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Dynamic HRA in outage from literature and outage personnel interview perspectives

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RESEARCH REPORT

VTT-R-00015-22

Dynamic HRA in outage from literature and outage personnel interview perspectives

Authors: Terhi Kling, Marja Liinasuo, Ilkka Karanta

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Summary

In 2021, the goal of the SAFIR2022 project NAPRA task T3.2 was to provide an overview of an outage of a nuclear power plant from the perspective of human reliability analysis (HRA). The general features of the outage as well as the specific matters related to human reliability and dynamism in the outage context were studied from literature and outage personnel interview perspectives.

The safety-critical nature of an outage is well recognized, and there is a wealth of literature on the specifics of outage and the challenges associated with the successful completion of work. HRA methods have mostly been developed for full power conditions where the operator's actions are well trained and laid down in procedures, in time frames typically less than 60 minutes. In the planned shutdown the work concentrates outside the control room, is less in procedures and less trained and the time frames may be much longer. The environment is continuously changing, there are huge number of workers, large variety of work activities, tight schedule and the requirements are high concerning both safety and productivity. The key issues that should be considered in the HRA are errors of commission (EOCs), dependencies between human actions and the dynamism of the operating environment.

One practical objective of this report was to identify a scenario to focus on in further work related to dynamic modelling. Based on interviews, heavy loads were identified as critical but also mentally and physically loaded. They also include features identified safety critical in scientific literature. This scenario will be studied in more detail in 2022. Work analysis will be performed with special emphasis on applying a combination of methods to elicit the key dynamic features from the HRA perspective.

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Espoo 27.1.2022

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Preface

This report is the deliverable of the task 'Human reliability analysis' (T3.2) of the project of 'New Development and applications of PRA' (NAPRA) in 2021. The project is part of SAFIR2022 research programme, funded by VYR.

The goal of NAPRA T3.2 is to define realistic or slightly conservative human error probability estimates and to identify the most relevant human failure events in hybrid control rooms. This realism includes dynamic HRA, contrasting the traditional static starting point of HRA.

Espoo 27.1.2022

Authors

Glossary

ABBREVIATION	MEANING
CDF	Core Damage Frequency
HI	Human Interaction
HRA	Human Reliability Analysis
LPSD	Low Power and Shutdown
NPP	Nuclear Power Plant
PRA	Probabilistic Risk Assessment

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1. Introduction

In the context of the Finnish nuclear safety research programme SAFIR2022, in the NAPRA project task T3.2, the goal is to utilize the concepts and methods of dynamic HRA in hybrid control rooms. The motivation to focus on outage is based on the results of a questionnaire of the year 2020 to Nordic stakeholders about dynamic HRA (Liinasuo et al., 2021). Based on the responses, existing development needs were identified and the study plan for 2021 was created. In the survey, activities during the outage (in other words, shutdown, a consequent maintenance and refuelling break, and start-up) of an NPP unit were identified as an exceptionally fertile application domain of dynamic HRA due to its special features. Outage is more work-intensive than full-power operation, many activities are relatively complex, and human error may contribute more to accident frequency than human error in full-power. Furthermore, personnel working during planned outage does not comprise of only own personnel of the NPP, but subcontractors are used to a large extent. This means that working for the outage is not routine nor highly familiar to many workers, even if they participate in training before they are allowed to work on site.

Thus, planned outage has been chosen as the topic within which the needs and possibilities of dynamic HRA were explored in 2021. First, a literature study was carried out to clarify in a general level what activities are involved in planned shutdown, how outage has been modelled and analysed in HRA, and what HRA issues have been identified. Then, Finnish outage experts were interviewed of the activities, which do or may take place at Finnish plants during shutdown, what their characteristics are, which activities the experts consider having dynamic features, which activities they consider to be most critical from the safety point of view, and what human errors might occur in those activities. These viewpoints are considered from the perspective of human error.

Based on the results, a generic description of shutdown process was created mostly from the human task perspective, also realising, though, that there may be differences in details both from one outage to another and between different units. For further analysis, a scenario was chosen that is relevant and interesting for Finnish nuclear facilities. This scenario will be studied in more detail in 2022, to identify human error related issues and especially the ones representing dynamics. Work analysis will be performed on the chosen scenario with special emphasis on its dynamic features. A combination of methods, relevant to the scenario, will be applied to elicit key dynamic features from the HRA perspective.

2. Goals

The goal of this research report is to provide an overview of an outage of a nuclear power plant from the HRA's perspective. The general features of the outage as well as the specific matters related to human reliability and dynamism in the outage context are studied. This information gathered serves the studying of dynamic features in outage in the context of HRA later in the project, from a more practical perspective.

3. Outage overview

3.1 General features of outage

Finnish nuclear power plants undergo a planned outage on an annual basis. During outage, reactor is shut down and all needed maintenance, repair and refuelling work is done. Outage

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has high requirements concerning both safety and productivity (Tang et al., 2014). Delays in the NPP outage schedule may cause significant economic losses (Zhang et al., 2017).

In Finland, PRA (and as a part of it, HRA) is required concerning outages: "The PRA shall be used to manage risks relating to maintenance outages, refuelling outages and the related operational states as well as the transfers between the operational states" (YVL guide A.7; STUK, 2019b). The outage-specific risk assessment must be submitted to STUK as a part of a report for information in accordance with Guide YVL A.6 (STUK, 2019a).

Nuclear power plant outage is a challenging event for the plant. As described by Tang et al. (2016), it involves a huge number of workers, both inside and outside the plant, in maintenance and repair activities with a tight schedule and zero-tolerance for accidents. For instance, in Loviisa nuclear power plant, 500 power plant employees and nearly a thousand external workers participated in the outage in year 2020 (Fortum's web page, 2020) and similarly, in Olkiluoto, 730 contractor employees were needed for the annual outages in 2020 (TVO's web page, 2020). Outage is carefully planned and performed by professionals. Still, delays and/or errors take place and/or unexpected tasks are added during outages, and all these issues are to be rapidly and proactively responded (Zhang et al., 2017).

Outage is challenging also for NPP personnel. Increased demands on concentration and vigilance, increased time pressure and strain on social relations characterise work during the annual outage (Jacobsson and Svensson, 1991). Most NPP outages require supplemental workforce, which may not be familiar with the workspaces and procedures that vary from one NPP to another, which increases the workload of permanent NPP employees, who train, guide, monitor, and coordinate the work. Interactions between permanent and contract personnel with diverse backgrounds also significantly increase the complexity of communication and information flow throughout outages procedures (Zhang et al., 2017).

According to Heinonen (2013), 25 % of the core damage frequency (CDF) in Olkiluoto 1 and 2 PRA is related to outage. In the Loviisa plant the share is 61 %. The most significant initiating events in the Olkiluoto plant are fire, loss of coolant and loss of residual heat removal. Respectively, in the Loviisa plant, the most significant initiating events are heavy load drops, boron dilution transient and oil accidents.

According to IAEA (2016), outages may be categorized into four different kinds:

1. Refuelling only (7–18 days)
2. Refuelling and standard maintenance (14–23 days)
3. Refuelling and extended maintenance (15–40 days)
4. Specific outages for major back fittings or plant modernization (more than 40 days).

An example of an alternative planned outage classification is used by TVO (IAEA, 2016, Appendix I) and consists of only two main types of outages. A refuelling outage (typically 9 days) consists mainly of "refuelling, corrective maintenance, periodical inspections, and tests required by the technical specifications and maintenance according to the preventive maintenance programme for annually overhauled components". A service outage is divided into two subcategories, normal (14 days) and extensive (20-30 days). It includes the activities of refuelling outage and additionally all major plant modifications and upgrades.

The timing of the annual outage is chosen in such a way that the resulting harm to the electricity market is as small as possible. For this reason, annual maintenance is not held in the winter in the Nordic countries when the demand for electricity is at its highest. The timing is also affected by the availability of external contractors required for annual maintenance work. For economic reasons, the duration is minimized (Heinonen 2013).

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3.2 Safety-critical features of outage

In outage management, the central objectives are the maintenance of plant and employee safety, as well as long-term component and plant reliability (IAEA 1991). Operational experience and performance of the low power and shutdown (LPSD) PRA have highlighted the magnitude of the risk contribution from those operating modes. In some cases, the LPSD risk was found to contribute up to 50% to the core damage frequency (CDF). This risk is not related to the plant design, but rather to the unavailability of equipment due to maintenance activities undertaken during an outage, presence of additional (contractor) personnel who may not be fully aware of the safety issues, presence of additional heavy loads and flammable materials etc. (OECD/NEA, 1998).

