SUPPORTING RESILIENCE IN NUCLEAR POWER PLANT OPERATIONS – CONCEPTUAL FRAMES FOR HUMAN FACTORS DEVELOPMENT AND VALIDATION

Wahlström M, Kuula T and Laarni J
VTT Technical Research Centre of Finland Ltd
Vuorimiehentie 5, FI-02150, Espoo, Finland
mikael.wahlstrom@vtt.fi

ABSTRACT

This is a summary paper of conceptual developments on nuclear power plant operation by the human factors team at VTT Technical Research Centre of Finland. While drawing together years of studies, the paper also discusses recent progresses in training development. Firstly, there is a long background in work analysis and system validation. The analysis model applied provides a model for assessing and identifying "core-task functions," that is, basic functions that should be fulfilled within work activity. Secondly, we have evaluated the existing training practices at a Finnish plant and identified challenges that could be generally prevalent in the nuclear domain – they seem to reflect the hierarchical and safety-critical nature of NPP operation. In terms of potential solutions, we are currently testing and developing some new self-evaluation and self-confrontation methods. First and foremost, however, we discuss the common theory basis for our research approaches. On the broadest level, our development and research work reflects the view of safety as expressed by resilience engineering literature: safety is not seen merely as "negative" lack of mistakes, but also as "positive" capability to solve and anticipate problems. For example, it is assumed that operators' capability for situational interpretation should be supported at all times: even if the emergency procedures dictate operator activity specifically, the operators should understand the influence of the operating procedures for the plant process and system state.

Key Words: human factors, validation and verification, training, safety theory

1 INTRODUCTION

Nuclear power plant operations evolve and change throughout the plant lifecycle: upgrades can be made to the control room systems and safety procedures develop as changes are made to the regulations. It should be ensured, however, that these changes support safety in terms usage. In particular, the changes should support operators' capability to maintain situation awareness and capability to solve and anticipate problems. Two issues are crucial here: Firstly, it should be ensured that the design of the control system upgrades supports operators' work performance; issues such as good user experience, support for team work practices and lack of errors and inconsistencies in the user interface are to be addressed. Secondly, good training practices essential: new learning is continuously needed due to the new system upgrades and procedures. The human factors team at VTT Technical Research Centre of Finland may provide services in terms of both of these aspects – human factors system validation and training development – thus being able to serve as a comprehensive human factors partner in supporting NPP development. Assumedly, this large portfolio allows that we may flexibly meet the needs of various complex NPP development projects.

This paper provides a short summary of theory and methods for human factors research for supporting NPP operations development, as applied at VTT. We will firstly cover some essential theoretical thinking and then discuss the research and development services. Finally, we will consider future research and development avenues; the implications of VR technology are considered in particular.

2 THEORETICAL CONCEPTS: RESILIENCE, INTERPRETATIVE PRACTICE, CORE-TASK ANALYSIS AND SYSTEMS USABILITY

The theory basis applied by us consists of concepts and analytical frameworks called "systems resilience," "interpretative practice," "core-task analysis" and "systems usability." The concepts are highly interrelated, that is, one is understandable in view of another within the overall theoretical thinking.

Firstly, resilience engineering emphasizes the positive impact of human activity as a part of a larger system in maintaining safety. A definition for system resilience, as offered by Hollnagel [1] goes as follows: "the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions." Resilience engineering, as a novel manner of considering safety, can also be explained with the terms of the Safety-I and Safety-II concepts [2]. Safety-I considers safety mainly in terms of identifiable failures or malfunctions, the human error is considered especially. In contrast, in Safety-II thinking the human element is viewed as a source of safety, that is, the professionals working in safety-critical domains are seen as providers of safety: they are able to perform adjustments as needed in response to the variable demands and conditions. Safety-II therefore steers the focus from mistakes to ability to cope in challenging situations. Resilience is needed in the NPP domain because one may argue that pre-preparation for everything is not possible: fault combinations can be immeasurable. The Fukushima Daiichi nuclear disaster also implies that preparedness for unlikely disasters can be insufficient in the nuclear domain [3].

A relevant question, however, following the concept of resilience, is what kind of operator activity then produces system resilience. Empirical studies by our human factors team [4] indicate that even in actualizing emergency procedures that strongly dictate operator activity, there are considerable differences in operators' work practices. Some work shifts were observed to employ additional work practices, with elements not directly dictated by the guidelines but that presumably contribute to the system's resilience. Activities of this kind included operators' interpretation of the situation; the following features were identified: questioning of the observed phenomena, dialogue within the team, anticipation of system state, and use of various information sources. Savioja et al. have identified differences in crews' activities in the use of safety procedures, and utilized three categories of practices in dissecting the differences between crews. The analytical categories (which were originally introduced by Norros [5]) were labelled as 1) interpretative, 2) confirmative, and 3) reactive practice. First, courses of action belonging to the "interpretative practice" category can be exemplified by that some operator shifts gathered diverse and redundant information before process interventions were conducted: different types of information were considered, such as trend values and automation information in addition to alarms and the minimally required plant state information: a strive for profound understanding of the actual present process situation could be identified. Second, confirmative practice can be exemplified by the behavior of double-checking information in a rule-following manner. Third, descriptive of the reactive practice was to utilize alarm information and minimal consultation of procedures and displays as the basis of behavior. On the other hand, it can be seen that the differences in the work practice categories reflect differences in human–environment connection: Some work practices echo the internal reflection of the operators (this was described by the above mentioned interpretive practice). Some, in turn, are seen as predominantly guided by the pre-defined rules (confirmative practice describes practices of this kind) or by the immediate features of the environment (as in reactive practice). Presumably, interpretive practice promotes system resilience.

