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WORK DOMAIN ANALYSIS AND OPERATIONAL CONCEPTS FOR ADVANCED NUCLEAR POWER PLANTS

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Abstract

The nuclear industry is currently designing and building a new generation of reactors that will include different structural, functional, and environmental aspects, all of which are likely to have a significant impact on the way these plants are operated. In order to meet economic and safety objectives, these new reactors will all use advanced technologies to some extent, including new materials and advanced digital instrumentation and control systems. New technologies will affect not only operational strategies, but will also require a new approach to how functions are allocated to humans or machines to ensure optimal performance. Uncertainty about the effect of large scale changes in plant design will remain until sound technical bases are developed for new operational concepts and strategies. Up-to-date models and guidance are required for the development of operational concepts for complex socio-technical systems. This paper describes how the classical Work Domain Analysis method was adapted to develop operational concept frameworks for new plants. This adaptation of the method is better able to deal with the uncertainty and incomplete information typical of first-of-a-kind designs. Practical examples are provided of the systematic application of the method in the operational analysis of sodium-cooled reactors. Insights from this application and its utility are reviewed and arguments for the formal adoption of Work Domain Analysis as a value-added part of the Systems Engineering process are presented.

Key Words: Advanced Reactor Technologies, Cognitive Work Analysis, Work Domain Analysis, Human Performance Requirements, Systems Engineering, Sodium Fast Reactors

1 INTRODUCTION

Advanced nuclear reactors currently being designed are all expected to be simpler, safer, and more economical. These plants will be characterized by unique structural and functional designs, unconventional processes, materials, structures, or operations. This includes, for example, modular structures, coolants other than water (molten salt, helium, carbon dioxide, or liquid metal eutectics like sodium/potassium or lead/bismuth), and also the ability to use excess heat for industrial applications such as hydrogen generation and seawater desalination. One of the most important operational changes will be automation; new instrumentation and control (I&C) technologies now make it possible to automate systems in ways not possible with the analog systems of older nuclear power plants. These new digital technologies will require many changes to how operators manage and interact with the plant. Developing detailed descriptions of how these plants will be operated and by whom will become one of the more challenging aspects of the introduction of these advanced nuclear power plants (AdvNPPs), not only into the U.S. nuclear fleet, but in the rest of the world.

Much of this difficulty is due to the lack of operating experience and valid technical bases for the operation of new systems. New automation philosophies must be informed not only by the technical capabilities, but also by the tasks that operators are required to perform, as well as their abilities and limitations in performing those tasks under various operational conditions. Human factors engineering and systems engineering methods currently practiced in the nuclear industry do not offer specific analytic tools for deciding how to design the operation of a new plant, including the application of new types of automation. A systematic process is needed to address this gap and produce reliable information for the design of robust and resilient systems that allow dynamic collaboration between operators and plant systems.

In response to these challenges, a methodology was developed at Idaho National Laboratory (INL) for the definition of operational concepts for new plants. The methodology, which includes the analysis of the expected roles of human and system agents, and the systems involved in a variety of operational conditions, is described in more detail below.

1 A METHODOLOGICAL FRAMEWORK FOR OPERATIONAL CONCEPT DEVELOPMENT

An Operational Concept for a new plant describes the characteristics of the plant and its systems from the viewpoint of people who will use those systems, while also communicating the quantitative and qualitative characteristics of the system to all stakeholders. An outline for the contents of an Operational Concept Document (OCD) might be derived from standards and guidelines like ANSI/AIAA G-043-2012, IEEE 1362-1998, the INCOSE Systems Engineering Handbook, or NUREG-0711 (see references [1], [8], [9], and [16]). However, none of these sources provides any guidance on methods to analyze available information and develop an OCD for first-of-a-kind (FOAK) systems.

As part of its contribution to the U.S. Department of Energy's (DOE) Advanced Reactor Technologies program, new operational concepts are being developed at INL for future Sodium Fast Reactors (SFRs), Advanced Fast Reactors (AFRs), liquid-metal reactors (LMRs) and High-Temperature Gas-cooled Reactors (HTGRs), their systems and their users (Hugo et al. 2013 [5], 2014a [6], 2014b [7]). This is done by conducting an in-depth analysis of their structural, functional, and operational characteristics. Insights are also developed of how the role and function of humans in the plant might be affected by advanced technologies and, conversely, how the operation of new plants might be influenced by the need to accommodate human abilities and limitations in the design.

