance personnel did not know to install hinge pin lock start washers in the cut-out switch assembly of electromatic relief valves
5	Latent	6	Maintenance personnel did not know to test the functionality of air pack pilot valves intended for use on an outboard main steam isolation prior to installation
5	Latent	6	Maintenance personnel did not know that a plunger associated with an electromatic relief valve had a bent upper guide bracket and thus incorrectly returned it to service
7	Active	6	An operator did not know to ensure that the cold leg temperature was being maintained within limits specified in the pressure and temperature limit report
7	Latent	6	Technicians did not know to ensure that there was proper alignment between a switch and its breaker switch cam during installation
7	Latent	6	Technicians did not know to ensure the correct adjustment of a breaker actuator arm
7	Active	6	Electricians did not know that they had wired transformers incorrectly.
7	Latent	6	Technicians did not know to identify proper alignment of the contacts on a cell switch when replacing the supply breaker
7	Latent	6	Electricians did not know that the wiring of two switches connected to two safety relief valves was incorrect
7	Active	6	Operations personnel had a poor understanding of technical specifications, leading to the inappropriate decision to bypass the rod position information system full-in indications prior to commencing fuel movement
7	Active	6	Transmission and distribution service provider personnel did not understand that they were injecting a test signal into an energized transmission line relay instead of into the intended de-energized relay.
2	Active	7	Maintenance supervisors incorrectly determined that the need to backfill the reference leg following rerouting of the reference leg tubing was not required
2	Active	7	Control room personnel applied incorrect pressure control procedures to address the cooldown rate conditions of a soft shutdown
5	Active	7	Operations personnel had the incorrect understanding that equipment was in working order, and therefore performed three plant start-ups with a primary containment vacuum breaker closed but not locked, as required
5	Active	7	An incorrect understanding about how to prevent trips of decay heat removal led operations personnel to overlook the need for jumpers in the start logic of a new residual heat removal hardening procedure
5	Active	7	Operations personnel incorrectly understood that one of the requirements of a technical specification limiting condition for operation was not met, and therefore

(*continued on next page*)

Table 5 (*continued*)

Mode	Failure	Error	Situation awareness error made
			incorrectly placed the reactor model switch from “refuel” to “shutdown” position
5	Active	7	Technicians had an incorrect understanding of the work steps required to perform excess flow check valve testing when applied to only one group of valves, and therefore erroneously omitted important steps
5	Active	7	Maintenance personnel had the incorrect understanding about plant status and critical procedural steps when performing turbine testing while the plant was offline for planned maintenance.
5	Active	7	Technicians had the incorrect understanding that pulling a relay connection plug would prevent actuation during relay testing.
5	Active	7	Operations had an incorrect understanding that an emergency diesel generator was operable based on operator logs
7	Active	7	Schedulers had the incorrect understanding that work on piping needed in the reactor building and in the control building basement would not be performed in parallel
7	Active	7	A maintenance electrician supervisor had the incorrect understanding of how to install an adapter in a way that eliminated the trip potential
7	Active	7	A plant control operator incorrectly understood that all four local leak rate testing procedures had been signed and released by the Operations Supervisor and that they could be carried out concurrently.

Notes. Mode 2 = Startup; Mode 3 = Hot Standby; Mode 4 = Hot shutdown; Mode 5 = Cold shutdown; Mode 7 = Refuelling. Error code 6 = Lack of or poor (incomplete) mental model; Error code 7 = Use of incorrect mental model. Descriptive text in the table indicates our interpretation of the situation awareness error made and is not a direct quote from the LERs analysed.

management oversight of inexperienced personnel engaged in field activities. For example, inadequate oversight of transmission and distribution service provider personnel was identified as a factor contributing to the lack of understanding that they were injecting a test signal into an energized transmission line relay instead of into the intended de-energized relay. In another event, verbal communication with a shift manager was said to create confusion among operations personnel about technical specifications, which lead to the poor decision to bypass the rod position information system full-in indications prior to commencing fuel movement.

Furthermore, lacking or insufficient work procedures were identified as a contributing factor in five of the 12 event reports associated with the use of an incorrect mental model (41.6 percent). This was evident, for example, when control room personnel were described as having applied pressure control procedures that were insufficient to address the cooldown rate conditions of a soft shutdown. As another example, the inappropriate classification of a procedure was identified as a factor contributing to operations personnel not understanding the need for jumpers in the start logic of a new residual heat removal hardening procedure.

In another five events that we associated with the use of an incorrect mental model, it was indicated that the error could have been prevented had work procedures been followed. However, in these five cases – unlike those coded as Level 1 errors - it was indicated that an error occurred when personnel relied on an incorrect mental model instead of following work procedures. In the remaining cases, we determined that the error occurred when personnel relied on an incorrect mental model, in situations where there were no explicit work procedures.

3.3. *Level 3 situation awareness errors*

As indicated in Table 3, all 14 situation awareness errors that we associated with the failure to project the situation into the future were classified as the lack of a good mental model or use of an incorrect mental model. Nine of the 14 events (64.3 percent) were associated with latent situation awareness errors that had been committed prior to the event. The high number of latent failures at this level was understandable given that errors of projection may not result in incidents until a future period. A brief interpretation of all Level 3 situation awareness errors that we identified in our analysis are provided in Table 6.