Kim et al. (2016) reviewed existing reports (Barriere et al., 1994; Gertman et al., 2005; Nowlen and Olivier, 2011; Wheeler and Whitehead, 1999; OECD/NEA, 1998; OECD/NEA, 2005; IAEA, 2000; Kang et al., 1997) to understand the nature of human performance related to the LPSD operation. As a result, they identified seven characteristics:

1) Mistakes and error of commission (EOC) are the predominant types and modes of human error.

2) Operators face continuously changing plant conditions and configurations.

3) Greater amounts of work activities are being performed, such as tests, maintenance, and repairs.

4) Many pieces of equipment are more frequently manually operated.

5) Even in the cases in which procedural guidance is present for the actions to be followed by human operators when an initiating event has occurred during the LPSD operation, it usually lacks detail and is insufficient.

6) Operators usually have less training in response to accidents during LPSD operation.

7) Since there is more available time to respond, operators feel less stress.

According to Kim et al. (2017), specific features regarding operator’s role during LPSD operation are related to time window, number of actions, manual operations, acquired operations and available procedures. Firstly, the time window for performing the action is generally sufficiently long, but some are short. Secondly, there is a great number of human actions due to extensive maintenance and tests being performed. Thirdly, a lot of equipment is more frequently manually operated. Fourthly, the acquired training is usually insufficient; and, fifthly, the related procedure is prepared with less than sufficiency.

The most significant difference in plant safety between power operation and annual maintenance is in the reactor operating state, which is in a subcritical cold state during downtime. This allows operators more time to take corrective action to keep the facility in a safe condition during events that threaten core cooling during annual maintenance. On the other hand, during annual maintenance, some safety systems must be deactivated, which increases the risks during downtime compared with full power operation (Heinonen, 2021).

Zhang et al. (2017) have identified two practical problems in NPP outages. In these problems, human factors play important roles. The first practical problem is about controlling the efficiency and error rates of handoffs, that is, the transitional stages between tasks. Handoffs are challenging, because they involve highly uncertain activities, such as transports of resources and labour, communication both among people and between human and computer, field preparation, mobilisation, and waiting. The second problem is about responding to many contingencies in an outage so that workflows can quickly recover from

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interruptions and incidents due to field discoveries. About 15% of tasks in outages are "discovered" in the field, because many problems can be covert due to the uncertainties regarding field conditions and resource availability.

These practical problems also affect safety. They cover all outage related phases and tasks. Specific tasks, which are important from the perspective of safety, can also be named. To start with, important safety functions must be ensured during downtime. These include systems that ensure the reactor remaining subcritical, reactor water volume and residual heat removal, containment leak tightness at required periods, reactor overpressure protection, operability of measurement and automation systems, and electricity supply (STUK, 2019a).

Assumably, workers need to execute their tasks at least partly in awkward postures that can strain body and result in fatigue or injuries (Ray & Teizer, 2012). As a planned outage takes place only annually and probably no worker only works in outages, this is not a permanent risk for workers. On the other hand, as outage probably represents a special event for workers, appropriate routines may not have been established, making workers more vulnerable to injuries.

Regarding the working environment in outages, there are locations with a lot of components and systems, with poor visibility around. Furthermore, the situation changes constantly, which diminishes further the possibilities to maintain an appropriate awareness of operational conditions (Carbonari, Giretti & Naticchia, 2011).

Workers may compete for limited workspaces and the availability of colleagues; miscommunication between workers in crowded job sites can cause unnecessary waiting or unexpected sharing of spaces and resources, which reduces productivity (Tang et al., 2016) and may result in working in haste. This, in turn, makes work more error prone.

In outage, shift duration may become temporarily longer than usually. A review (Smith et al., 1998) of research project reports and journal papers was conducted to compare 8-hour and 12-hour shifts. As a whole, the potential impairment to vigilance and performance possibly associated with fatigue due to excessive hours on duty is an area of some concern with 12-hour shifts. Consequently, care was suggested to be taken when designing overtime staffing.

In 2000, it was stated that it is generally agreed that workday durations of 12 hours or more are not advisable where workload levels are high (Macdonald & Bendak, 2000). At that time there was still no clear research basis for the identification of workload levels, which should preclude extended shifts. In a field study, Macdonald and Bendak had workers working 8-hour days or 12-hour days with workload measurement after half-day work. The combination of higher workload and 12-hour workdays produced more fatigue, shown in increased bodily discomfort, decreased alertness, decreased hand steadiness, and increased errors in grammatical reasoning task.

A literature review on 105 studies on the effect of extended daily working hours was conducted by Knauth (2007). Many negative effects were found, and the positive ones focused mainly on leisure time, except for increased satisfaction with working hours, fewer handovers, and less overtime. To conclude, no firm conclusions were drawn in the review due to partly contradictory results and methodological problems identified in many studies. 12-hour shifts are used in nuclear premises among some professionals based on at least partly workers' wishes without obvious drawbacks. From that perspective, temporary long shifts are not necessary a problem in outage either. Based on a checklist in the review (Knauth, 2007), long shifts could be appropriate in outage if the following prerequisites are fulfilled. Also, this list indicates that at least temporarily, long shifts are not necessarily an issue:

- physical work demands are not too high (this depends on the task in question)

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- adequate rest breaks are allowed
- working time arrangements are designed to minimize fatigue accumulation (this is not a problem if long shifts are not used consistently)
- staffing level is sufficient to cover absences of colleagues
- exposure to toxic chemicals is limited (whether this is relevant depends on the task)
- workers can recover completely after work (no noisy environment during sleeping time etc.)
- early signs of adverse effects of extended work shifts are systematically assessed (this is probably for situations where extended shifts are frequently used)
- demographic change with ageing workforce may aggravate problems so the change is taken into account in work arrangements.

4. Outage process

4.1 Pre-outage planning

Good planning can contribute to the success of annual maintenance, both in terms of safety and economy. The following information is from (IAEA 2016), and is complemented by TVO-specific information from that publication's Appendix I. According to IAEA, outages are planned on long, medium, and short-term depending on the plant strategy. In the long-term planning (IAEA 5–10 years, TVO 10 years), the plant determines the occurrence and duration of outages according to the fuel management, equipment ageing, need of major back fittings and refurbishment. Planned maintenance and inspection measures are fitted together with plant modifications. The goal is to optimize plant availability to the grid, total outage duration and cost. The medium-term plan (IAEA 2–5 years, TVO 3 years) is used to coordinate the outages of all units and take into account electricity market needs. The short-term plan is the detailed planning for the next outage.

According to YVL A.6 (STUK, 2019a), outage work must be grouped into clear entities to simplify work control and ensure safety. The licensee shall plan the implementing organization and its operational guidelines, specific requirements for training, radiation protection, preparedness, fire protection, safeguards and security arrangements, safety-critical work and work relevant to radiation exposure as well as work and inspections related to fuel and control rods.

In a general level, outage management value chain can be described according to the following outage activities and processes (Mwale & Davidson, 2014):

- Plan and schedule planned outage yearly
  - develop and authorise outage schedule
  - provide approval to start an outage
- Conduct planned outage
  - conceptualise a pre-outage plan
  - define and schedule activities for an outage
  - execute a planned outage
    - manage outage execution
    - manage variation from plan
    - finalise planned outage

- Close-up planned outage
    - conduct post outage activities.

Outage scheduling is an issue of its own; one way to consider it is to see it as a resource constrained project scheduling problem. A central issue in project scheduling is to manage the computational requirements of optimization. McKendall et al. (2008) make the following assumptions to yield reasonable computing times and yet to keep the models reasonably realistic:

1. Single mode: Jobs can be performed in only one way
2. Non-pre-emption: Once jobs start, they cannot be interrupted
3. Each resource assigned to an activity is assigned to the activity for its duration
4. The availability of space may vary due to high radiation levels
5. All the toolboxes required to perform the maintenance activities are initially moved into the building using the pedestal crane, and the storage space required to store the toolboxes when not used to perform activities are available
6. If unanticipated jobs are created, then all related incomplete jobs must be rescheduled.

4.2 Outage execution

A well-planned outage also needs to be well managed throughout its execution. The primary safety functions to be monitored are residual heat removal (RHR), sufficient coolant inventory, and maintaining criticality safety; ensuring electricity supply is important to first two of these (IAEA, 2016). Outage is successful when it has proceeded with only low risk; when there is no deviation from, or violation of licencing conditions; when there is minimum impact on personnel and the environment; when there has been no unscheduled event; when there has been an optimised scope of work; schedule has been adhered to; work quality has been good (i.e., no need to re-work); and use of material, human and financial resources has been efficient (IAEA, 2006).

In the following, the main steps of outage are briefly described. The description is mainly based on the master’s thesis of Heinonen (2013).