Obtaining good results from early engineering design phases requires a structured approach to the analysis and application of a large amount of information. It is also critical for integration of human factors considerations into the systems engineering process throughout the project lifecycle. Lessons learned from some recent publications (e.g., Naikar, 2013 [14]; Sanderson et al., 2012 [18]; and Woods & Hollnagel, 2006 [20]) helped the INL analysts to conclude that the only rational approach to incorporating human considerations in the development of FOAK power plants is to follow a formal, structured methodology like cognitive work analysis (CWA). This approach not only satisfies the need for a robust methodological framework for development of operational concepts, but also supports the analysis and description of the environmental and functional constraints that would be placed on human actors by the new design. It is particularly important to make a distinction between design decisions that are mandated by the physics of the process, and those that are subject to analysis and optimization by considering a large number of factors, such as cost, complexity, available technology, regulations, and human abilities and limitations. In fact, there is ample evidence in the literature that adding CWA to the systems engineering process supports industry best practice and contributes to the validity and quality of the overall system.

Sanderson et al. (2012 [18]) emphasize that CWA can be used at all points in the system life cycle, and not just for system design. However, because of the long hiatus in the nuclear industry, there has until now never been an opportunity to apply CWA to modeling of new plants. Recent experience at INL indicates that CWA helps significantly to understanding the structural and functional characteristics of a large socio-technical system. In particular, Work Domain Analysis (WDA), as the first phase of CWA, provides a framework for developing requirements by helping users, operators, owners, designers and analysts to think about why a new system should exist, what its operational and environmental contexts will be, and what functions it should implement. Some requirements may be derived from predecessor systems, where they exist, but CWA really comes into its own when it is used to support the development of FOAK systems that are unconstrained by previous solutions.

The five phases (Work Domain Analysis, Control Task Analysis, Strategies Analysis, Social Organization and Cooperation Analysis, and Worker Competencies Analysis) described in the literature are meant to guide the analyst through the process of answering the question of why the system exists, what activities are conducted within the domain, how the activities are achieved and who performs it (Jenkins et al. [10]). CWA focuses on identifying properties of the work environment and of the workers themselves that determine possible constraints on the ways that humans might interact with systems in the environment, without explicitly identifying specific sequences of actions (Hassall & Sanderson, 2012 [4]; Naikar 2013 [14]). [1]

As part of the DOE's Advanced Reactor Technologies program, the method has been thoroughly evaluated over the past three years and several shortcomings and difficulties were identified for its practical application in the development of operational concepts for new plants. The classical CWA method is by definition a generic method because it is not specific to any work or application domain. It was therefore no surprise to find that the implementation of classical CWA for new and especially FOAK AdvNPP designs presented some methodological difficulties. For example, it was found that some of the classical products of the various CWA phases described by authors like Naikar [14], Rasmussen et al. [17], and Vicente [19] are not always suitable or necessary, especially when the power plant and system designs are still very immature. A specific example is the so-called Abstraction-Decomposition Space (ADS), which is intended to explain the relationships between the functional hierarchy and the system hierarchy of the sociotechnical system. It is also used to explore the problem-solving strategies of workers and how they navigate the various representations of the work domain to identify the origin and cause of an operational condition and to determine the appropriate actions to take. However, when the design is immature there are typically many uncertainties about lower-level systems and their functions and the ADS therefore makes very little contribution to the definition of operational concepts when the system breakdown of the new design is still incomplete or unstable.

In starting to address the challenges of FOAK designs, the five CWA phases had to be adapted to accommodate the many uncertainties that exist early in a project. A slightly modified version was therefore developed as a framework for the analysis of operational concepts. The adapted method places particular emphasis on WDA, but also includes Contextual Activities Analysis and Strategies Analysis, as will be described later. These are the most useful phases of CWA when plant design information is still immature.

Because operational concepts need to be developed for a new plant during the very early phases of design, it was found more beneficial to focus on the mission of the plant, its primary functions and the main systems required for those functions. This approach does not eliminate the ADS, but postpones its analysis until the plant design has sufficiently matured to enable the identification and analysis of lower-level systems and their functions. The result is a stronger emphasis on the functional aspects of the Abstraction Hierarchy, which is a representation of the hierarchical structure of missions, goals, values, primary and secondary functions, and the key systems and processes required to achieve the operational mission.