In five of the 14 events corresponding to Level 3 errors (35.7 percent), it was suggested that lacking or insufficient work procedures

Table 6
Failures to project situation into the future.

Mode	Failure	Error	Situation awareness error made
2	Latent	9	Plant engineering and leadership did not correctly predict the negative effects of noise intrusion on the intermediate range monitor system and thus failed to implement a solution to the noise susceptibility issue before it caused an unexpected scram signal
2	Active	9	Maintenance personnel were unable to predict that the planned maintenance they were carrying out on the feedback distributed control system would interrupt steam and feedwater flow signals used by the gland seal exhauster instrumentation
2	Latent	9	Maintenance planners were unable to predict an accurate monitoring maintenance strategy for a high-pressure core spray jockey pump
2	Latent	9	Maintenance failed to predict that a seal rebuild procedure, revised four years earlier, would not prevent coolant leakage from a pump shaft
5	Latent	9	Technicians were unable to foresee that applying too much lubricant to a valve stem bottom O-ring of an airpack manifold would negatively affect a main steam isolation valve closure time
5	Latent	9	Technicians were unable to foresee that applying too much lubricant to a valve stem bottom O-ring of an airpack manifold would negatively affect a main steam isolation valve closure time (second, seperate occurrence)
5	Latent	9	During an earlier rebuild process, the manufacturer was unable to foresee that lubricant and thread sealant would accumulate on the internal surfaces on an airpack and slow main steam isolation valve closure times
5	Active	9	Transmission and distribution service provider personnel were unable to predict that applying a current signal to circuits being modified without taking the necessary precautions to prevent an actuation of the protection logic would result in the unanticipated trip of the circuit breaker
5	Latent	9	Station personnel were unable to predict that a certain model of circuit breakers was susceptible to a failure mode that could prevent the automatic closure of the breakers
7	Latent	9	Technicians failed to predict how a material deficiency on check valve componentry could cause the valves to not close properly during surveillance testing
7	Latent	9	Operations and engineering failed to predict the need for a preventative maintenance strategy to replace or refurbish subcomponents of battery chargers that are vulnerable to age degradation failures
7	Active	9	Technicians failed to predict that installation of a primary containment isolation system relay on a shared plastic DIN rail could disturb contacts in the adjacent relay
7	Active	9	A work team flushing an in-vessel nozzle did not predict that using a new tip for flushing would require compensatory actions to reduce signal perturbations in transmitters connected to the nozzle
7	Active	9	The operations shift manager and control room supervisor incorrectly predicted the risks of carrying out a draining activity during outage as compared to when the plant was online

Notes. Mode 2 = Startup; Mode 3 = Hot Standby; Mode 4 = Hot shutdown; Mode 5 = Cold shutdown; Mode 7 = Refuelling. Error code 9 = Lack of a good mental model or use of an incorrect mental model. Descriptive text in the table indicates our interpretation of the situation awareness error made and is not a direct quote from the LERs analysed.

were a contributing factor to the errors made. For example, in one event, having no procedural guidance rendered maintenance workers unable to predict that the planned maintenance they were carrying out on the feedback distributed control system would interrupt steam and feedwater flow signals used by the gland seal exhauster instrumentation. In another event, technicians lacked step-by-step instructions to alert them of the actions needed to prevent an actuation of the protection logic. This contributed to a situation where personnel were unable to predict that applying a current signal to circuits being modified would result in the unanticipated trip of the circuit breaker. In two similar events occurring at two separate plants, technicians were unable to project that applying too much lubricant to a valve stem bottom O-ring of an airpack manifold would negatively affect a main steam isolation valve closure time. A contributing factor stated in the event report was that procedures did not specify the amount of lubricant to apply on the O-ring.

Furthermore, in two cases, successful experience with procedures used previously led to the belief that the same procedures would work in the current situation, and thus the inability to project how differences in the present situation could lead to unique safety issues or hazards. In one case, an operations shift manager and control room supervisor incorrectly predicted the risks of carrying out a draining activity during outage as compared to when the plant was online. This was stated as being because successful experience with the procedures used to conduct the work when the plant was online led to predict that the same plan would work during shutdown. In the second event, a work team flushing an in-vessel nozzle did not predict that a new tip being used for the first time in this activity would necessitate compensatory actions to reduce signal perturbations in transmitters connected to the nozzle. This was said to be because their previous experience told them that flushing did not lead to signal perturbations. Carrying out the activity with the new tip created a momentary low pressure in the variable leg of the transmitters connected to the nozzle, initiating the automatic primary containment isolation system.