The outage is started with **plant shutdown**, by running the nuclear power plant from power operation to cold downtime. The shutdown is performed by interrupting the heat-generating chain reaction in the reactor core, i.e., by driving the reactor to a subcritical state. The implementation of the shutdown is different for different reactor types. Subcriticality maintenance of the reactor during shutdown is ensured by transferring all neutron-absorbing control rods to the reactor, in addition to which, in pressurized water reactors, neutron-absorbing boric acid is mixed with the primary circuit coolant.

Residual heat removal must be taken care of throughout downtime. This has to be done because even if the reactor is shut down, the power production of the reactor does not stop completely, but the decomposition of fission products causes residual heat power, which is removed by the residual heat removal system. The residual heat power is highest in the beginning and decreases during downtime. Cooling the reactor is important, as the residual heat power alone is sufficient to melt the fuel if cooling is lost.

The timing of **fuel exchange** depends on reactor status. Once the reactor temperature and pressure have been lowered sufficiently, it is possible to proceed to refuelling. The cover of

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the reactor pressure vessel and part of the reactor interior is removed to allow the fuel to be changed. In addition to refuelling with new fuel, refuelling work also includes internal fuel transfers. Upon completion of fuel exchange, final inspection will be performed, ensuring that the refuelling has been carried out in accordance with plans. Finally, the parts removed from the reactor and the cover of the reactor pressure vessel are reattached.

Other **maintenance and inspection work** is carried out during the downtime according to pre-made plans. In addition, any faults and deficiencies in the various systems are repaired and efforts are made to determine the cause of the fault. For maintenance work, some of the plant's safety systems must be temporarily separated. Maintenance is both preventive and corrective by nature (IAEA, 2006).

During **plant start-up**, the power of the plant is gradually increased, and the required tests related to start-up are performed. Eventually, the plant is synchronized back to the grid and a new operating cycle can begin.

4.3 Post-outage evaluation

IAEA (2006) suggests that after outage, its success is evaluated in a measurable way. In the following, the indicators are briefly described, without the measurement details.

- After outage, information needs to be gathered about the adherence to the **budget** (outage cost).
- Outage duration is evaluated, compared with the **duration** as planned (outage duration).
- Duration extension is evaluated separately; this also is compared with the planned **duration** (outage extension).
- Start-up effectiveness, encompassing the quality of the outage and the effectiveness of control-room operations during the start-up phase is evaluated based on the **time** spent in start-up (start-up period effectiveness).
- Trends in the condition of the plant equipment needs to be identified and maintenance strategy is evaluated, based on the number of **tasks** performed during outage (ratio of corrective and preventive maintenance).
- Also, unplanned work during outage is assessed, based on the number of work **tasks** (unplanned work).
- The extent to which planned work is deferred is assessed, based on number of work **tasks** (not executed planned work).
- Unplanned **energy losses** is assessed to measure the quality of outage work (unplanned energy losses resulting from poor quality work).
- Number of **failures of the equipment** maintained in the outage during the next cycle is followed as an indicator to measure the quality of outage work (failure reports during the next cycle related to work during the outage).
- **Radioactive waste volume and releases** during the outage are calculated against standards (radioactive waste volume and releases).

- The effectiveness of the procurement process is assessed based on the number of **tasks** not executed as planned due to the lack of material or spare parts (material availability).

- **Foreign material intrusions** to the plant systems, and the resulting **problems** need to be avoided and measured (foreign material intrusions).

- The effectiveness of radiological protection programmes in minimising radiation **exposure** to plant personnel is assessed (collective radiation exposure).

- Trends in the performance of the contractors and NPP personnel is identified based on **human-related events and near misses** (human errors).

- Finally, the effectiveness of the outage suggestion system is assessed based on the **number of suggestions to improve** outage performance (suggestions for improvements).

To conclude, many outage related assessments are related to time and tasks performed during the outage but also many other means were suggested to be used to evaluate the effectiveness of outage.

5. Human reliability analysis of outage

5.1 History of outage HRA

Already in the “Handbook of human reliability analysis with emphasis on nuclear power plant applications”, Swain & Guttmann (1983) reflected on some HRA issues related to outage as follows:

- Certain start-up and shutdown procedures may be so demanding on the operator, diverting his/her attention so completely that the likelihood of not noticing a safety-related annunciator in time may increase and therefore they estimate that when the plant is in shutdown or start-up mode, the probability that the user will not respond to a reported indicator that is not directly related to these conditions increases by an order of magnitude.

- During outage, nuclear power plants often require longer working hours than normal, as the presence of certain key personnel is always required. For HRA, it would be important to be able to assess the impact of additional working hours on the probability of human error related to e.g., that the operator does not detect deviations in a timely manner, or the impact on any decision that may be required, particularly related to non-routine circumstances. In addition to the effects of extra working hours, staff can be under time pressure because everyone is aware of the economic impact of plant downtime. From military studies it is known that the combined effects of stress and fatigue are usually greater than the sum of their separate effects.

- The question of interest to HRA is which tasks or situations are particularly stressful. The workload of a situation is, of course, also affected by a person’s skill and experience, but since the analyst is not expected to define the skill and experience levels of individual operators, a conservative solution is suggested that certain NPP situations shall be classified as imposing a heavy task load on the operators. In addition to transients and situations requiring protective clothing in a radiation environment, these situations are suggested to include certain tasks during start-up

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and shut-down that must be performed within time constraints, as well as other situations that generally cause time pressure.

Human actions during LPSD conditions have been recognized as critical contributors to safe operation of an NPP. According to IAEA (1994), shutdown probabilistic risk assessment (PRA) has shown that risks can be comparable to those during full power operation even when the duration of an outage is short. Human errors need to be quantified in full power PRAs as well as for shutdown risk assessment. The importance of human errors seems to be higher in shutdown conditions. Operators have reported higher work demands and less satisfaction with their work result in annual outage compared to normal operations (Kecklund & Svenson, 1997). According to He (2008), PRA results have shown that human failure events (HFEs) are one of the major contributions to CDF in LPSD conditions.

In the IAEA Technical Committee meeting on modelling of accident sequences during LPSD conditions (Stockholm, 1992), the committee members considered that computer models could accurately simulate LPSD conditions and that these models should be implemented on plant specific operating simulators to train operators (IAEA, 1994). LPSD procedures and other administrative controls could and should be tested and refined on the operating simulators. Training on LPSD conditions needs to go beyond operators to other plant personnel, especially maintenance personnel. It was also noted that simulator training was a valuable source of human reliability data. Such data could address operator related initiating events as well as operator related exacerbating events. Such errors could be errors of either commission or omission.

The U.S.NRC (1993) report NUREG-1449 contains data from commercial power plants in the United States. The NRC staff had collected operating experience of shutdown and low-power operations as well as probabilistic risk assessment related to such conditions. According to Barriere et al. (1994) that report and previous nuclear power plant events (e.g., Chernobyl, Diablo Canyon, and Vogtle) led to concerns regarding human reliability during LPSD conditions and limitations of HRA methodologies in adequately representing the LPSD environment. Research projects were initiated about the influence of LPSD conditions on human reliability at pressurized water reactors (PWRs) and boiling water reactors (BWRs). Based on the analysis an improved HRA program plan was created.

The studies of Barriere et al. (1994) showed that the unique combination of unusual plant vulnerabilities together with the increased possibilities for errors during unusual evolutions make LPSD operations a special concern. The principal errors in such conditions are related to manual control actions and control of equipment configuration for maintenance and testing. The quality of procedures and information systems and control and coordination of plant status influence human performance and play an important role in the error frequency. For most problems there are recovery actions available, but failures during the early stages of an outage present greater challenges because the decay heat levels are still significant. Below some specific observations on their studies are listed:

- During LPSD operations human-system interactions are more direct, with operators more frequently manipulating equipment and changing plant configurations, which leads to a greater possibility to mistakes leading to errors of commission. Both latent and active errors were present in most of the detailed event descriptions to cause the situation.

- Procedures were the most frequently identified factors affecting human reliability. Often the procedures were deficient, either by providing inadequate guidance or in omitting instructions for unexpected contingencies while performing evolutions. This is especially troublesome with temporary procedures for special evolutions during shutdown.

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- The analysis also identified multiple influences (e.g., procedures, human engineering, organizational factors, and communication) for specific events, achieving an effect of which each individual influence is incapable of. It was noted that the synergistic effects of multiple influences were not practically considered in any commonly used human reliability methods.

- Deficiencies are symptomatic of poor planning and preparation, as indicated by frequently concurrent deficiencies in training, communications, and organizational factors.

- Unlike full power operations, all classes of human actions and errors (i.e., initiator, pre-accident, and recovery) seem to play a significant role in LPSD operations and events. In addition, there are frequently dependencies between the activities leading to the initiating event and those required for most expeditious recovery response.