Because of the emphasis on high-level functions and the need to establish a framework for further detailed analyses like Function Allocation and Task Analysis, the term "Functional Abstraction

[1] A detailed description of the classical Cognitive Work Analysis method is beyond the scope of this paper and interested readers are referred to the literature sources in the Reference section.

Framework" was adopted as the product of the WDA, instead of "Abstraction Hierarchy". This framework maps missions, purposes, functions and processes to the physical systems that are identified for conceptual operational conditions. Choosing a specific operational condition, such as "normal operations" or "plant startup" helps to bound the initial analysis and avoids the complexity of trying to analyze the whole plant at once. This initial selection of operational conditions is refined progressively as more information becomes available, specifically during the "Contextual Activity Analysis", which includes more detailed definitions of specific plant conditions, such as start-up, shutdown, full-power operations, and so on. Complexity is also avoided by not attempting analysis of any safety-related functions until sufficient functional and structural information is available on systems required for safety.

2 OVERVIEW OF THE MODIFIED CWA FRAMEWORK

The modified CWA framework for operational concepts that is currently being refined at INL consists of three phases: Work Domain Analysis, Contextual Activity Analysis, and Strategies Analysis.

The emergent properties of the system as a whole will be revealed through the remaining two phases of CWA: Social Organization and Cooperation Analysis, and Worker Competencies Analysis. These phases are postponed until the plant design is mature enough to allow more detailed analysis of function allocations, automation requirements, and operator tasks.

The principles and methods of the first three phases required for the development of operational concepts are described briefly below.

2.1 Work Domain Analysis, Means-Ends Relationships, and Constraints

The modified WDA process follows the basic approach described by Vicente [19], but some terminology and definitions were adopted from Jenkins et al., [11], Lintern [12] and Naikar [14], [15].

The main aim of WDA for the development of operational concepts is to model the relationships between missions, goals, functions, processes, systems and constraints in such a way that a clear path is developed from high-level requirements to operational strategies.

The analysis typically starts by studying the overall mission and goals of the enterprise. For nuclear power plants this is usually described in three very clear statements: 1) generate electricity economically, 2) protect workers, the public, and the environment, and 3) protect assets. This is followed by an analysis of the primary and secondary functions required to achieve these goals and how their achievement would be measured in terms of operational or productivity values, such as supply capacity and availability, net generation, thermal performance, coolant inventory, water consumption, etc. Next, the physical processes and effects (for example, produce fission heat, transport coolant, and generate electricity), necessary to support the functions are identified, and finally the systems (reactor, pumps, steam generators, heat exchangers, etc.) that are used to produce those physical effects are identified.

In addition to developing a coherent hierarchy, the identification of means-ends links between the levels in the Functional Abstraction Framework is a very practical way to ensure traceability of the relationships between entities and also to identify important constraints and dependencies.

An example of the application of this framework in the analysis of a generic SFR is shown in Figure 1. The diagram illustrates how the different levels of the WDA can be populated and how the links between the entities in each level provide information about the "why, what, how" dependencies and relationships. For example, the links between "Physical functions and effects" and "Physical components" indicate that often more than one system is required for a process, and that several processes may require the same systems.