4. Discussion

The safe and effective execution of nuclear power plant outage work relies on outage personnel being able to quickly and accurately process relevant information in their immediate environment (St Germain et al., 2017; Sun et al., 2020). Furthermore, there are certain factors present in outage work that may impact the demand for information processing, or people's ability to process situational information (Bourrier, 1996; Hinze, 2005; Hollnagel & Gauthereau, 2001; IAEA, 2005; Reiersen & Gibson, 1995). Accordingly, we believed that the situation awareness concept and error taxonomy could help to better understand the human errors occurring during planned outage periods. In this study, we classified the human errors identified in 58 U.S. LER for incidents occurring during outage periods using Endsley's (1995a; Jones & Endsley, 1996) taxonomy of situation awareness errors. The value we sought to derive from this analysis was a better understanding of what situation awareness errors occur in outage work and at what level of information processing, information that could inform interventions aimed at improving human performance in this context.

An interesting finding from our LER analysis was that most situation awareness errors identified were associated with the failure to comprehend the situation, which led to the failure to know that some action was necessary to prevent an incident from occurring in the present or in the future. That is, they related to failures at Level 2 and Level 3. Failures in perception (Level 1) only accounted for 24 percent of errors. This finding is interesting, because empirical research conducted in other domains have most often found situation awareness to fail at the perceptual level (Level 1), particularly from the failure to observe or monitor safety information in the environment. The discrepancy in our findings could be because other research has typically studied situation awareness in operational settings where personnel are largely engaged in monitoring (i.e., perception-heavy) tasks. Furthermore, other research has typically been conducted in domains where personnel involved are experts with extensive training and long experience performing the same tasks in the same environment. Outage work, on the other hand, involves large numbers of contract workers and newer, less experienced staff who may not have the knowledge necessary to fully comprehend the tasks and tools they work with or project how a situation will develop.

Our analysis also revealed that work procedure deficiencies were a contributing factor in a significant portion of the situation awareness errors identified at Level 2 and Level 3. As previously stated in the paper, outage work is guided by detailed and specific work procedures (Bourrier, 1996). Procedural compliance is a primary mechanism to achieve desired outcomes in this context. However, it is also known that some outage procedures are less descriptive and information-rich than others (Gotcheva et al., 2013). Furthermore, studies of incidents occurring in earlier time periods find that insufficient procedures contribute to many of the incidents occurring during planned outages (St Germain et al., 2017). Our findings lend support for the prevalence in which insufficient procedures contribute to human errors during outages. However, we also extend the understanding of this finding by suggesting that insufficient work procedures could contribute to human errors because they generate a poor mental model about how to correctly conduct and verify the execution of work activities. We expect this is particularly the case in a workforce that may not have the training or experience to have developed a good mental model of their tasks independently, which work procedures contribute to and can be compared against. However, we also recognize that an alternative explanation might be that outage workers generally view work procedures as dependable, which could prevent them from identifying that a particular procedure is lacking, or from using human performance tools that would help them challenge procedural sufficiency. Unfortunately, there was not enough information available in the LERs we analysed to be able to identify if insufficient work procedures contributed to a poor mental model of the task, which we assume to be more likely in this context, or if incorrect mental models about procedural sufficiency contributed to the inability to recognize issues with work procedures. However, seeking to understand the extent to which one or both apply could be an interesting avenue for future research.

We also found that most human errors that we classified as Level 1 situation awareness errors (13 of 14 in total) concerned the failure to monitor or observe relevant information in the situation, notably, information that was specified in work procedures. Our findings align with previous research that also finds inadequate procedure use as being associated with many incidents occurring during planned outage periods (St Germain et al., 2017). Unfortunately, however, our analysis did not provide much insight about why work procedures and the information in them were not attended to. In other research, factors known to exert a negative influence on people's information processing capabilities, such as the physical demands of the work environment and the level of task complexity and workload, have been more prevalent in explaining the situation awareness errors observed at Level 1. Given that outage work is characterized by uncertainty, high workload, time-pressure, physical demands, coordination challenges, and stress (Bourrier, 1996; Haber et al., 1992; Hinze, 2005; Hollnagel & Gauthereau, 2001; IAEA, 2005; Reiersen & Gibson, 1995), we expected that more situation awareness errors identified at Level 1 and other levels would be attributable to these work characteristics. But alas, only one LER attributed an error in perception to work characteristics (time pressure). Furthermore, it is possible that in some events, work procedures were not followed because outage personnel relied on an incorrect mental model instead of following work procedures. Perhaps people themselves did not understand that a particular work procedure was needed (internal causal factor), or maybe they had been misguided or a technical error had occurred (external causal factors), making them believe that a work procedure was not applicable. Had this been specified, the error would have been coded at Level 2, relating to the use of incorrect mental model. Again, our analysis provided very little insight into why outage workers did not follow work procedures and thus did not observe the information provided in them, or why they failed to perceive that work procedures are necessary to follow. Future research could address our limited findings in this area, particularly qualitative research such as interviews or focus groups that are better suited to collect such in-depth information.

