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DEVELOPMENT OF OPERATIONAL CONCEPTS FOR ADVANCED SMRs: THE ROLE OF COGNITIVE SYSTEMS ENGINEERING

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ABSTRACT

Advanced small modular reactors (AdvSMRs) will use advanced digital instrumentation and control systems, and make greater use of automation. These advances not only pose technical and operational challenges, but will inevitably have an effect on the operating and maintenance cost of new plants. However, there is much uncertainty about the impact of AdvSMR designs on operational and human factors considerations, such as workload, situation awareness, human reliability, staffing levels, and the appropriate allocation of functions between the crew and various automated plant systems. Existing human factors and systems engineering design standards and methodologies are not current in terms of human interaction requirements for dynamic automated systems and are no longer suitable for the analysis of evolving operational concepts. New models and guidance for operational concepts for complex socio-technical systems need to adopt a state-of-the-art approach such as Cognitive Systems Engineering (CSE) that gives due consideration to the role of personnel. The approach described here helps to identify and evaluate human challenges related to non-traditional operational concepts. A framework for defining operational strategies was developed based on an analysis of the Experimental Breeder Reactor-II (EBR-II), a small (20MWe) sodium-cooled reactor that was successfully operated for thirty years. Insights from the application of the systematic application of the methodology and its utility are reviewed and arguments for the formal adoption of CSE as a value-added part of the Systems Engineering process are presented.

Key Words: Advanced Small Modular Reactor, Cognitive Systems Engineering, Cognitive Work Analysis, Human Performance Requirements, Systems Engineering

INTRODUCTION

Modern small 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, new materials, more automation, and also the ability to use excess heat for industrial applications such as hydrogen generation and seawater desalination. One of the more challenging aspects of the introduction of advanced SMRs into the nuclear fleet involves the detailed description of how these plants will be operated and by whom. (Note that “advanced” in this context refers to non-light water reactors, (LWRs) that is, reactors that use coolants such as molten salt, helium, carbon dioxide, or liquid metal eutectics like sodium/potassium or lead/bismuth, etc.). This also requires consideration of the appropriate allocation of functions between the crew and various plant systems that are likely to be highly automated. This is challenging because operating experience with SMRs other than shipboard reactors is limited. There is also a lack of a technical basis for plant operational staffing that takes into account static or dynamic allocation. In addition, existing human factors and systems engineering design standards are not current in terms of human interaction basics for automated systems. Some AdvSMR designs propose a multi-unit configuration with a single central control room as a way to be more cost-competitive. These differences not only pose technical and operational challenges, but they will undoubtedly also have regulatory compliance implications, especially with respect to staffing requirements and safety standards.

New instrumentation and control (I&C) technologies make it possible to automate systems in ways not possible with the analog systems of older nuclear power plants (NPPs). However, new digital technologies will require many changes to how operators manage and interact with the plant. These new systems may even cause plant systems to operate in ways that are unfamiliar to the operator. Thus, 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 including failure signatures different from those experienced in analog applications. Ultimately, design decisions must be based not only on an understanding of the criteria for allocating functions to humans or to systems, but on the synergistic collaboration between them during the different plant states. Current human factors engineering and systems engineering methods 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 comprehensive, systematic process that would be formally called out, for example, as part of the system life cycle described in the International Council on Systems Engineering (INCOSE) Systems Engineering Handbook 3.2.2, is needed to address that shortcoming and produce reliable information for the design of robust and resilient systems that allow dynamic collaboration between operators and plant systems.

One of the aspects of the operation of emerging reactor designs not well documented in the literature is the organizational and operational impact associated with implementing these new reactors, specifically the expected impacts on engineering, operations, I&C, and maintenance functions. This is especially true for multiple-purpose hybrid energy plants where the boundaries between processes may intersect and operating staff may have multiple roles. No information is currently available on the type of safety critical operational scenarios that might include AdvSMR interaction with other processes. Other less safety-significant issues, but important from an economic perspective, is the approach to a clear process for monitoring and resolving conflicts among the interconnected processes. This is particularly challenging because it seems clear that operators will be faced with new tasks due to the increased ability of multi-modular plants to load-follow, to distribute load demand among multiple units, and to transition among different product streams. The supposition is that this must be achieved easily and reliably, however, without the proper guidance, the results from a human performance perspective may be more 'miss' than 'hit'.