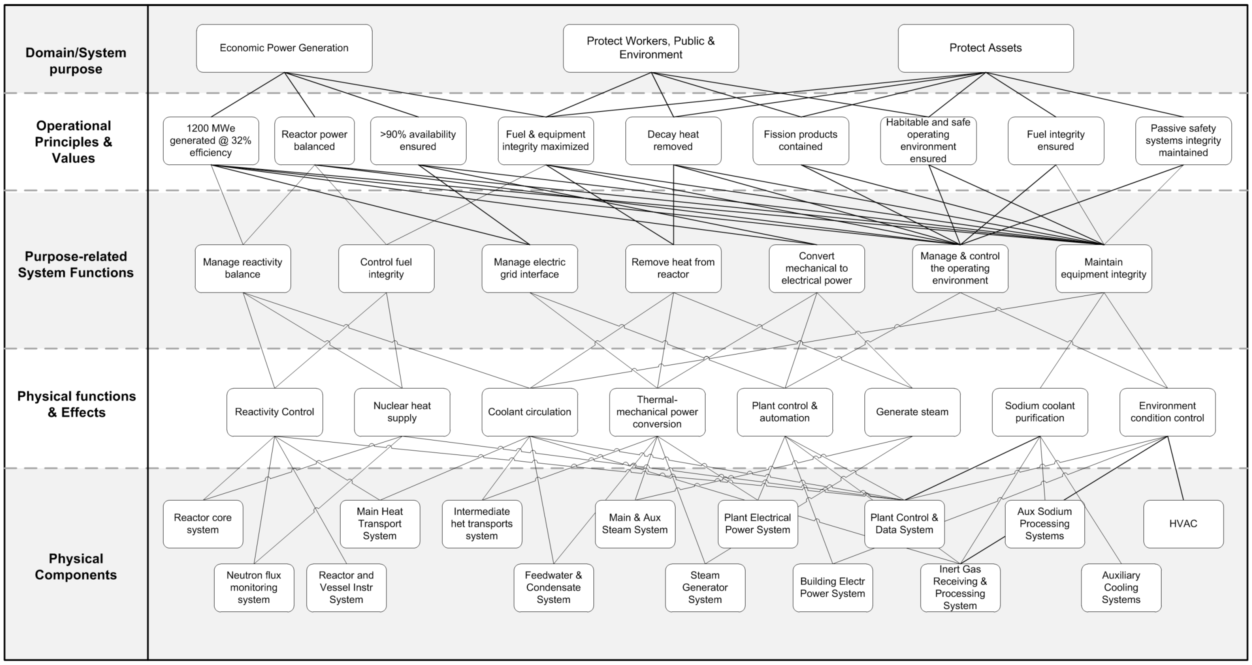

Figure 1: Functional Abstraction Framework for a Generic SFR (simplified)

This analysis also helps all stakeholders to understand the functional and physical context within which workers of the AdvNPP will perform their tasks. For example, the environmental, physical and functional requirements of the plant will impose physical as well as mental constraints on workers. These constraints will determine the functional capabilities and limitations of those objects as well as the physical objects or tools that must be available to the operators to perform their tasks.

In combination, the goals and purposes of the work domain define the fundamental operational space of the sociotechnical system and include the values, priorities, and functions that must be achieved by a work system with a given set of physical resources.

2.2 Contextual Activity Analysis

Contextual Activity Analysis (CAA) analyzes how the physical processes in the plant (e.g., nuclear fission, electrical, thermohydraulic, or pneumatic processes) are managed to achieve various stages of the overall energy production process, such as start-up, power maneuvering, shutdown, fueling, or maintenance. The CAA includes consideration of performance requirements at every stage, as well as high-level control strategies for systems. The results are represented in a Contextual Activity Template (CAT), which depicts the relationship between operational conditions and the functions identified in the WDA, and particularly which functions are typically performed in specific operational conditions. For example, electricity generation functions are performed when the reactor is critical and in the Normal Power Operation mode, but not in Shutdown mode.

Most industrial processes are influenced by situation and resource, and therefore the value of the analysis will also be influenced by the extent to which the sociotechnical system succeeds in mobilizing the available resources under the conditions imposed by these constraints. The focus in the CAA is therefore on identifying constraints and their effect on the relationship between anticipated plant operations and the anticipated role of humans. Constraints could be any one or a combination of technical, environmental, economical, psychological, organizational, political, or regulatory conditions. These constraints form part of the basis for the Functional Requirements Analysis part of Systems Engineering, as well as the further allocation of functions to humans or systems, the analysis of tasks, determination of skills, rules and knowledge involved in those tasks, the definition of operating principles and requirements, and ultimately the design of human-system interaction tools to enable operators to perform the identified tasks effectively, efficiently and safely.

The example below illustrates a CAT that results from the mapping of functions to operational conditions. Each intersection between function and operational condition identifies a potential constraint or requirement that must be considered in the design. For example, some functions may be mandatory in certain conditions, while others may be either optional or prohibited:

SFR Operational Concepts

Contextual Activities: Upset Events (End State conditions)