More generally, our findings also underscored that outage work is highly collaborative both within functional groups (e.g., technicians working together on a task) and between functional groups (e.g., operations and engineering working together on a task). Indeed, it was more often the case that an error was associated with a group of people than a single individual, suggesting that shared situation awareness (Salas et al., 1995) is a very relevant unit of analysis in this context. The intended contribution of the present research was to identify what situation errors occur in outage work and at what level of information processing, a classification that also applies to situation awareness errors occurring in a group. However, our findings suggest the need for future work to consider how shared situation awareness is achieved in outage work. This requires moving from a cognitive perspective of situation awareness, as was applied in the present paper, to a transactional perspective. The DSA concept could be applicable in this research, as it is concerned with the exchange of knowledge between agents in a system and how to facilitate these exchanges, so that the right people have the right knowledge at the right time (Salmon et al., 2015; Stanton et al., 2006; Stanton et al., 2014).

4.1. *Implications for practice*

Our study identified that situation awareness issues exist in outage work and that insufficient work procedures contribute significantly to these errors. Procedures, when well-designed, can reduce information processing demands and positively influence a person's information processing abilities, enhancing situation awareness (Lin et al., 2016; Yang et al., 2012). Yet, the work procedures required for outage work are unlikely to ever be fully complete and error free (Bourrier, 1996). This could be problematic, particularly as they guide the performance of staff, many of whom may not have the knowledge and experience needed to question their sufficiency. Accordingly, one obvious implication that our research suggests for practice is that procedures should be continuously improved – as we expect that they are.

However, beyond procedure improvement, another consideration for practice is the use of human performance tools such as self-checks or verification of work, as discussed by Oedewald et al. (2014). Such tools may work as mitigating factors when work procedures are not as sufficient as they should be. Indeed, we found many events related to a lack of verifying that a step in the work procedure had been performed correctly, e.g., verifying that a part had been properly installed. A third approach is to improve training provided to outage personnel. This should improve their risk awareness and their ability to think more critically about the tasks they are involved in, thereby enabling them to display the questioning attitude needed to identify procedural deficiencies themselves. These latter two approaches for dealing with the issues created by insufficient work procedures would be less demanding for procedure writers, who, understandably are unable to anticipate all possible conditions that may affect the sufficiency of a procedure. However, they would also be challenging, as they would require delivering training to the large number of temporary and new personnel engaged in outage work.

4.2. *Implications for future research*

In addition to the suggestions for future research made in the general discussion, research could also build on our findings by investigating how the situation awareness errors identified in this study could be reduced. We have pointed to three general approaches: improvement of procedures, use of human performance tools, and improved training/competence of outage personnel. There may also be technological solutions that could enhance these three approaches, for instance: tools to help outage personnel in performing verification of work, or tools to make it easier to include the experience and competence of roles in different parts of the organisation in work planning.

Furthermore, our finding that several situation awareness errors relate to lack of work verification suggest that verification might be useful as a separate category in the taxonomy of situation awareness errors. Verification would relate to the active tasks performed to check that information is present in the situation and understood. It could complement more passive perceptions or comprehension of information. Future research could consider if adding more active elements to the taxonomy of situation awareness errors is useful for understanding and addressing the phenomenon better.

4.3. *Limitations*

As noted in other similar studies (e.g., Sandhåland et al., 2015), we acknowledge limitations concerning our ability to ensure the accuracy of event information provided in the LERs included in our analysis and concerning our ability to draw correct conclusions based on the information provided in the LERs. The quality of coding applied in this study relies on the quality of information provided in the event reports, which by their nature vary in terms of breadth and depth of information. To counter this limitation, we have attempted to be transparent about our coding procedures and our interpretations of the situation awareness errors identified in the LERs analysed.

Another limitation relates to the data that informs our study. U.S. nuclear power plants are known to organize outage work differently than plants in other countries (Reegård et al., 2020). This could create a unique context for studying situation awareness errors made during outage work. Furthermore, the 58 LERs we analysed in the present study were submitted by only 23 plants, all of which were boiling water reactors (BWRs). No event reports from pressurized water reactors (PWRs) were included in this study. According to the process expert involved in this study, there is no real evidence as to why the LERs during this period were exclusively related to BWR plants. However, it could be because all areas of BWR plants are considered contaminated. This could create a work environment where small incidents could create events defined as reportable by the U.S. NRC. These limitations of our sample could provide limitations with regards to the generalizability of findings to other plants and other plant types.

5. Conclusion

Several studies indicate that situation awareness errors contribute to adverse events in safety–critical industries (Jones & Endsley, 1996; Patrick & Belton, 2003; Sandhåland et al., 2015; Sneddon et al., 2006). The present study aligns with these findings, by demonstrating that human errors leading to incidents during planned outage periods in nuclear power plants can also be classified as situation awareness errors. However, the present study also extends our understanding of the types of situation awareness errors made in outage work. While research conducted in cockpits, ship bridges, and control rooms finds that most situation awareness errors occur at the perceptual level of information processing (Level 1 errors), our research found most errors occurring at the comprehension and projection levels (Level 2 and 3 errors). Furthermore, we find that insufficient procedural contributes to a large portion of the situation awareness errors occurring at Level 2 and Level 3, more so than individual and contextual factors typically associated with situation awareness errors. Taken together, our study provides evidence that situation awareness errors are made in outage work. But it also finds that the types of errors occurring in this context and the contributing factors could be different than what has been identified in other, significantly different work environments. Our research suggests practical implications, including the continuous improvement of procedures and developing reliable human performance tools to compensate for insufficient procedures. We also identify avenues for future research, including the need to further investigate the factors contributing to Level 1 situation awareness errors, the need to understand how shared situation awareness is achieved in outage work groups, and the need to test various interventions that could be used to reduce the situation awareness errors identified to occur in this context.