- Mistakes (versus slips) and errors of commission (versus omission) predominate the types and modes of human errors which occur during LPSD. In addition, mistakes and errors of commission occur both inside and outside the control room during LPSD.

- Errors important to safety, particularly those that initiate events, are very context specific. Consequently, the context in which actions are taken should be accounted for and may require more information about dynamic plant conditions than a typical PRA cutset scenario provides.

As a result of the assessment of LPSD events, Barriere et al. (1994) concluded that the key issues that should be taken into account in the HRA are **errors of commission (EOCs), dependencies between human actions and the dynamism of the operating environment**.

In the OECD/NEA (1998) report, human interaction analysis is considered the most important issue in LPSD PRA and the human actions to be considered are categorised as follows:

- Human actions before initiating event, affecting availability of equipment,

- Human actions as initiators,

- Procedure based human interactions to terminate an event,

- Human actions in attempt to follow the procedure which failed to terminate an event, and

- Human actions to recover the failed equipment or to terminate an event.

As a whole, in OECD/NEA (1998), human interaction analysis is considered to be much more complex in LPSD PRA compared with full-power PRA, as it requires identification of actual ways of work and consideration of interactions which are not obvious. Human action types are pre-initiator actions (maintenance, functional tests and calibrations), post-accident actions or actuation of systems, the automatic actuation of which is inhibited. When evaluating human interactions, the following issues need to be addressed:

- Lack of Technical Specification requirements and limits, and lack of Operating Procedures,

- Lack of supervision on maintenance activities,

- Lack of appreciation of risks during Shutdown, and

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- Lack of comprehensive and appropriate training.

5.2 General considerations for outage HRA

The actions of the operator often dominate the results of shutdown PRA because there are few automatic device functions during shutdown. This has been shown by numerous analyses of shutdown and highlights the importance of operating personnel and the HRA (Zoulis & Mitman 2012).

IAEA (2000) Tecdoc-1144 identifies the key risk factors to be the required manual activation of systems, use of external maintenance staff from outside organizations, frequent overtime work and increased requirements for control room work. It is noted that due to the complexity of the analysis of human interactions during shutdown it is very important to perform the HRA in a structured and logical manner and aim to generate failure probabilities which are consistent with one another and the ones in other portions of the PRA. The detailed assessment can be limited to the most important human interactions (HIs) by using screening cycles, where the emphasis is first given to the completeness of the identification of human interactions (HIs) and the use of preliminary conservative screening values. Model evaluations are then carried out to find out for which of the HIs a more detailed assessment is required and useful. In the HRA task the human interactions are categorised as follows:

- **Pre-initiator HIs (Category A)** consist of actions associated with testing, maintenance, repair and calibration which may degrade system availability by causing a failure of a component or component group or leaving equipment in an inoperable condition. Although the numerical value of some of these errors may be different from those used in the full power PRA, the basic approach to their quantification is similar.

- **HIs that may cause an initiating event (Category B)** and thus contribute to the frequency of initiating events.

- **Post-initiator HIs (Category C)** during the sequences caused by an initiating event, when the operator may be called upon to perform actions in order to ensure a successful plant response. These HIs are particularly important during shutdown because of the reduced level of plant automation and their tendency to be dominant contributors to core damage frequency.

According to Boring (2015), LPSD HRA is often closely related to event analysis, whereby the analysis often focuses on maintenance activities. LPSD activities are often characterized as being long-duration, ex-control-room, and less proceduralised. As such, the analyses need to include a greater consideration of the consequences of errors of commission, which can serve as triggering points for events at the plant.

Furthermore, in a survey of human reliability needs in the U.S. Nuclear Industry (Boring 2015), 34 subject matter experts from the U.S. nuclear industry were interviewed to determine specific needs for human reliability analysis (HRA). One of the conclusions was that there is still need for development of HRA approaches suitable for LPSD applications. Several specific needs were identified:

- more explicit modelling of errors of commission

- determining the adequacy of procedures for LPSD activities

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- identifying similarities and differences between LPSD maintenance activities at current plants and at-power maintenance activities in advanced reactors
- establishing credible lower bounds for quantification of LPSD events
- developing more comprehensive dependence models for HRA quantification of LPSD events.

5.3 Outage HRA methods

Most HRA methods have been developed for full power conditions in which the operator's actions are usually laid down in procedures and frequently well trained, in time frames which are typically less than 60 minutes (IAEA 2000). During shutdown the situation may be different with less detailed guidance, less training and longer time windows. The methodology that is selected for HRA should account for the increased difficulties the operators may face because of lack of procedural guidance and training. It should also account for the positive effect of the increased time available for many actions in shutdown. The methodology should provide error probabilities which are reasonable compared to the ones of the full power PRA.

The first generation of HRA methods was developed primarily for control room activities at power. Newer methods like ATHEANA were directly borne out of the need also to address in- and ex-control room activities under different conditions such as LPSD, while methods like SPAR-H have included specific coverage of LPSD considerations like the increased time windows for task completion. Even with the development of HRA to address LPSD, there remain limitations. For example, the dependence modelling used in HRA quantification is largely based on THERP and may prove incompatible with the longer time windows of many LPSD activities. (Boring 2015)

Kim et al. (2016) describe HRA methods considering LPSD operation as follows:

- ATHEANA (Forester et al., 2007), a technique for human event analysis, has been developed for different conditions including full power, start-up, and LPSD conditions. This method covers most situations of the plants, but it requires considerable expertise and does not provide a formal list of activity types, performance shaping factors (PSFs), nor explicit guidelines.
- SPAR-H (Gertman et al., 2005), standardized plant analysis risk - human reliability analysis method, includes for LPSD an identical set of PSFs that are used for power mode, even though the researchers performed a review of the existing reports, investigation of the event-based data sources, and interviews to find the important influencing factors on human performance during LPSD operation. The only difference is the criteria to assess the weighting of available time which is one of given PSFs. There is no difference in definition or range of weights for other PSFs.
- K-HRA (Kang et al., 2005; Jung et al., 2005), Korean standard HRA method, modified the original K-HRA for full power operation and suggested their own different criteria to estimate the weightings of procedures and time pressure for LPSD operation. Thus, the method applies the same process to analyse human errors with respect to LPSD operation. Although different criteria to estimate the weightings of procedures and time pressure are used, the same set of PSFs with definitions and range of weight are used.

Zoulis & Mitman (2012) analysed a shutdown issue (pressurized water reactors reduced inventory) using the SPAR-H methodology and compared the results with those obtained using the Electric Power Research Institute
(EPRI) Cause-Based Decision Tree (CBDT) method (Parry et al. 1992) and the Technique for Human Error Rate Prediction (THERP) (Swain & Guttman 1983) method. The HRA sensitivity analysis resulted in a conditional core damage probability (CCDP) that was very close to the original analysis. The analysis was made to a 4-loop pressurized water reactor (PWR) during reduced inventory operations as part of the NRC Reactor Oversight Process (ROP), where inspection findings were evaluated using the significance determination process.

PRA typically focuses on the Errors of Omission (EOOs), i.e., errors that lead to the non-performance of required actions (Podofillini et al. 2013). However, in relation to SDLP conditions the Errors of Commission (EOCs), i.e., inappropriate, undesired actions that aggravate an accident scenario, should also be considered (Barriere et al. 1994, Boring 2015, Kim et al. 2016). Podofillini et al. (2013) introduce the Commission Error Search and Assessment (CESA) method for their identification (which error events should be included in the PRA) and to the quantification of their probabilities.

Kim & Kim (2015) suggest a systematic procedure to identify and quantify human-induced initiating events (Category B actions). The procedure is based on the Commission Error Search and Assessment (CESA) method (Podofillini et al. 2013) and includes several steps: selection of initiating events, selection of systems or components, the screening of unlikely operating actions, and the quantification of initiating events. A detailed instruction for each step is also provided, such as operator's action, information required, screening rules, and the outputs.

As a first step towards the development of a new LPSD HRA, Kim et al. (2016) investigated main drivers that can increase or decrease the possibility of human error during LPSD operation. They reviewed “foreign” reports published by nuclear and nuclear-related institutes, as well as “domestic” (Korean) NPP operating experience during LPSD operations. By a so-called root cause analysis (RCA) method, four main drivers were derived, including procedure, experience level, workload/stress, and training. In addition, other root causes such as HSI, communication, task planning, and supervision also led to human or human-related events. The conclusion was that these root causes should also be considered as drivers in the implementation of HRA methods for LPSD operation.