Situations / Functions	Reactor Scram with normal Decay Heat Removal	Trip and Coastdown of one Primary Pump	Sodium leakage from intermediate piping	Decrease of intermed. coolant flow	Increase of primary coolant flow	Decrease of feedwater flow	Loss of offsite power	Spurious control rod insertion	Spurious control rod withdrawal	Seismic Event OBE
Control Reactor Startup and/or Shutdown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Remove Decay Heat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Transport Heat from Primary to Secondary Sodium Systems	✓	✓	?	?	?	?	⃠	?	?	⃠
Cool Plant Equipment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Convert Mechanical Energy to Electricity	⃠	⃠	⃠	⃠	?	?	⃠	⃠	⃠	⃠
Generate Steam	⃠	⃠	⃠	?	?	?	⃠	⃠	⃠	⃠
Provide Personnel Comfort and Safety	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Symbol Explanation:

✓ The function can and typically does occur in this condition

? The function could occur in this condition, but typically does not

⃠ The function is not possible, not necessary, or prohibited in this condition

Figure 2: Example of a Contextual Activity Template

The results from the WDA and CAA are interdependent and are used in the next phase, Strategies Analysis (also called course-of-action analysis), to develop a preliminary operational strategy for the plant. Initially the emphasis would be on activities for normal operations that would affect the design of the Main Control Room. As more information is obtained from functions required for off-normal operations, additional strategies may be developed.

2.2.1 Strategies Analysis

Strategies Analysis (StrAn) is the third phase of CWA and its main emphasis is on developing an understanding of the different ways of accomplishing the contextual activities identified in the WDA and CAA stages. These different ways are generally defined as an operational strategy, which is part of the basis for the OCD.

The activities in a nuclear power plant are determined by the goals, mission and functions described earlier. The way these activities are conducted is also influenced in particular by such constraints as standards, policies, regulations, operating procedures, and physical properties, all of which will influence the strategies available to a human or system agent. The development of operational concepts and strategies for specific conditions must therefore also consider the performance limits and ranges of specific constraints and allowable workarounds.

StrAn is conducted on two levels: the macro or high level analysis deals with overall plant operational strategies; the micro or low level analysis deals with how specific human or system agents might perform those functions. The low level analysis is closely tied to function allocation, automation system design, and task analysis, and is therefore delayed until the technical design is more mature and broad operational strategies have been defined and verified.

The higher-level strategic analysis of contextual activities deals with the effect of work actions on the work domain, or of the demands that the work domain places on the ability of the human or system agents to perform the actions. Both the WDA and the CAA show that every process in the plant requires one or more sets of structures, systems and components. The analysis also identifies the need for human decision-making to achieve effective and safe operations. Technical processes as well as human actions are responsible for performing the functions that may need to be controlled individually or jointly by humans and the automation system. Some technical processes may need human manipulation for effective and safe operation.

The StrAn models the alternative pathways from one system state to another. In the case of off-normal operations, these alternatives could include different ways to mitigate the consequences of an adverse condition. The strategies adopted under a particular situation may vary significantly, depending upon the constraints within that situation. For example, either a human or an automated agent could perform an activity, or each may perform different parts of an activity. Also, different agents may perform tasks in different ways, and the same agent (either human or nonhuman) might perform the same task in a variety of different ways, for example, at different locations, at different times, or with different resources. The strategy that the human agent selects will be dependent upon many variables, for example, their experience, training, workload, familiarity with the current situation, available of tools, environmental conditions and accessibility of work areas, familiarity with procedures, and many more. The strategies that the system agent selects would usually be more deterministic and are instantiated in programmed sequences, with specific limits and setpoints and inputs from many sensors in the plant.

Figure 3 illustrates an Information Flow Map from the analysis of an operational strategy for a specific condition – in this case, four alternative strategies to scram the reactor if automatic scram had failed:

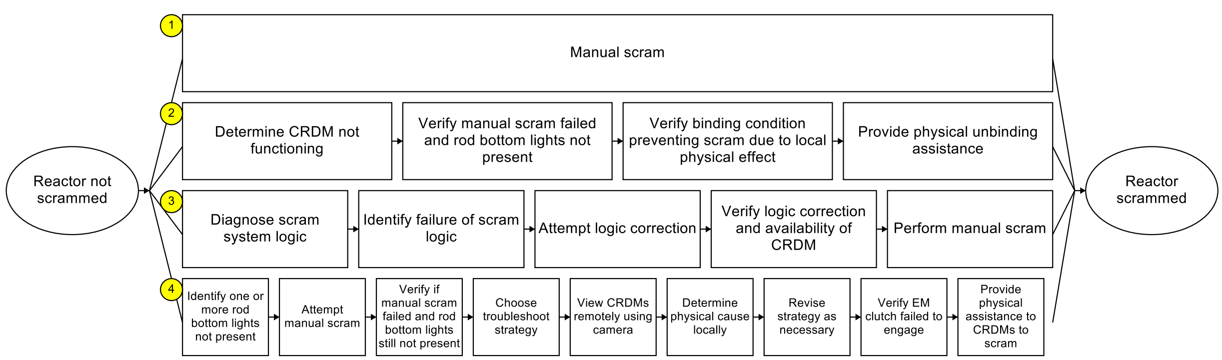

Figure 3: Example of Strategies Analysis (Information Flow Map)