CRediT authorship contribution statement

Elizabeth Solberg: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Espen Nystad:** Writing – review & editing, Writing – original draft, Formal analysis. **Robert McDonald:** Validation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the OECD Nuclear Energy Agency (NEA) Halden Human-Technology-Organisation (HTO) Project. Thanks to the members of the Programme Review Group of the Halden HTO Project for review and constructive comments.

Appendix A

In the tables below, several sample event descriptions and event causes extracted from the LERs are shown together with the situation awareness errors we assigned in our analysis. (Date and plant information have been concealed out of respect to the reporting organizations).

Reported event description	At 12:55 EDT on DATE, with Unit 1 in Mode 2, stabilized at 2% power, during startup from a refueling outage, all four main turbine Bypass Valves (BPVs) [JI] fully opened unexpectedly. This created an unexpected reactor depressurization and cooldown which resulted in the operating crew inserting a manual reactor scram. The scram was uncomplicated and all control rods inserted as expected during the scram. In accordance with plant procedures, the main control room closed all Main Steam Line Isolation Valves (MSIVs) [JM] to arrest the cooldown resulting from BPVs remaining open. The condensate system [SD] remained aligned for injection and pressure control was initially via main steam line drains [JM]. Residual Heat Removal (RHR) shutdown cooling [BO] was placed in operation for decay heat removal and pressure control once the MSIVs were closed. All systems responded as designed.
Reported event cause	The direct cause of all Unit 1 BPVs fully opening during startup was the Turbine Control System (TCS) [JJ] pressure setpoint being set incorrectly. Procedure 0GP-01, “Prestartup Checklist,” requires the pressure setpoint be set to 100 psig at this point during startup. However, at the time of this event, the pressure setpoint was incorrectly set to 1 psig. This error went undetected until the low main condenser vacuum isolation signal to the BPVs cleared during the startup sequence, at which time the BPVs fully opened. This event resulted from a less than adequate technical review of procedure 0GP-01, “Prestartup Checklist,” during development for the TCS upgrade project. In addition, there was a lack of proficiency in adjusting pressure set.
Situation awareness error assigned and interpretation	3 – Failure to monitor or observe data in the environment.Operations personnel did not monitor or observe information in the situation, including information provided in procedure 0GP-01 and on instrumentation, which would have indicated that the pressure setpoint was set to 1 psig and not 100 psig.
Brief interpretive text provided in Table 4	Operations personnel failed to notice that the turbine control system pressure setpoint was incorrectly set to 1 psig, instead of 100 psig

Reported event description	On DATE, PLANT Instrument & Control (I&C) technicians started a Reactor Vessel Water Level Transmitter Calibration Surveillance. At 1551, the technicians inadvertently opened the low pressure isolation valve instead of the equalization valve. This resulted in a decrease in sensing line pressure, which appeared as a low water level signal to the transmitters. As a result, Division 1 Emergency Core Cooling System (ECCS) initiated, and Shutdown Cooling was isolated. All systems responded as expected, including RHR “A”, which automatically aligned to inject into the Reactor. The RHR “A” suction source remained from the spent fuel pool, and thus there was not a net change in RCS inventory. The ECCS actuation resulted in minimal flow from the RHR “A” pump through the “RHR ”A“ Heat Exchangers. After a 5 degree F rise in local Reactor Coolant System (RCS) temperature, Operations realigned RHR ”A“ from Injection to Shutdown Cooling mode.
Reported event cause	The technicians inadvertently opened the wrong valve because of a failure to use human performance tools. l&C technicians failed to use various human performance tools, including procedure adherence, operating experience, questioning attitude, verification/validation, peer check, and self-check. Furthermore, flagging or robust barriers were not used in valve manipulations.In addition, Operations did not implement an adequate risk mitigation strategy for the surveillance. This task had been previously categorized as high impact; however, it was screened as medium during this event.
Situation awareness error assigned and interpretation	3 – Failure to monitor or observe data in the environment.Technicians failed to monitor or observe data in the environment, including information provided in work procedures, or that could have been identified by using other human performance tools, that indicated they were opening the low-pressure isolation valve instead of the equalization valve.
Brief interpretive text provided in Table 4	Technicians failed to notice that they were opening the low-pressure isolation valve instead of the equalization valve

Reported event description	On DATE, at 1445 Central Standard Time (CST), during routine maintenance of the PLANT, Unit 3 Core Spray (CS) system [BM], Operations personnel were unable to verify that the Division II CS 3B Pump Automatic Start Signal (3-RLY-075-14A-K25B) and Valve Automatic Initiation Permissive Signal (3-RLY-075-14A-K13B) relays [RLY] were energized. This was due to relays on the 3ED 4kV Shutdown (SD) Board (BD) found de-energized, preventing the normal automatic startup of the 3B and 3D CS Pumps [P], the 3D Residual Heat Removal (RHR) [BO] pump, and the D1 Residual Heat Removal Service Water (RHRSW) [BI] pump.