Kim et al. (2017) continued the work by quantifying the weightings of PSFs when performing HRA during LPSD operation. A profiling technique
suggested by Kirwan (1997) was adopted, and human error data were collected from “domestic” (Korean) NPP operational experience. In the profiling technique each human error datum is described in terms of the same PSFs. Comparison and extrapolations between human error data can be performed and this creates a profile for human each datum. PSFs were investigated for describing each human error datum by using a root cause analysis method HuRAM+ (KINS, 2015). In HuRAM+, root causes are regarded as factors that may contribute to the occurrence of improper human activities. These root causes are directly comparable to PSFs when performing HRA. As a result, the probabilities of human errors were provided and the weightings of several single PSFs and combined PSFs which affect the probabilities of human errors were quantified when implementing HRA during LPSD operation. In this study, the profiling technique was applied with the assumption that every PSF is independent of each other. Since there were limited data, it was difficult to investigate dependencies between PSFs.

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6. Dynamic HRA of outage

6.1 Dynamic features of outage

There are several sources of dynamism in outage. Liinasuo et al. (2020) have scrutinised dynamism from the perspective of human performance as follows. To start with, human performance is dynamic in nature. Different matters are perceived, depending on the cognitive map, or mental model, of the situation, which means that already perception depends on background factors that can be permanent, transient, or a combination. Perception depends also on the environment encompassing the actual focus of perception. Environment may present clearly or hide the relevant information, from the perspective of a person in that specific situation. Furthermore, both the outside situation changes and the matters depending on the person change, as perception and the related cognitive processes are both person and context dependent. People are affected differently by, say, stress, perceived familiarity of the situation, as well as uncertainty and complexity of the situation, depending on personality, previous experience, and the situation at hand. Hectic situations may support some individuals to excel themselves and exhaust others, and some endure long-lasting stressful situation when others are fatigued. Work context dependent and independent emotions may intervene and affect teamwork and individual decision-making and consequently, the operations made.

There are many factors related to dynamism or change in the operating environment of a nuclear power plant (Liinasuo et al., 2020). These contextual, that is, situation or environment related, or objective factors, opposed to cognitive and subjective factors related to human performance, are about changes that take place in the operating and surrounding circumstances as well as in the event or accident progression. All special events, deviating from operations in full power such as shutdown, start-up, maintenance work, incidents and accidents, cause changes in the state of the plant and can be considered dynamic by nature. Being exceptions from the daily routines, these events are prone to be context driven, opposed to routine-driven situations. Only the state of full power is not especially dynamic as such, even if the state of the plant slightly changes in accordance with the abrasion of components and parts of the plant system.

Thus, these above mentioned, general-level dynamism-eliciting factors naturally also apply to outages. Mental model is probably not as representative (extensive, solid) for outage situations as for situations related to normal operation. Weak mental model is not capable of guiding the understanding of the situation and making the related decisions. This is not to state that the outage personnel would not be professionals but that the outage represents an exception to the usual situation, that is, normal operations, meaning that outage is not as thoroughly understood as normal operations. The less informed the operator or worker is, the more the person is led by contingencies instead of relevant matters and, correspondingly, the more prone the person is to make an error. Perception is more obstructed during outage, in which components and machines removed from their ordinary location. The location also changes during the proceeding of an outage. This makes the perception of critical matters more complicated. Finally, working in outage is far more hectic in nature than working during normal operations. Thus, the dynamic factors identified during normal operations (Liinasuo et al., 2020) are intensified, making the human more prone to make errors, during outage.

Specific situations occurring often during outages are prone to have dynamic features. Contingencies often have surprising elements in them and cannot be handled purely by relying on instructions. Handovers of work at the start and end of work phases also have dynamic features, such as communication between people some of whom do not necessarily have much experience in conducting work at an NPP and obeying its many safety rules.

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Dynamic phenomena are also related to incidents and accidents, as contemplated by Liinasuo et al. (2020). Based on their considerations, the starting point may trigger some other events, and the situation as such changes by time. Incidents and accidents may take place also during an outage. It is noteworthy that the situation evolves also when nothing extraordinary happens: New alarms may appear, others disappear etc. Additionally, by controlling the nuclear processes during shutdown and start-up, operators intervene the proceeding of events; intervention is especially true if an accident takes place. The situation does not remain the same after each involvement and, due to their role and responsibilities, operators are to manage the situation and update their situation awareness constantly. It is also possible to get flawed measurements and erroneous alarms, originating from false measurements or no measurement at all, and this burdens operators, affects their tasks, and changes the situation. Incidents and accidents may take place during outage, mainly in the beginning and at the end of it, as they are the transitional phases with radioactivity involved. A case of its own is an incident or accident, which may take place due to an error in maintenance, during outage. Such an error may remain latent during outage but become obvious during normal operations.

Situation awareness (SA) is especially crucial in the highly dynamic NPP outage projects because things can change from a normal operating status to an unexpected one in a short time (tens of minutes) (Zhang et al., 2017).

According to Zhang et al. (2017), about 15% of tasks are "discovered" in the field only in NPP outages. This is the case because many problems may not become apparent due to the uncertainties about the field conditions and resource availability. These two matters, combined with the need to incorporate additional work in outages, add pressure to NPP outage control. After all, the work context of outage means that workflows, workspaces, and large crew sizes must be quickly adjusted and reconfigured to perform outage related work efficiently and at least about within the defined time limitations.

Also, personnel related changes modify situations. For instance (Liinasuo et al., 2020), each person has his/her style and competences, which affect, say, the way operations are performed, and communication conducted. Shift changes affect personnel's situation awareness and subsequently operations, even if they are neutral events by nature. It is also possible that an operator falls ill during the shift or works tired due to poor sleep, making poor decisions or operations due to that, or becomes too stressed to handle a demanding situation. These situations can take place also during an outage and the stress, which is probably higher during outage, increases the possibility of making an error.

6.2 Dynamic models and their applicability in outage HRA

The most used HRA methods are static and do not take into account how PSFs can dynamically change HEP over time (Boring, Joe, & Mandelli, 2015). In contrast, dynamic methods do not base modelling of the outcome of events on a fixed set of events or fault trees. Rather, they construct the progression of the event dynamically because of ongoing actions (Boring & Rasmussen, 2017). Liinasuo et al. (2020) presented a list of dynamic methods that have been proposed and/or used for HRA purposes (

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Table 1). We consider each of these methods in turn concerning their suitability to the HRA of outages.

Table 1. Dynamic methods for HRA (Liinasuo et al. 2020).

Method	**Features**
Dynamic event tree analysis method for accident sequence analysis (DETAM) (Acosta & Siu 1993).	Stochastic variation can be treated both in operating crew states and in hardware states. Sources of dependencies between failures can be defined.
Dynamic reliability model to analyse operators' decision making and to perform HRA for accident sequences (Holmberg et al. 1999).	Description of the activity context, probabilistic modelling, and psychological analysis form an iterative interdisciplinary sequence of analysis in which the results of one subtask may be input to another.
Cognitive simulation (e.g., Pew 2008, Zhang & Xue 2013).	Represents human cognitive processing including perception, diagnosis, and decision-making. Action can also be included. There are several implementation possibilities, e.g., discrete event simulation (Lockett 1997) or intelligent agents (Resconi & Jain 2004), general platforms e.g., MIDAS (Gore & Jarvis 2005), ACT-R (Pew 2008) or SOAR (Laird, 2012), and frameworks for HRA (e.g., Boring et al. 2006, Fotta et al. 2005, Chang & Mosleh 2007a).
Semi-static approach (e.g., Trucco & Leva 2007, Di Pasquale et al. 2015, Petrillo et al. 2017)	Integrate the quantification capabilities of the so-called 'first-generation' human reliability assessment (HRA) methods with a cognitive evaluation of the operator.
Crew behaviour model (Shu et al. 2002, Chang & Mosleh, 2007b, Ekanem et al. 2016, Xing et al. 2017)	Simulate and analyse the response of an operator team to an incident in a dynamic and context-sensitive situation. Crew interacts with the system through the actions of its individual members. One implementation possibility is multi-agent modelling (Weiss 1999, Sycara & Lewis 2008).

DETAM serves here as a representative of a wider class of models/methods: dynamic event trees (DET) such as DYLAM, RAVEN and MCDET (Karanki et al. 2018). Although we do not consider other DET methods here, we believe that the benefits and issues concerning the suitability of other DET methods to outage HRA are reasonably similar. DETAM's benefits concerning outage HRA:

- DETAM's analysis is holistic: random events, plant response and human actions are handled in the same model. Thus, the multitude of contingencies and possible situations of outage can be handled in a single model.
- Nominally, the DETAM framework is quite general, and thus in principle allows the construction of quite realistic models of outage.
- Human mental states (stress level, tiredness etc.) can be handled as state variables that evolve dynamically as events unfold.