Ultimately, an operational strategy would be defined as one or more sequences of short-term and long-term operations that transform goals, plans, decisions, policy, rules and procedures into the technical processes necessary for humans and systems to produce the defined production outcomes of the sociotechnical system.

3 USING WDA TO DEFINE OPERATIONAL CONCEPTS FOR ADVANCED REACTORS

SFRs and all AdvNPPs will require descriptions of the plant, its structure, systems and their functions, and the unique operating scenarios that will influence the design of systems and procedures and the interaction of humans with systems and the environment. In spite of the typical lack of detailed design information early in the engineering process, it is very important that this phase of the analysis be as thorough as possible because the level of accuracy at this stage will determine the accuracy and validity of the remaining phases. Available information needs to be investigated and resolved in sufficient detail early in the project life cycle to enable designers to include the operational as well as human requirements in their designs, technical specifications, and procedures. Especially with FOAK designs, it is incumbent upon the designers to assemble these definitions, structures, functions and scenarios and make them available for the WDA. Without the WDA, it will be difficult to provide assurance that the evolving design will be usable by operators. WDA is the foundation upon which everything else is built and perhaps more important, it provides a large part of the necessary traceability for design decisions throughout the project life cycle. Past experience reported in the literature (Bisantz et al., 1994 [2], Jenkins et al., 2006 [10], Militello et al., 2009 [13] and others) has shown that engineering efforts that skip WDA and only perform functional requirements analysis and system design are unlikely to deliver a viable system that supports optimal human performance.

For an NPP, the implementation of the "What, Who, When, Where, Why, and How" derived from the WDA will produce an OCD that is a collection of a large amount of high-level operational and technical information that would include, for example:

- A description of the plant's main and subsystems, their purpose and functions.
- A description of the operational modes and states of the plant, including normal transitions, anticipated operating occurrences and transients.
- A description of the staffing strategies for the plant and the high-level roles that are to be assigned to operational and maintenance personnel, including the basis for the allocation of control functions to the main control room and other facilities.
- Operating requirements for facilities such as the control rooms, remote shutdown facility, human-system interfaces (HSIs), local control stations, communication equipment, and the requirements for monitoring, interacting, and overriding automatic systems.
- An overview of operational procedures, including I&C architectures, automatic and manual operations, outage management, normal and emergency operating procedures, and alarm handling.

In spite of more than 400 reactor-years of successful operation of a total of nineteen SFRs, there is still only minimal documented operating experience that adequately informs the development of an OCD for advanced SFRs and other Generation-IV designs (see [3] p. 10). However, a considerable amount of conceptual design information is available in published literature and the INL research relied extensively on design information from predecessor designs. [2]

Given these sources of information, it was possible to make significant progress in developing preliminary operational concepts for SFRs. The results achieved from the phases shown above have already produced sufficient information to enable the development of a framework for analysis and the definition of operational strategies and requirements, definition of conceptual operator functions, human-

[2] A review of these sources is beyond the scope of this paper. For a more extensive review of fourth-generation designs see the CEA Nuclear Energy Division's report "4th-Generation Sodium-Cooled Fast Reactors – The Astrid Technological Demonstrator".

automation collaboration and staffing concepts for SFR operations. All of these are essential for informing the development of a Reference Operational Concept Document for SFRs, which is currently in progress at INL. System engineers and operational experts will be able to use this document in future as a template to develop a plant-specific OCD, which will help them to verify system designs described in their System Design Documents against the operational principles and requirements defined in the OCD.

The SFR Reference Operational Concept Document project will include validation of the various frameworks described in this paper. Once the WDA and the rest of the CWA for a generic SFR is complete, there will be sufficient information to test the whole CWA framework's process steps and methods and validate whether its underlying models work effectively and produce the expected outputs.