(*continued on next page*)

(*continued*)

	Troubleshooting determined that the NVA relays were de-energized due to a failure of the 6-6C contacts on the MJ(52STA) switch associated with the 3ED 4kV SD BD breaker and a binding of the 52STA Cam Linkage. This was caused by a misalignment of the switch to linkage interface, due to improper installation. On February 23, 2016, at 1520 CST, the 52STA switch and the 52STA CAM linkage associated with the 3ED 4kV SD BD breaker was declared operable following an inspection, cleaning, and adjustment.
Reported event cause	*A. The cause of each component or system failure or personnel error, if known:* Troubleshooting determined switch failure was caused by a failure of the 6-6C contacts on the 52STA switch, from and a binding of the 52STA Cam Linkage. This binding was caused by a misalignment of the switch to linkage interface, due to improper installation. *B. The cause(s) and circumstances for each human performance related root cause:* A review of procedure ECI-0-000-SWZ001, Replacement of Type SB switches, which was used to install the 52STA switch found there were no procedural steps for verifying proper alignment between the 52STA switch and the Breaker 52STA Switch Cam.
Situation awareness error assigned and interpretation	6 – Lack of or poor (incomplete) mental model.Insufficient work procedures contributed to a poor (incomplete) mental model about the task and its requirements, such that technicians did not know to ensure that there was proper alignment between a switch and its breaker switch cam during installation.
Brief interpretive text provided in Table 5	Technicians did not know to ensure that there was proper alignment between a switch and its breaker switch cam during installation

—

Reported event description	On DATE, at 0200 CDT, at 0% power with the unit shutdown for refueling outage C1R19, while performing Safety Relief Valve [RV] (SRV) testing, SRV 1B21-F0416 did not open upon demand using the Division 1 Main Control Room (MCR) switch [HS]. Further investigation identified that the Division 1 MCR switch for SRV 1621-F041B opened SRV 1621-F051B and the Division 1 MCR switch for SRV 11321-F051B opened SRV 1B21-F041B. The Division 2 MCR switches for SRV 1621-F041B and SRV 1621-F051B operated correctly. The affected SRVs are adjacent to each other in the Reactor Drywell. Initial investigation determined this condition was a Division 1 SRV wiring issue that occurred during refueling outage C1R17 in DATE.
Reported event cause	The causes of this event were determined to be: (1) Imprecise work instructions combined with performance of multiple actions within a single work step resulted in inadequate human performance and verification practices being applied by electricians performing de-termination/re-termination work on SRVs 1621-F041B and 1621-F051B. (2) Lack of adequate signage on SRVs 1621-F041B and 1B21-F0516 resulted in personnel relying on conduit numbers to identify proper valve operation and wiring during post maintenance testing.
Situation awareness error assigned and interpretation	6 – Lack of or poor (incomplete) mental model.Imprecise work procedures contributed to a poor (incomplete) mental model about the task and the components involved, such that electricians did not know that the wiring of two switches connected to two safety relief valves was incorrect
Brief interpretive text provided in Table 5	Electricians did not know that the wiring of two switches connected to two safety relief valves was incorrect

—

Reported event description	On DATE, SDC isolation valves RHR-MO-17 and RHR-MO-18 were open with RHR Loop A in RHR SDC flush lineup, with an intention of placing RHR Loop A in SDC. The Alternate Decay Heat Removal (ADHR) system was maintaining Reactor Pressure Vessel (RPV) and Spent Fuel Pool temperature. Work orders were created to replace twenty-seven PCIS relay coils, including relay coil for PCIS-REL-K27, in Refueling Outage (RE29). During testing after completion of the work order, it was identified that the PCIS-REL-K27 relay did not actuate as expected (delayed response). This led to a revision of the workorder to replace the entire relay instead of just a coil replacement. This required more wires to be lifted and the relay to be removed from the DIN rail and replaced. SDC was placed in service at 08:49 hours on DATE. Subsequently, during replacement of the PCIS-REL-K27 relay, the action of installing a new relay onto the shared plastic DIN rail disturbed the mounting rail in a manner that caused the 1-2 contact of the adjacent relay, PCIS-REL-K30, to open. This caused RHR-MO-17 to close, which actuated the logic to trip the running 'A' RHR pump. Operations declared A RHR SDC subsystems inoperable at 09:24 hours and entered Technical Specification (TS) Limiting Condition for Operation (LCO) 3.9.7, Condition A, Required Action A.1, "Verify an alternate method of decay heat removal is available within 1 hour and once per 24 hours thereafter;" entered TS LCO 3.9.7, Condition C, Required Action C.1, "Verify reactor coolant circulation by an alternate method within 1 hour from discovery of no reactor coolant circulation and once per 12 hours thereafter;" and also entered TS LCO 3.9.7, Condition C, Required Action C.2, "Monitor reactor coolant temperature hourly." ADHR remained in service throughout the event and the plant remained aligned for natural circulation. Spent fuel pool weir temperature monitoring was commenced to verify natural circulation. No increase in RPV temperature was observed and there was no impact to plant operations. While SDC was out of service, PCIS relay K27 work was completed. SDC was declared operable at 05:30 hours on DATE, and TS LCO 3.9.7, Condition A was exited. The plant remained in TS LCO 3.9.7, Condition C, and aligned for Natural Recirculation, until SDC was placed in service-at 18:30 hours on DATE, at which time TS LCO 3.9.7, Condition C was exited.
Reported event cause	The root cause is that PLANT did not identify the risk from mechanical agitation during PCIS relay installation; therefore, the risk was not adequately evaluated or mitigated.
Situation awareness error assigned and interpretation	9 – Lack of or poor (incomplete) mental modelTechnicians lacked a good mental model to predict that the installation of a primary containment isolation system relay on a shared plastic DIN rail could disturb contacts in the adjacent relay, as this risk and how to mitigate it was not addressed by work procedures.
Brief interpretive text provided in Table 6	Technicians failed to predict that installation of a primary containment isolation system relay on a shared plastic DIN rail could disturb contacts in the adjacent relay