However, as suggested by Norros [5], not just any kind of course of action entailing workers' active reflection can be seen as "interpretive practice" in safety-critical work: the activities should be suitable in consideration to the demands and tasks of the given work assignment. She suggests that to delineate which activities these are, it is possible to use the theoretical model of human–environment interconnection of the core-task analysis method. The core-task model assumes that safety-critical work activity can be analyzed by dissecting control demands related to 1) dynamism (i.e., temporal demands, such as a need to make decisions efficiently), 2) uncertainty (i.e., unexpectedness of events, or insufficient or imprecise information), and 3) complexity (i.e., multiple, reciprocally connected influencing elements, such as the complex plant dynamics). The model then also assumes three basic features of work activity as resources with which these control demands are addressed, these being 1) skill, 2) collaboration, and 3) knowledge. It is then possible to analyze work activity through exploring of how these control demands and resources connect with each other. The connections found are called core-task functions of the relevant work domain [6]. In sum, the interpretive human–environment connection takes place as the workers use their skills and knowledge (i.e., not only procedures and obvious environmental cues) for collaboratively handling the at times quickly emerging complex and uncertainty-involving demands associated with their work assignments in a way such that is meaningful to a specific situation.

A core-task function can involve mitigating an internal conflict within a work activity: for example, surgeons have to heal the patient (by, say, removing cancer tissue) while at the same time tissue damage is inevitable [7]. In NPP operation a conflict can be found there that during emergency situations the procedures should be followed to the point, yet one may assume that not all situations and fault combinations can be cowered in plant and procedure design – interpretation would indeed be needed in such a challenging situation.

An additional theoretical frame is systems usability model [8]. It provides a fairly comprehensive human factors framework for assessing a certain control system. The frame proposes three functions, which represent three different effects of the control system tool: the instrumental function relates to the effects on the environment (that is, to the plant itself, in particular), the psychological function relates to the effect on self (that is, to the operator), and, finally, the communicative function relates to the effects on the community (that is, especially to the operator crew as a group). These three functions can then be viewed by three different perspectives, these being performance (outcome of the system), way of acting (how the outcome has been achieved) and user-experience (subjective experience within actualizing an outcome). It is important to differentiate between performance and way of acting because good operators may be successful with bad tools (i.e., focusing on performance only would not reveal the insufficiencies in tool design). Additionally, the "way of acting" -perspective resonates with the concept of "interpretive practice:" it is important to consider the work practices that support system resilience even though some of the work practices (such as considering redundant information sources) would not be absolutely essential for task accomplishment. Overall, nine categories of systems usability indicators can be differentiated when the abovementioned three functions are considered by three different perspectives.

It is notable that the nine systems usability indicators of the systems usability model are anchored to the core-task functions within certain work activity. For example, appropriate "task completeness," relevance of "time spent" or "meaningfulness of established practices" depends on the task at hand.

Overall, one can see the interrelatedness of the theoretical concepts applied by us for human factors development and research on NPP operations: operators' interpretativeness provides system resilience, yet whether the operators could be considered "interpretative" depends on whether or not they address the relevant core-task functions; similarly, the actual content of systems usability model elements depend on the core-task functions.

3 MAIN APPLICATION AREAS

In the following we will discuss the two main application areas linked to the theoretical frames proposed above. However, many kinds of problem solving and research cases have been addressed, that is, these two – systems validation and training development – merely provide very prominent examples.

3.1 Systems validation

Bigger system developments in NPP operations should be validated in terms of usage and safety prior taking into use. Laarni et al. [9] discuss that in NPP control system development projects, which stretch over several years and are realized in multiple phases, the human factors engineering verifications and validations should be conducted in stepwise manner. Therefore a sub-system validation (SSV) approach was generated by Laarni and colleagues. It involves that a certain sub-system of the control room (e.g., specific system for emergency handling) is the main focus of the specific validation research session. However, even during validating specific system, the overall operational concept (that is, the generic model on the way in which the plant is operated) can be considered.

In practice, the methods for identifying issues and problems within the control system under evaluation include observations of simulator sessions, immediate interviews after these test sessions, informal heuristic evaluations by the operators and researchers as well as questionnaires and generic post-session interviews. The systems should be tested with different scenarios – that is, in regular use and during emergencies.