In reviewing the normal and abnormal/emergency operating scenarios and developing the WDA described above, our interim findings for SFR designs include three basic concepts:

- New concepts in physical and functional plant layout will lead to dramatic changes in operational and maintenance procedures. For example, different plant configurations such as multiple power conversion units per reactor will require special attention to I&C and HSI design, as well as unconventional operating procedures.
- Operator roles and responsibilities are likely to change in various ways. The biggest change will be a shift from many manual tasks to monitoring and supervising highly automated systems. Automation systems will allow operators to manually intervene in automated processes in many cases, but this will be the exception rather than the rule. It is expected that an advanced automation systems may even monitor the operator's performance and take over when a potential error is detected.
- Compact plant footprints will make it difficult for field operators and technicians to reach certain areas; this will require increased attention to the changing role of operators in plant control, remote monitoring, surveillance, and diagnostics.

4 CONCLUSION

The characteristics of SFRs and other emerging AdvNPP designs will require definition of operational modes and states that are not common with more conventional reactors. Innovative operational strategies will have to make provision for conditions unique to SFRs, AFRs, LMRs and HTGRs, such as high levels of automation, load following, multi-modular operations and maintenance, multiple product streams, among others. These new operational modes will require new operator tasks such as production planning for more than one energy product, managing non-electrical processes, or novel refueling methods. New plant modes and tasks will also create complexities and require innovative treatments in the design and use of advanced HSIs. Ultimately, all of these conditions will require development of a new family of normal and emergency operating procedures for conditions not familiar to operators of conventional NPPs. The experience at INL to date shows that WDA is an excellent tool for supporting this development.

Based on practical application over the past three years, WDA has proven valuable in creating a structured approach to OCD development that accounts for human performance, even for FOAK systems such as SFRs. It can make an important contribution to the design process by helping the design team as well as project managers to understand the operational requirements from a human perspective and how technology can help or hinder operators in meeting those requirements. Some HFE practitioners still think that WDA is complex and that it is difficult to translate the results into design, but our experience has shown that it is only the need for several iterations that make it seem complex. Unfortunately it is beyond the scope of this paper to examine more broadly how the results can translate into design, but WDA is actually a very logical and process that guides the analyst to identify all the key issues early in the life cycle. Specifically, it offers a structured and systematic way to consider the effect of human abilities and limitations on operational requirements, to analyze design trade-offs, and to specify requirements. The method can also aid project managers by describing the systematic integration of human functions in the systems engineering process. Above all, an integrated WDA approach helps the design team understand the human requirements of work and how technology may help or hinder operators, technicians, engineers and managers in meeting those requirements. WDA experts can facilitate design discussions by describing the impact of various design choices on the execution of human work. In this way WDA supports the engineering design process at different levels.

WDA is not limited to operational concepts for SFR only, but is widely applicable to varied operational design situations where operational principles are being defined or modified. It would also apply to NPP plant upgrades and consideration of emergency response to long-duration events such as extended station blackout. In going from an older design to a new FOAK design, the Contextual Activity Analysis part of the WDA will prove to be particularly valuable in helping to identify and characterize expected differences in responsibilities, roles, and automation for normal and abnormal operations. Early assumptions, such as modularity, plant layout, and higher levels of automation will be highlighted and verified in the analysis. For a new SFR design, information like this, combined with human performance criteria, could also be used during later stages of the project life cycle to assess the crew performance aspects associated with identified SFR operational concepts.

The extensive literature on CWA and WDA and recent results from the Operational Concepts project at INL suggest that the nuclear industry is in serious need of a methodological makeover, especially with regard to the way operating concepts are developed and the roles of humans are defined. All of the results so far make a strong case for not relying on paradigms that might have applied thirty or forty years ago when control system technology was primitive compared to today's advanced automation systems and HSIs. We should recognize that new technology often requires not just new design techniques, but also new mental models. This will enable us to cross the chasm between the old, often ineffective paradigms, and advanced design approaches that are not just different, but add significant value in both human and technological terms. From a project management point of view, the appropriate use of WDA in the design life cycle also has the potential to reduce the risk of additional iterations, project cancellations or rejected deliverables, reduces the time associated with trial and error approaches. Successful integration of WDA into existing project activities such as modeling, simulation, and prototyping can mitigate rising project costs.

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