The technical basis for operational choices will be achieved through detailed evaluation of operational concepts that would include high levels of automation, advanced human-system interface (HSI) technologies, computerized procedures, different physical plant layout, different environmental conditions, and on-line maintenance of multiple reactor units. All of the features enabled by advanced technology will result in new challenges for the definition of operational concepts, systems design, and staffing and training. For example, it is expected that operational sequences will include failure phenomena such as high temperature excursions and other types of disturbances not associated with light water reactor designs. At the same time, the increased emphasis on passive safety may eliminate several familiar design requirements associated with LWRs, for example the need for redundant active cooling systems. Past research has shown that the new generation of reactors will include an extensive list of human performance issues associated with such conditions that have not been empirically evaluated in detail (O'Hara et al. 2011, 2012; Hugo et al. 2013). The impact of AdvSMR designs on the human aspects of operations, such as workload, situation awareness, human reliability, staffing levels, and the appropriate allocation of functions between the crew and various plant systems that are likely to be highly automated, is largely uncertain and will remain uncertain until empirical research data become available to support the development of sound technical bases. Given these uncertainties and other issues, it has become critical that new operational concepts must be researched, developed, and held up to analysis for this next generation of NPPs.

Although there is no AdvSMR operating experience that completely informs the development of Operational Concepts, a considerable amount of conceptual design information in published literature is available, along with operating experience from predecessor plants, such as Argonne National Laboratory's Experimental Breeder Reactor-II (EBR-II) that was operated on the Idaho National Laboratory site and the PRISM Advanced Liquid Metal Reactor Design, which was far advanced but never built. Given these sources of information, it was possible to make significant progress in developing preliminary operational concepts for AdvSMRs. Research to date has established the basic framework for analysis and definition of the operational strategies and requirements to define the functions and staffing requirements aspects for AdvSMR operational concepts, which are essential to informing the allocation of functions and the collaboration of humans and automation within the AdvSMR operating context.

This paper summarizes the progress to date on our efforts to develop a framework for the analysis and definition of operational concepts. It also describes how the cognitive systems engineering (CSE) methodology and in particular the Cognitive Work Analysis framework, are suited to and can be applied to support the identification of operational concepts, the expected roles of human and system agents, and the systems involved in a variety of operational conditions.

WHAT IS AN "OPERATIONAL CONCEPT"?

"Operational Concepts" describe the characteristics of a new or existing system from the viewpoint of people who will use that system while communicating the quantitative and qualitative characteristics of the system to all stakeholders. Operational Concept documents are widely used in the military, governmental services, industry and other fields. In industrial applications these documents are usually a formal Systems Engineering deliverable. The exact definition and application of Concept of Operations or Operational Concept differ among various organizations, but most share a common vision. All organizations agree that an Operational Concept document is highly beneficial, not only for design or acquisition of new systems, but also for the operation of the system after implementation (Roberts and Edson, 2008).

Note that some literature (IEEE 1362-1998; O'Hara et al. 2004) refers to "Concepts of Operations", and this is often confused with "*conduct* of operations" (NUREG-0800; INPO/WANO 01-002, etc.), which is a very different concept. INCOSE further makes a distinction between "concept of operations" and "operational concept" and points out that the two concepts are very similar, but there are important differences. To avoid confusion we have adopted the term "operational concept" and the abbreviation "OpsCon" from the INCOSE Systems Engineering Handbook, which defines it as follows:

> "…*a verbal and graphic statement of an organization's (enterprise's) assumptions or intent in regard to an operation or series of operations of a specific system or a related set of specific new, existing or modified systems. The operational concept is designed to give an overall picture of the operations using one or more specific systems, or set of related systems, in the organization's (enterprise's) operational environment from the users' and operators' perspective. It is also called the OpsCon.*"

From a licensing perspective, the definitions in NUREG-0711 (Revisions 2 and 3) – "Human Factors Engineering Program Review Model" (O'Hara et al., 2012) are important. Revision 2 of NUREG-0711 states several requirements for the concept of operations, including descriptions of the primary design and operating characteristics of the plant or system and the specific staffing goals and assumptions necessary to implement the concept of operations. It also states the need for descriptions of the roles and responsibilities of individuals, the overall operating environment and primary human system interfaces (HSIs) to be used by control personnel.[1]

New operational concepts are being developed at the Idaho National Laboratory by conducting an in-depth analysis of the operational characteristics and attributes of future AdvSMRs and their systems and users. By doing this, insights are developed of how the role and function of humans in the plant might be affected by advanced AdvSMR technologies and, conversely, how the operation of these plants might be influenced by the need to accommodate human abilities and limitations in the design.

