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Addressing work design in future operations of advanced nuclear reactors

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Abstract. In this early stage research paper, we outline our approach for a three-year study that aims at examining the potential influence of work design on control room operators' performance in the context of advanced nuclear reactor operations. The study is inspired by ongoing developments in the nuclear industry towards small modular reactors (SMRs) that are expected to partly transform the work of control room operators. The research intends to answer three key questions concerning anticipated work characteristics in SMRs, their differences compared to conventional plants, and how these characteristics can affect control room operators' performance. The proposed approach, along with the study's strengths and potential challenges, are outlined.

Introduction

Current developments in the nuclear industry are increasingly focusing on small modular reactors (SMRs). These innovative designs offer the potential for safer and more efficient energy production and are expected to be operated in a substantially different manner compared to current nuclear power plants. Some of the main differences from operations of conventional plants are the prospect of multi-unit operation, increased use of automation, and reduced staffing (O'Hara et al., 2012). The work of control room operators is therefore expected to change, referring to their tasks, their responsibilities, and relationships. Decades of research has solidified the importance of how work is designed for human motivation and performance (Parker et al., 2017). It is therefore paramount to pay attention to the implications for work design implicit in concepts of operations of SMRs to ensure that operators' work is designed in a way that matches their capabilities and needs (Parker & Grote, 2020).

Earlier research has shown how new design features and concepts of operation can be associated with human performance issues more generally (Hallbert et al., 1997; O'Hara et al., 2012). However, different SMR designs may be associated with different concepts of operation, and thus have different implications for control room operators' work. Although some aspects are likely to apply across concepts of operation in advanced reactors, e.g. digital control rooms and high levels of automation, other aspects may not, e.g. multi-unit and/or remote operation. It is therefore important to assess the potential influences on operator performance that are implied in **distinct** concepts of operation.

In the OECD NEA Halden HTO project (https://www.oecd-nea.org/jcms/pl_61937/halden-human-technology-organisation-hto-project), we are initiating a three-year study with the aim to develop

conceptual model(s) of how design of control room operators' work in SMRs can influence their performance. Three main research questions will be addressed: 1) How are work characteristics anticipated to be in concepts of operation in SMRs? 2) In what ways do these characteristics differ from those in conventional plants? 3) How can these work characteristics influence control room operators' performance? In the following we outline our proposed approach in this study and its strengths and challenges that we currently see a need to address.

Study approach

Advanced reactor designs are currently in their development with the first designs planned to be operational by end of 2026 (e.g. Changjiang ACP100 reactor). For most SMR designs, several operational aspects are still under development. Therefore, our study will likely need to make assumptions regarding aspects of work design within single concepts of operation and draw on existing theory and empirical research in developing conceptual models of their potential influence on operator performance. Thus, we need a solid theoretical framework for characterizing and comparing work designs for control room operators and specify their potential impact on performance in conceptual model(s), and a pragmatic strategy for collecting data that can inform the development of these conceptual model(s). The development of conceptual model(s) is important for defining relationships between work design in SMRs and control room operator performance that can be empirically tested and thus inform assessments of safety in advanced reactor operations.

Theoretical framework

Among work design perspectives, the job demands-resources model (JD-R) has become one of the dominant ones since its introduction by Demerouti et al. (2001). This model considers job demands (e.g. role ambiguity, workload) to cause strain, while job resources (e.g. autonomy, social support) can alleviate these demands and at the same time stimulate work engagement.

JD-R is flexible and enables prediction of operator performance by characterizing work in terms of either job demands or job resources in different work environments. This means that the model itself does not prescribe characteristics, but rather that it can be tailored by focusing on job demands and resources that are relevant to the specific work environment or occupation (Bakker et al., 2014). While other work design models can offer relevant insights as well, they may be less suitable for assessing differing concepts of operations in a unified manner. For example, a focus on design of teamwork may be appropriate for many concepts in which monitoring and control of the nuclear processes are performed by control room crews, while it may be less appropriate for concepts that are exploring single person monitoring and control. Furthermore, other well-known work design models such as the Job Characteristics model (Hackman & Oldham, 1976) pre-define characteristics that may be less relevant for control room operators' work. For example, job autonomy can be assumed to be experienced as relatively low given that control room operators' work is highly prescribed by both schedules and procedures. A key advantage with JD-R that we consider is thus that we can both characterize control room operators' work in terms of the job demands and resources that are most applicable to their work generally, as well as specify characteristics that are "unique" for different concepts of operations, all within the same overarching framework. The dual path perspective of JD-R is assumed to support our efforts in examining different combinations of work characteristics as implied in the concepts of operations and their potential impact on performance. Another advantage of using the JD-R which we consider is that it enables us to build on and extend research on control room operators' performance in general, and in nuclear in particular, that have