In analyzing the data, the found problems in terms of usage (which can major or minor) are not only coupled with the requirement criteria – for assessing whether the design criteria are met – but also with the abovementioned systems usability criteria. This allows for a more profound interpretation of the data in making of a human factors safety case: not only do we see whether formal criteria are met but also in view of the theoretical elements defining a good system. Furthermore, the formal criteria are simultaneously categorized by the elements of the systems usability model – if certain aspects of the systems usability model are not being addressed by the design criteria, one may justifiably question the comprehensiveness of those criteria.

The recent developments in validation and verification are more profoundly discussed by Koskinen et al. in their paper "Systems usability case in stepwise control room validation" featured in the present conference.

3.2 Developing training

Based on studying NPP operators and trainers of a specific plant, Wahlström and Kuula [10] have identified four broad and interrelated learning-related development goals, which might be relevant in the NPP domain even on a generic level. Firstly there seems to be need for more collaborative learning – as suggested by the literature [11] dialogue between peers would enhance exchange of good practices and new ideas. Secondly, more operator-driven setting of learning goals seems necessary – this is in line with the common thought within the learning literature according to which learners should be considered active and critical subjects rather than mere objects [12]. Thirdly, development of problem-solving ability seems necessary – this reflects the above discussed resilience engineering literature and the interpretative practice concept [5]: safety is not merely the "negative" lack of mistakes, but also "positive" capability to solve and anticipate problems [2]. The final fourth issue which could be further promoted is "inventing new." This relates to the notion that the continuous development of work practices is necessary in the NPP domain, given the development in technology and safety requirements. This also associates with the "expansive learning" [13] concept within learning literature, according to which learning involves creative generation of new ideas rather than mere "input" of existing thinking.

In summary, we propose that NPP training could benefit from development of problem solving capabilities, creation and exchange of good work practices and operator-based establishment of learning goals. We assume that these issues could be promoted by developing self-evaluation and self-reflection. These, in turn, could be enhanced with two basic method approaches for developing vocational learning, which have been studied by VTT in collaboration with the Finnish Institute of Occupation Health. Firstly, double-stimulation, which has been applied especially in the Finnish Change Laboratory tradition [14], is a technique for enhancing problem solving, concept formation and promoting worker agency: it typically involves considering certain problem area with new kind of presentation (or "stimulus"). Secondly, self-confrontation is a French developmental intervention method [15, 16], which involves assessment of one's own work practices together with others with the help of some kind presentation of one's own activity (e.g. a video). In simple self-confrontation the professional (e.g., a NPP operator) reviews sequences of their activities together with the researcher. In crossed self-confrontation, in turn, two or more professionals review their activities collaboratively. We assume that both of these techniques (double-stimuli and self-confrontation) afford discussion needed for developing operators' training as outlined above: ideally the operators could utilize material of their own work as well as some kind of presentation related to good work practices and good operator work (the second stimuli) for learning purposes – they could then consider whether their own behaviors reflect features of good work activity. Specifically, we are currently developing a method for post-simulator training session self-reflection; we hope to influence and promote the self-reflection that takes place in the dialogue between and within the operator crews as well as in operators' internal reflection. Additional NPP training development endeavors of VTT include enhancing operators' stress-management, organizational disaster management, and learning from successful situations and work practices; these take place in a large collaboration research consortium with the Finnish Institute of Occupation Health.

3.3 Future study avenues

Novel technological arrangements imply future study avenues for system validation and NPP training. Most evidently these include new plant types in the nuclear domain: for example, construction of a new digitally operated plant is being finalized in Finland. Related domains are of interest as well – VTT is taking part in fusion power plant development.

Furthermore, a prominent practical tool for training development seems to be virtual reality (VR) spaces. The problem with the physical simulator room is its cumbersomeness: that it can only be applied in a specific place and within a suitable schedule. In view of our observations of a single plant site, the formal training requirements and relatively fixed curriculums in practice dictate the use of the simulator room [10]. VR based simulator spaces could provide flexibility for the operators to engage into studying and exploring the plant dynamics by their own terms, as needed. The VR also allows replaying the simulator session from the operator "point-of-view." Reflecting the discussion above on self-confrontation methods, these replays could then be observed and discussed collegially for learning purposes.

Additional interesting development, which was communicated to us by an energy company representative and perhaps taking place in the future, concerns the application of virtual avatars (that is, digital representations of individuals) side-by-side with real operators. The operators could see the avatar operator with augmented reality glasses and the remote operator (represented by an avatar for the others) could view the actual operators in a VR mock-up of the control room (or via camera-feed, which, however, would require a movable camera in the control room). The avatar operator, perhaps a specialist needed to resolve a particular challenge, could then provide guidance remotely for the actual operators. In principle, even operation activities could be done remotely in VR, but this would require that the VR-based remote operation system would pass rigorous safety verifications and validations.

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