DETAM's drawbacks concerning outage HRA:

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- The existing and documented implementation of DETAM, concerning steam generator tube rupture in the full power mode of an NPP unit, does not give much support to the construction of DETAM elements for outage, and thus the construction of a DETAM implementation for outage would have to start almost from scratch.

- To control the combinatorial explosion of the event tree – a common ailment of dynamic event tree methods – it is likely that severe constraints on the rules guiding event tree branching would have to be set, thus reducing the realism of the model.

- No commercial implementation of DETAM exists, and thus the development effort needed to construct the DETAM framework, and an outage accident model would be very large.

There is also an open question concerning DETAM's suitability for outage HRA:

- Although human actions and the outage process have some dynamic features, it is not known whether dynamism contributes to risk sufficiently to warrant the deployment of a tedious method like DETAM.

To summarize, constructing a DETAM model covering the whole outage would be a large undertaking and it is doubtable whether the increased realism and accuracy of analysis would warrant such an undertaking. However, DETAM (or some other dynamic event tree method) could be applied to a limited scenario selected from outage PRA; such a study would bring valuable information on the applicability of dynamic event trees in this domain.

The method of Holmberg et al. (1999) is promising for dynamic HRA in the sense that it combines probabilistic modelling and analysis with psychological considerations. Influence diagrams are a powerful way to describe scenarios. However, it is unclear how the method would handle feedback loops in scenarios – for example, a situation where a crew would manage to repair a broken pump and thus return the situation to an earlier stage in the scenario. Nevertheless, it could be worthwhile to try to apply the method in dynamic scenarios.

Many methods, also the one of Holmberg et al. (1999) described above, include cognitive simulation or other means to include the relevant part of cognitive processes in the methodology.

Some benefits of cognitive simulation in outage HRA are:

- Human behaviour and probable courses of actions can be modelled and analysed much more realistically and accurately with them than the descriptions of human behaviour in conventional HRA models.

- Combined with, e.g., a multiagent model for communication and cooperation, a cognitive simulation model could provide a reasonably realistic way to simulate crew behaviour that can be combined with deterministic analyses (plant response) and PRA model (random events) to model and analyse even very complex and dynamic situations in outage

- Software platforms for the construction and execution of cognitive simulation models exist and some are freely available.

Some drawbacks of cognitive simulation in outage HRA are:

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- Construction of a realistic cognitive simulation model is difficult and tedious, requires psychological expertise, and can currently be done only one specific scenario at a time. Thus, the construction of cognitive simulation models is practicable for only limited scenarios.

- Cognitive simulation models do neither produce information on when and how often a human makes a mistake, nor information that could readily be quantitatively used in assessing the probability of human error. They produce predictions on how a human would act in certain situations in narrowly defined scenarios; these predictions have somehow to be interpreted to judge when the behaviour was correct and when the human made an error. It is difficult to computerize such interpretations, and therefore it is tedious to produce human error probabilities from cognitive simulation results.

- There is not much experience on combining cognitive simulation with crew models (communication, coordination, cooperation), and thus it is within the realm of scientific research to consider how well these two aspects of crew action can be combined in a single framework.

To summarize, cognitive simulation has the potential to provide the most accurate dynamic model of human and crew behaviour from the alternatives considered. On the other hand, construction of a realistic cognitive simulation model is expensive, and the resulting model would be applicable only in the narrow and limited scenario it was constructed for. Thus, at the present stage of technology and psychology, it is realistically applicable for only some limited and critical scenarios where increased accuracy pays back the effort.

The PROCOS simulator (Trucco and Leva, 2007) aims to solve one of the problems of cognitive simulation: that cognitive simulation models are by necessity very specific. Their approach combines cognitive simulation with first-generation HRA models and models of the plant. This allows analysis of rather general scenarios. On the other hand, this approach is static on essential parts: only the cognitive simulation model is dynamic, whereas the first-generation HRA methods and the plant (hazard) model are static, and the results of cognitive simulation are used in a qualitative way. It remains unclear whether the benefits of incorporating cognitive simulation results in conventional HRA and hazard analysis would be worthwhile the effort.

The SHERPA method of di Pasquale et al. (2015) also combines simulation and traditional HRA methods. Task classification and performance shaping factors are taken from HRA methods, and SHERPA has been implemented on a general-purpose discrete event simulation platform (ARENA). Utilizing a general-purpose discrete simulation platform provides flexibility and facilitates implementation, but it also raises questions on how the simulation of human cognitive processes can be implemented credibly and accurately. Modelling and simulation of human cognitive processes is very challenging even when using special-purpose cognitive modelling programs; a general-purpose simulation program is unlikely to provide full possibilities of representing and simulating cognitive architectures and processes, and therefore it is unclear what kinds of approximations have to be conducted to enable implementation using the simulation platform's means.

EHEA model of Petrillo et al. (2017) is a hybrid post-initiator HRA model for emergency conditions in industrial plants based on the SHERPA method. Its main improvement to SHERPA is more sophisticated handling of performance shaping factors dependences. As with SHERPA, a major open question is whether the simulation platform provides sufficiently powerful conceptual and computational prerequisites for accurate modelling of human cognitive processes.

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7. Outage related interviews

Five nuclear professionals were interviewed, all representatives of one Finnish NPP. In the following, interviews over the various outage related professions and tasks are presented. In some case, the interviewee talked about his/her own work only and in another, a description of the role in question was provided. To protect interviewee privacy, interview results are presented in a similar way and by hiding such details, if possible, which could reveal the personality of the interviewee. The descriptions are, then, of the tasks of one professional or the tasks of the role. Because the number of interviewees is small, it was not possible to learn when the described tasks are unique and when the task description is valid for all working in that role. This must be taken into account when reading the work descriptions. As a whole, however, interview data provides insight of the quality of the work at the plant during outage.

7.1 Mechanic of mechanical maintenance

Mechanic fixes mechanical devices with manual tools (which may use electricity). During outage, one mechanic acts as a “head man” (‘kärkimies’, i.e., a person who leads the tasks in a small team and takes care that subcontractors, being less familiar with the tasks and environment, are able to perform their work correctly). In-house mechanics and subcontractors maintain spare valves and conduct startup tests during outage. Each team has his own specialty; the interviewee has some special valves under his and his subcontractor team’s responsibility (regulating units for some special valves). No work list is needed during outage because the work is always the same. Contrasting to many other workers in outage, the work of a mechanic in outage is rather independent. The time slot when valves can be detached depends on the level of water in reactor, and the humping of the valves to and from the working point requires other professionals, too. Timetable depends on the readiness level of other reactor related work (especially the level of water in reactor). Authority inspects the valves and follows the testing at the working room before the valves are taken back to the site. Greatest risk during outage is that a heavy part falls on someone.

Error possibilities with mechanic maintenance

- work requires precision and patience, if the surface of the valve is not smooth, it will leak (and during grinding, cuts always emerge, they just have to get smoothened, not to perfection but smooth enough)
    - physically hard to grind, can last from 4 hours to 3 days
    - tasks in general last form 10 minutes to 3 hours
- if spare parts were not found, that would be a problem [which could cause stress and hurry and make a person prone to make an error] but in practice, this “never” takes place
- if an experienced mechanic fell ill, there would be a lot more work to others and if they were not experienced, work would be delayed, causing stress, and making people error prone
    - falling ill during short outage would be a catastrophe
- a valve can erroneously be opened so that there is pressure; this has never happened, involves the possibility of getting something hot on face or the like [which probably makes the mechanic even more careful)

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General factors affecting error appearance

- when short outage is in question, time is limited and there is hurry
- timetable is the only really challenging matter, especially during short outage; tasks are always the same, irrespective of the nature and duration of outage
- personality-sensitive work, subcontractors must be of the right kind (patient and accurate in their work), otherwise the result is not good enough and the time of head man is spent in guiding others' work; however, subcontractors are usually familiar with the plant and work.

7.2 Electrician

Electrician works in the radioactive area during annual outage. In a team with also subcontractors, one acts as a "head man" ('kärkimies', see section 7.1 for clarification). In-house electricians are responsible for regulating units connected to valves. Shift supervisor in the main control room must be asked to get the permission to start working. Work is done in one shift.

Regarding this task by nature, if the valve is moved when it should not be done, water can go to a wrong direction. Additionally, one electrician is responsible that the machine, which loads fuel rods to reactor, is functional.