DEFINING OPERATIONAL CONCEPTS FOR ADVSMRs

For an NPP, the implementation of the "What, Who, When, Where, Why, and How" described by INCOSE will produce an OpsCon document that is a collection of a large amount of procedural and high-level 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, HSIs, local control stations, communication equipment, and the requirements for monitoring, interacting, and overriding automatic systems.

1 See also NUREG-0711 Revision 3 for a description of the six dimensions of a Concept of Operations.

- An overview of operational procedures, including I&C architectures, automatic and manual operations, outage management, normal and emergency operating procedures, alarm handling, etc.

INCOSE recommends the development of an initial Operational Concept by the users and operators at the inception of the project who then jointly maintain the OpsCon throughout the production, utilization, support and retirement phases of the system life cycle.

In addition to the items above, the OpsCon document should also provide an overall methodology to realize the goals and objectives for the system. It is not a standalone document but is typically linked to a Systems Engineering Management Plan and plans that are more detailed for all specialty-engineering disciplines. One of the latter is the Human Factors Engineering Program Plan that describes how human factors activities and products are to be synchronized with other engineering activities.

In support of our objective of supporting non traditional concepts of operation, our research is pursuing two important issues: (1) the operating principles of advanced multi-modular plants, and (2) the requirements for human performance, based upon work domain analysis and current regulatory requirements.

OPERATING SCENARIOS

The determination of operating scenarios is an invaluable aspect of Operational Concept development. This is yet another big challenge for the AdvSMR industry because of the lack of appropriate operating experience. There are many ideas and opinions about the operational impact of plant configurations. These include, for example, the effect of core design, different coolants, reactor-to-power conversion unit ratios, modular plant layout, modular versus central control rooms, plant siting, and many more. Multi-modular plants in particular are expected to have a significant impact on overall OpsCon in general, and human performance in particular. For example, in one case with advanced automation, a single operator may simultaneously monitor and control multiple modules. In another case, multiple operators may be required to manage multiple modules from the same control room. To support these modes of operation, the modern control room of a multi-module plant would typically require advanced HSIs that would provide sophisticated operational information visualization, coupled with adaptive automation schemes and operator support systems to reduce complexity. These all have to be mapped at some point to human performance requirements.

Several other factors need to be considered in the operational design of multi-modular plants:

- Operating states - Different modules in a multi-modular plant can be at different power levels or different states, such as shutdown, startup, transients, accidents, refueling and various conditions of maintenance and testing.
- Control systems for multiple units - Control systems may need to be able to manage multiple units in an integrated fashion. This could include systems that the modules share in common, such as for secondary plant cooling water or the ultimate heat sink for removing decay heat, and also systems for instrument air, service-water cooling and electrical distribution. It may also include common control of systems that are similar but not shared between modules, such as balance-of-plant systems. The integrated control of multiple modules and their shared systems would thus be not only an automation challenge, but also an operational challenge. The demand placed on operators to maintain situation awareness, not only of the plant overall, but of individual units and shared systems, may impose a severe cognitive workload. In fact, without evidence to the contrary, this may challenge current assumptions that workload in AdvSMR control rooms will be lower,

thus theoretically allowing operators to handle more than one module at a time.

- HSI for multiple units - The detailed design of HSIs (alarms, displays, and controls) to enable a single operator to effectively manage one or more modules will be an additional challenge. HSIs must enable monitoring of the overall status of multiple units (or multiple reactors), as well as easy retrieval of detailed information on an individual reactor module.