—

Reported event description	On DATE, while Unit 2 was in Mode 4 for refueling outage Q2R24, Operations was performing surveillance, "MSIV Closure Timing," in accordance with Technical Specification (TS) Surveillance Requirement (SR) 3.6.1.3.6. During the surveillance, two of the eight Unit 2 Main Steam [SB] Isolation Valves [ISV] (MSIVs) failed to close within the required cold shutdown TS limit of greater than or equal to three seconds and less than or equal to five seconds. The two affected MSIVs were the inboard MSIVs on the A and C Main Steam lines. The closure times for those two MSIVs were 5.3 and 5.6 seconds, respectively. The other six MSIVs all closed within the required TS time. This condition is being reported in accordance with 10 CFR 50.73(a)(2)(i)(B), which requires reporting of any operation or condition that was prohibited by the plant's TS.
Reported event cause	

(*continued on next page*)

(*continued*)

	The cause of the slow closure timing for the MSIVs was due to an inadequate procedure on how to apply Super 0-Lube to valve stem bottom 0-ring of the airpack manifold. The slow closure times were due to excess Super 0-Lubeon the airpack manifold solenoids. The maintenance procedure for applying the Super 0-Lube was not specific on the amount of lubricant to be used on the bottom 0-ring.
Situation awareness error assigned and interpretation	9 – Lack of or poor (incomplete) mental model.Insufficient work procedures contributed to a poor (incomplete) mental model of the task and the components involved for maintenance personnel to predict that applying too much lubricant to a valve stem bottom O-ring of an airpack manifold would negatively affect a main steam isolation valve closure time.
Brief interpretive text provided in Table 6	Technicians were unable to foresee that applying too much lubricant to a valve stem bottom O-ring of an airpack manifold would negatively affect a main steam isolation valve closure time

References

Bourrier, M., 1996. Organizing maintenance work at two American nuclear power plants. J. Contingencies Crisis Manage. 4 (2), 104–112.

Endsley, M.R., 1988. Design and evaluation for situation awareness enhancement. Proc. Human Factors Soc. Ann. Meet. 32 (2), 97–101.

Endsley, M.R., 1995a. A taxonomy of situation awareness errors. In: Fuller, R., Johnston, N., McDonald, N. (Eds.), Human factors in aviation operations, Vol. 3. Ashgate, pp. 287–292.

Endsley, M.R., 1995b. Toward a theory of situation awareness in dynamic systems. Hum. Factors 37 (1), 32–64.

Endsley, M.R., 2000. Situation models: An avenue to the modeling of mental models. Proc. Human Factors Ergonom. Soc. Ann. Meet. 44 (1), 61–64.

Endsley, M.R., Robertson, M.M., 2000. Situation awareness in aircraft maintenance teams. Int. J. Ind. Ergon. 26 (2), 301–325.

Gertman, D. I., Halbert, B. P., Parrish, M. W., Sattison, M. B., Brownson, D., & Tortorelli, J. P. (2002). Review of findings for human performance contribution to risk in operating events. (NUREG/CR-6753 INEEL/EXT-01-01166). Idaho National Engineering and Environmental Laboratory Retrieved from https://www.nrc.gov/docs/ML0209/ML020930077.pdf.

Gotcheva, N., Macchi, L., Oedewald, P., Eitrheim, M., Axelsson, C., Reiman, T., Pietikäinen, E., 2013. Final report of MoReMO 2011-2012. Modelling resilience for maintenance and outage.

Grech, M.R., Horberry, T., Smith, A., 2002. Human error in maritime operations: Analyses of accident reports using the Leximancer tool. Proc. Human Factors Ergonom. Soc. Ann. Meeting 46 (19), 1718–1721.

Haber, S. B., Barriere, M. T., & Roberts, K. H. (1992). Outage management: A case study. Conference Record for 1992 Fifth Conference on Human Factors and Power Plants.