Error possibilities with regulating units:

- one error possibility is to start working with the regulating unit without a permission.
- another possibility, identified by researchers, is to work without procedures and fail due to this as the practice seems to be that procedures are looked at only if it is not remembered what to do.
- some valves are operated remotely, and those valves are in locked rooms – it is possible to go in a locked room when it is operated.
- in electrical devices, voltage must be measured; if not, the consequences can be serious
- with regulating units, it must be ensured that the direction of rotation is correct (getting open/closed); if wrong direction, it can break the valve
    - in the worst-case scenario, pipe gets broken when the valve is closed too hard, and the content burst out (steam/water/radioactive water); it can be hard to replace, and the pipeline must be closed during that time
- flaw in a regulating unit can be challenging and if a flaw appears, also the error becomes more possible

Error possibilities with the machine loading fuel rods

- machine is old and complex to fix if it becomes broken
- error possibility grows if the flaw is so difficult that it takes several days to fix; usually flaws are not easy if they appear
    - timetable gets disorganized with prolonged flaw fixing

General factors affecting error appearance

- when a flaw appears, timetable becomes obsolete
- there is constant pressure regarding timetable, everything must be ready before start-up
- it is not always possible to start working with own task due to work performed by other people
    - work is interdependent, there are lots of dependencies among tasks in outage
- each outage is unique
- tiredness may trigger some risk

7.3 Crane driving and humping

Some workers in site maintenance conduct heavy lifting with a crane as well as humping. The experienced person who works at the site with subcontractors acts as a "head man" ('kärkimies', see section 7.1 for clarification) for a group in each shift in outage. Work contains two 12-hour shifts and during them, crane driver must be constantly alert. The crane for heavy lifting locates in the reactor hall. During driving, one reads coordinates and the other drives the crane, there can be 2-4 people in each shift.

The order of tasks changes constantly. A preliminary list with tasks in some order is written, but it is known from the start that it will change. Lifting or humping is needed in many tasks and it is very hard if not impossible to evaluate the exact timing of each task. Consequently, head man communicates with own supervisors and other workers about the phase of the tasks, to evaluate whether (s)he is needed as planned or some other tasks can be taken for the time slot in question instead. This communication is performed on the run, no predefined meetings are held.

Error possibilities with heavy lifting

- work is done with constant compromising: drive safely so that the load does not fall (and get broken or fall on somebody and hurt people) but quickly, no errors in driving coordinates are allowed as an error can have fatal consequences, look at both where the load is and where people are
- the load can drop and then, material or people are at risk
    - presently, they have been obliged to lift so that the load is high; the load should be lifted low so that if it dropped, it would not fall through the floor
- without being careful, load can get drifted to an incorrect track and bang around
- when driving a crane, colleague reads the coordinates and driver is supposed to follow the value in question; it requires constant concentration and, moreover, other graphs must be followed, and the driver also needs to be aware whether there is somebody moving in the vicinity
- lifting is done also during night shift so if a demanding lifting task occurs at the last hours of night shift, it is very challenging

General factors affecting error appearance

- heavy lifting is performed only during outage, which means that crane drivers have the only practice in heavy lifting during such a time when it is not possible to try and learn
- timetable is in constant change, continuous communication is needed to know the status of work, reactor related work is the most important and crane work organization is based on that (what to do next, is there a possibility to do something in between etc.), even if there is an updated list in the email every morning about work to be done for the day
- there is constant hurry in performing the work tasks, people are hurrying up
- constant background noise (so crane drivers use signs)
- if there are only two people working at a time for a task, it is difficult to have any pause (cf. 12-hour shifts)
- the amount of personnel is too small so that people must work in constant pressure and if somebody falls ill, work becomes even harder
- the long shifts are very intensive, and they can get prolonged, everybody is hurrying at home when the shift is over, no time to discuss in shift change
- there is no overlapping time between two shifts, so it takes time to become familiar with the situation when arriving at work

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  - for instance, supervisor may have written a message but when arriving to night shift, supervisor has left work already and the situation may have changed
- general atmosphere is challenging, everybody is under great stress, people are tired and shout to each other
- background noise hampers concentration
- no errors have occurred (authors, not interviewee, conclude that this is due to skillful personnel, not the lack of challenges in work)

7.4 Automation maintenance

Automation maintenance requires some tasks to be done for outage preparation; for instance, predictive work needs to be done before outage, and needed spare parts must be available for outage. Turbine related work is done beforehand as much as possible, so there is more reactor related work in automation maintenance during outage. Measurement calibration and I&C tests play a major role in outage. Some tasks must be performed by a defined time period but as a whole, the work does not depend very much on other workers; collaboration related questions are not demanding but the timetable is if surprising faults appear or something lasts longer than expected. I&C systems must be returned to the original state after maintenance work. Fault diagnosing can be demanding; new I&C systems can be challenging to fix as there is not much experience on that. Automation maintenance is aimed to be done individually so that the two persons who start the work also finishes it (work is performed as pairs).

Error possibilities with automation maintenance as a whole

- planning material is available rather late for maintenance planning purposes
- after planning, there is a gap in summer before outage starts so it is not known whether something more challenging occurs before outage (which affects outage)
- during outage, calibration work is a great part of work at the site and there, no mistakes are allowed; is not complex work but requires concentration
- errors in automation are sometimes unique and cannot be anticipated which makes error fixing more challenging
- spare parts may not exist to older I&C
  - if the old safety system gets broken, spare parts can be hard to find
  - if no spare part can be found, it is ordered or the device is replaced, this requires planning

General factors affecting error appearance

- in automation maintenance, concentration is important, but outage is the kind of context, which does not support concentration, with all the people around, people peeping above your shoulder what you do etc.
  - magnetic strings are procured to close the gaps between cabinets, this prevents outsiders from disturbing work, the string is respected, and nobody crosses it
- the dedicated time slots to do the work are demanding, especially due to dependencies of work between different parties; difficulties arise if something unexpected appears or something takes longer or shorter than expected
  - sometimes there is not enough time and then more time is used to get work done in good quality
  - not pressure on workers, people can do their work in peace (earlier it was the other way round)
  - collaboration is not highly needed, collaboration related matters are not an issue

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- there can be disturbance during outage by other workers, not aware of all restrictions related to automation maintenance

7.5 HRA

Work with PRA also includes HRA. In HRA, the plant model, which is used for risk estimates, is divided into several constant or standard states and the risk is estimated for each state. Normal operation is represented by one model and outage is divided into several models. Each model takes into account what the state of the plant is and how long time delays are; the reliability of machinery changes from one state to another, and the same applies to the probability of human error.

How outage is handled in HRA

- a lot of work is done in outage, causing initiating events
- there are long time windows for human actions but smaller probability of human errors, because there is more time to react
- special features in outage are identified and the most significant events are taken into account
- briefly, different matters are focused on, but the basic methodology is the same as in full power; some alarms are disconnected, and longer time window is the most significant feature in outage related HRA

The most critical events regarding human error in outage

- heavy load drops
- boron dilution transient
- valve leakage in primary circuit (due to valve maintenance operations; accidentally a valve in the used redundance is opened

Comments to literature-originating error potentials

- task interdependencies sound familiar – everybody's work depends on other's work, starting from the effect of planning to operation
    - we have a rough model in HRA, work is not divided into small details; the most significant matters are taken into account in a more detailed manner
- situations in which many tasks are performed simultaneously does not sound familiar, tasks are performed one after another; perhaps this means that if something is being fixed, many separate tasks are done
- situations in which task is transferred to another group; modeling is not so detailed but sound like something, which affects (for example, one makes a mistake, shift changes, and then, error is noticed)

Development or research needs

- dynamic phenomena are important to study
- HRA methods are well applicable to outage but they do not take into account error with long time windows
    - if it is a question of several hours in outage, present methods are valid but if it is a question of days, weeks or months, present methods are not valid
    - Swain's ASEP-HRA is used, and other methods have affected too, the method is further developed
        - different plants may use slightly different methods, but the main features are the same; for instance, PSFs can be similar but with different values

8. Discussion

The safety-critical nature of outage is well recognized, and there is a wealth of literature on the specifics of outage and the challenges associated with the successful completion of work. Typical outage features presented in different literature sources are:

- Continuously changing plant conditions and configurations.
- High requirements concerning both safety and productivity.
- Huge number of workers, both inside and outside the plant as well as greater amount and variety of work activities.
- Tight schedule and increased demand on concentration and vigilance, but longer working hours.
- Insufficient procedural guidance and less training, but longer time windows.
- During annual maintenance, some safety systems must be deactivated.

Outage is an annual event in all NPPs. It is hectic and even if the plants have a lot of experience to conduct outages, it is still a period in which flexibility and constant communication is needed, making human prone to make an error. Outage represents a unique time frame, compared with the one of normal operations. This means that human errors are to be considered differently when focusing on outage related errors.