provided important insights on cognitive job demands referring to processes of strain (Wickens, 2014; Young et al., 2015). Furthermore, JD-R has been explicitly linked to safety outcomes which is of critical importance to nuclear power operations (Homann et al., 2022; Nahrgang et al., 2011).

Data collection to inform conceptual model(s)

Since there are few advanced reactor designs that (will) have defined their concepts of operations within the study period, we will primarily employ qualitative methods to collect and analyze data.

First, we will review information available to the public and to members of the Halden HTO project regarding SMR designs and their concepts of operation with the purpose of identifying different concepts of operation and reference reactor designs to pursue further. We recognize that this classification of concepts of operations may be iterative as we learn more about them or are unable to obtain their information. Second, we plan to collect data on concepts of operations through reviewing documentation available to the public or the Halden HTO project, and through individual interviews with relevant roles with vendors of the reference reactor designs. We will draw on a six-dimensional concept of operations model (O'Hara et al., 2012) that was developed for and is utilized by the US Nuclear Regulatory Commission to structure the data collection. Furthermore, we will collect information on concept of operations and conduct a function allocation analysis of control room operators' current work in a conventional plant that will serve as a baseline to compare against for assessing changes in control room operators' work design.

The data collection on concepts of operations for SMR designs and conventional plants have a dual purpose: First, it is the primary data for developing conceptual model(s) of the potential impact of work design on operator performance in SMRs. Second, it enables us to compare control room operators' work across different concepts of operation in SMRs and with conventional operations, as well as assess their similarities with control room operators' work in other industries. The latter is geared towards assessing the relevance of pursuing empirical data collection on control room operators' experiences of (aspects of) work in other industries such as the petroleum industry. This may be particularly valuable for gaining insights into the impact of design aspects that are new to the nuclear industry, for example the prospect of remote process monitoring and control.

Preliminary results on a multi-unit SMR concept

We conducted a comparative analysis between a multi-unit SMR concept of operations and conventional operations (i.e. large, single unit) based on their documentation together with two nuclear process experts. As the full analysis is reported in Reegård et al. (in press), we only provide a brief summary of results here. We find that the two concepts of operations share a common mission and management of maintenance and modifications. However, we identified three main changes to operators' work in the multi-unit concept for normal and off-normal conditions: Increased number of reactor units to monitor and control in which responsibility for units will be divided between the operators, reduced staffing in the control room with three operators being responsible for up to 12 units, and increased automation and information availability in which automation will perform several tasks that the operators perform manually in conventional operations. With these changes, the multi-unit concept is found to indicate potential increases in cognitive demands, higher potential for role conflict and work over-/underload, increased access to information and tools, reduced skill and task variety, and reduced social support. As such, operators' work may change with increases in both

challenging and hindering job demands, as well as increases in support from automation and human-system interfaces, and reductions in job resources of social support and skill variety.

Beyond developing conceptual model(s)

The conceptual model(s) in which we specify work characteristics for control room operators in discrete concepts of operations in advanced reactors and their relationships with performance should be tested to determine their ability in predicting operators' performance. We aim to investigate these characteristics in realistic simulation environments that the research team has access to in the Halden HTO laboratories. These facilities can be used to conduct experiments that examine the influence of specific aspects of work design on operators' short-term performance. However, a main limitation of such an approach is that we will not be able to test the influence of work design on operators' performance in medium-to-long time frames which is a quality that the JD-R model outlines through the dual processes of strain and motivation. This would require a longitudinal study performed with control room operators in real operations. Longitudinal studies set in other industries may provide useful insights depending on the similarity with work design and concepts of operations in advanced reactors.

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