Hinze, J., 2005. Practices that influence safety performance on power plant outages. Practice Periodical Struct. Des. Constr. 10 (3), 190–194.

Hollnagel, E., & Gauthereau, V., 2001. Operational readiness verification, phase 1: A study on safety during outage and restart of nuclear power plants (SKI 01:47).

IAEA. (2005). *Safety culture in the maintenance of nuclear power plants* (Safety Report Series, Issue. https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1210_web.pdf.

Jones, D. G., & Endsley, M. R. (1996). Sources of situation awareness errors in aviation. Aviation, space, and environmental medicine.

Lin, C.J., Hsieh, T.-L., Yang, C.-W., Huang, R.-J., 2016. The impact of computer-based procedures on team performance, communication, and situation awareness. Int. J. Ind. Ergon. 51, 21–29.

Naderpour, M., Nazir, S., Lu, J., 2015. The role of situation awareness in accidents of large-scale technological systems. Process Saf. Environ. Prot. 97, 13–24.

Oedewald, P., Skjerve, A.B., Axelsson, C., Viitanen, K., Pietikäinen, E., Reiman, T., 2014. The expected and experienced benefits of Human performance tools in nuclear power plant maintenance activities: Intermediate report of HUMAX project. NKS Retrieved from, Roskilde, p. (NKS-300)..

Patrick, J., Belton, S., 2003. What's going on? Nucl. Eng. Int. 48 (582), 36–40.

Reegård, K., Solberg, E., Drøivoldsmo, A., Nystad, E., Farbrot, J., Svengren, H., & McDonald, R. (2020). Outage organizations and distributed situational awareness. Is there a link? (HWR-1310). Halden, Norway: Institute for Energy Technology.

Reiersen, C., & Gibson, W. (1995). Indentification of, and Protection Against, Human Error During Maintenance. International Symposium on Human Factors and Organization in NPP Maintenance Outages: Impact on Safety, Stockholm, Sweden.

Salas, E., Prince, C., Baker, D.P., Shrestha, L., 1995. Situation Awareness in Team Performance - Implications for Measurement and Training. Hum. Factors 37 (1), 123–136. <Go to ISI>://WOS:A1995RL73500008.

Salmon, P.M., Walker, G.H., Stanton, N.A., 2015. Broken components versus broken systems: why it is systems not people that lose situation awareness. Cogn. Technol. Work 17 (2), 179–183. <Go to ISI>://WOS:000353465700005.

Sandhåland, H., Oltedal, H., Eid, J., 2015. Situation awareness in bridge operations–A study of collisions between attendant vessels and offshore facilities in the North Sea. Saf. Sci. 79, 277–285.

Simons, D.J., 2000. Attentional capture and inattentional blindness. Trends in cognitive sciences 4 (4), 147–155.

Sneddon, A., Mearns, K., Flin, R., 2006. Situation awareness and safety in offshore drill crews. Cogn. Technol. Work 8 (4), 255–267.

Spooner, K., Vassie, L., 1999. The influence of workplace factors on employee safety awareness in the nuclear industry. Nuclear Energy 38 (02), 91–97.

St Germain, S. W., Hugo, J., Manic, M., & Amarasinghe, K. (2017). Technologies for Detecting Interactions between Current Plant Configuration States and Component Manipulations Directed by In-Use Procedures.

St. Germain, S., Hugo, J., Manic, M., & Amarasinghe, K. (2017). Technologies for Detecting Interactions between Current Plant Configuration States and Component Manipulations Directed by In-Use Procedures. https://doi.org/10.13140/RG.2.2.16423.85926.

Stanton, N.A., Chambers, P.R., Piggott, J., 2001. Situational awareness and safety. Saf. Sci. 39 (3), 189–204.

Stanton, N.A., Stewart, R., Harris, D., Houghton, R.J., Baber, C., McMaster, R., Salmon, P., Hoyle, G., Walker, G., Young, M.S., Linsell, M., Dymott, R., Green, D., 2006. Distributed situation awareness in dynamic systems: theoretical development and application of an ergonomics methodology. Ergonomics 49 (12-13), 1288–1311.

Stanton, N.A., Salmon, P.M., Walker, G.H., 2014. Let the Reader Decide: A Paradigm Shift for Situation Awareness in Sociotechnical Systems. J. Cognitive Eng. Decision Making 9 (1), 44–50. https://doi.org/10.1177/1555343414552297.

Sun, Z., Xing, J., Tang, P., Cooke, N.J., Boring, R.L., 2020. Human reliability for safe and efficient civil infrastructure operation and maintenance–A review. Develop. Built Environ. 4, 100028.

Wickens, C. D., & Carswell, C. M. (2021). Information processing. *Handbook of human factors and ergonomics*, 114-158.

Yang, C.-W., Yang, L.-C., Cheng, T.-C., Jou, Y.-T., Chiou, S.-W., 2012. Assessing mental workload and situation awareness in the evaluation of computerized procedures in the main control room. Nucl. Eng. Des. 250, 713–719.