Some general features have been found, eliciting human errors in outage. Zhang et al. (2017) have identified handoffs as challenging, because they involve highly uncertain activities. The second problem they have found is about responding to many contingencies emerging in field discoveries in an outage; the responding must be done quickly and efficiently so that workflows can recover from interruptions and incidents. About 15% of tasks in outages are “discovered” in the field, because many problems can be covert due to the uncertainties regarding field conditions and resource availability. Accordingly, fluent proceeding of outage requires communication; miscommunication between workers in crowded job sites can cause unnecessary waiting or unexpected sharing of spaces and resources, which reduces productivity (Tang et al., 2016) and makes workers more error prone.

Most HRA methods have been developed for full power conditions in which the operator’s actions are usually laid down in procedures and frequently well trained, in time frames which are typically less than 60 minutes. The key issues that should be taken into account in the HRA are errors of commission (EOCs), dependencies between human actions and the dynamism of the operating environment. LPSD activities are often characterized as being long-duration, ex-control-room, and less proceduralised.

HRA has its own ways to deal with outage, depending on the solution assumed by the NPP in question. They are, however, static by nature. Dynamism has been suggested and cognitive modelling appears as a promising way to get forward. Such modelling is not straightforward, though, as cognitive processes depend on the human and the context in which the human is, making such models both detailed and cumbersome. Dynamic HRA seems to be a somewhat elusive concept; it is still somewhat unclear how to build a dynamic model, what the result would be from HRA perspective and how it should be used. Being a dynamic model, will the result from the HRA perspective be of the kind, which is easy to modify to a slightly different situation, for instance? Or should the result provide some maximum and minimum error estimates, depending a variable, which can be represented by

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different values, depending on the situation? This and other similar questions are still unanswered.

Regarding outage related interviews, there seems to be several general-level challenges or features (see Figure 1). Outage related work seems to have timetable pressure and the timetable may become irrelevant if flaws in machinery appear; if the flaws are hard to fix, the fixing takes time and the timetable for that task and the possibly related tasks to be done by other work groups must be updated.

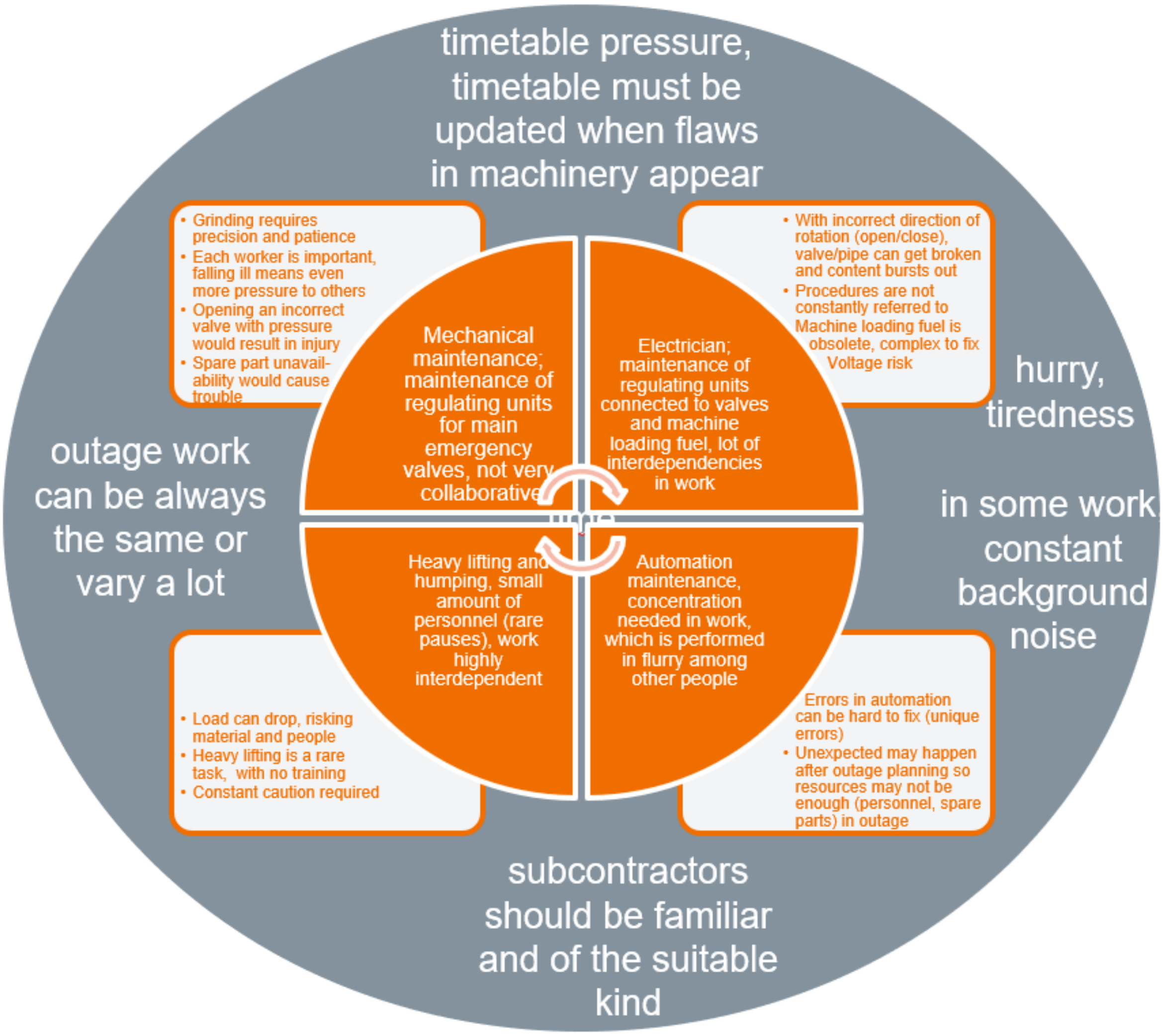

Figure 1 Outage related work qualities as revealed by interviews. Text on orange background shows some basic features in the role of outline workers, four roles as a whole; text with outline provides more details to the role in question. Text on the grey background describes general outage related features.

Workers are in a hurry. The atmosphere has been more hectic earlier and now it is better understood that it is not always possible nor efficient to perform according to the predefined timetable if an unexpected flaw or other obstacle appears. However, there is still haste and workers are more tired than usually. In some cases, depending on where the work takes place, there can be constant noise in the background, making the work environment more stressing.

From a more neutral or positive side, the role of subcontractors is important and well identified. Interviewees tended to emphasise how important it is that subcontractors are familiar with the plant and outage related work, and that they should fit well with the rest of

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the workers in the same group. This is usually the case as the same workers tend to participate in outage repeatedly.

Finally, work tasks vary considerably based on the worker's role. In some cases, outage work is always the same, repeating similarly year after year, and in others, each outage is unique. The latter situation includes higher possibility to increased workload and errors.

9. Conclusions

In the context of the Finnish nuclear safety research programme SAFIR2022, in the NAPRA project task T3.2, the goal is to utilize the concepts and methods of dynamic HRA in hybrid control rooms. Activities during the planned outage have been identified as an exceptionally fertile application domain for dynamic HRA due to its special features. During the year 2021, a literature study was carried out to link the research to international and scientific background, and Finnish experts were interviewed about the activities, which take place at Finnish plants during planned shutdown, what their characteristics and dynamic features are, which activities are considered to be most critical from the safety point of view, and what human errors might occur in those activities.

Outage represents a deviating time frame in the life cycle of an NPP. It has features, which support error handling and removing error effects in case it would happen; and on the other hand, it also has a unique setup for making an error. In this report, outage is contemplated from many perspectives, including the outage specific features from the work perspective and the way HRA has approached outage.

One practical objective of this report was to identify a scenario to focus on in further work, with the aim to provide ideas and example of how to make a dynamic model of some outage related work. Literature review does not answer this question but provides general-level knowledge about outage. The choice of scenario is made based on interviews. In HRA, heavy loads are identified as critical and in interviews, work with heavy loads proved to be also mentally and physically loaded. The work with heavy loads also includes features identified safety critical in scientific literature – the area in which heavy loads are lifted is the one in which also other workers move. Moreover, heavy lifting is the kind of work in which task interdependencies seem to culminate – it is needed in many tasks and requires constant communication with many parties.

This scenario will be studied in more detail in 2022. Work analysis will be performed with special emphasis on applying a combination of methods to elicit the key dynamic features from the HRA perspective. This line of research continues in the next SAFER research program, with dynamic HRA modelling and analysis of example cases, comparisons between dynamic and more conventional HRA approaches, and empirical work. The goal is to help in identifying and concretizing the benefits and drawbacks of dynamic HRA, finding meaningful roles for it in the broader spectrum of HRA approaches, and envisioning how to incorporate dynamic features in the usually used, more conventional HRA.

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