The design characteristics of AdvSMRs will inevitably require the definition of operational modes and states, some of which may be similar to those for LWRs, but also new ones that are unfamiliar, such as unplanned shutdowns with degraded conditions in one module that may affect other modules, off-normal conditions at more than one module, or adjusting module power levels to enable load following. These modes will require new operator tasks such as: load following operations, managing non-LWR processes and reactivity, and novel refueling methods. New plant modes and tasks will inevitably create complexities and require innovative treatments in the design and use of appropriate HSIs. Ultimately, all of these conditions will require development of a new family of normal and emergency operating procedures for multi-unit disturbances. The experience at INL to date shows that CSE is an excellent tool for supporting this development.

COGNITIVE SYSTEMS ENGINEERING IN THE NUCLEAR INDUSTRY

The development of operational concepts and identification of the associated challenges for operators is a key aspect of the technical basis for the next generation of SMRs. Obtaining good results from this phase requires a structured approach such as CSE to the analysis of a large amount of information. It is critical to integrate human factors considerations into the systems engineering process throughout the project lifecycle. Some recent publications (e.g., Naiker, 2013; Sanderson et al.; 2012; and Woods & Hollnagel, 2006) emphasize that the only rational approach to incorporating human considerations in the development of first-of-a-kind power plants is to follow a formal, structured methodology like CSE that supports the analysis and description of the environmental and functional constraints that would be placed on human actors by the new design. In particular, these authors highlight the importance of making 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. The INCOSE Handbook also mentions the need for the involvement of a number of specialty engineering disciplines in Systems Engineering; adding CSE competency as just another engineering specialty to assemble and interpret the human-related information would therefore support industry best practice as promoted by the Systems Engineering Process.

In simple terms, CSE is an integrated, multidisciplinary engineering approach to the design of technology, processes and functions intended to manage the cognitive complexity in sociotechnical systems. In this context, it "…refers to activities such as identifying, judging, attending, perceiving, remembering, reasoning, deciding, problem solving, and planning" (Klein et al., 2003, 2008). Lintern (2009) describes CSE as "a specialty discipline of systems development that addresses the design of socio-technical systems. … The focus is on amplifying the human capability to perform cognitive work by integrating technical functions with the human cognitive processes they need to support and on making that cognitive work more reliable." CSE is actually a family of frameworks that all focus on knowledge elicitation and the analysis and description of the cognitive aspects of systems. These frameworks include Cognitive Task Analysis (CTA), Human Factors Engineering (HFE) and Cognitive Work Analysis (CWA), with the latter being the dominant framework. CWA, in turn, includes various phases of analysis, starting with Work Domain Analysis (WDA), which is further described below.

CSE has grown out of a need to understand and describe the dynamics of complex sociotechnical systems, of which an NPP is a prime example. Experience tells us that effective operational strategies that involve humans cannot be designed by an engineer's intuition alone. The design of I&C, operating procedures or HSIs should be informed not only by physical processes and technology characteristics, but also by knowledge of how people think and act in the context of their work environment. Clearly, operational concept design must take into account those technological considerations, but if the technologies fail to support cognitive functions, they will very likely lead to error or even failure of the system as a whole.

It is a well-known fact that major systems such as transportation systems, military systems, energy systems and information systems have become more information-intensive, more automated and more distributed. Such advanced systems, many of which are first-of-a-kind, are more difficult to design due to demands imposed on users by complex infrastructures, large amounts of information, complex displays, unfamiliar technologies, ill-defined tasks, lack of operating experience and many more. These challenges have become a troubling area for Systems Engineering (SE) and HFE alike. As an analytical, integrated and systematic engineering approach, CSE offers methods and tools to address the challenge of designing system functionality that will support human participants as they undertake the essential cognitive work as well as the physical actions within the sociotechnical system. Ultimately, the aim of CSE is to amplify and extend the human capability to know, perceive, decide, plan, act and collaborate by integrating system functions with the cognitive processes they need to support. In spite of the label "cognitive", CSE does not imply a separation of cognitive from physical, but it is a convenient way to emphasize the shift of focus, where necessary, to those human functions that require significant cognitive work in order to achieve mission objectives. Figure 1 illustrates CSE in relation to CWA, WDA, SE and HFE. The intersections between these frameworks and methodologies, especially HFE, SE and CSE suggest many opportunities for collaboration and added value.

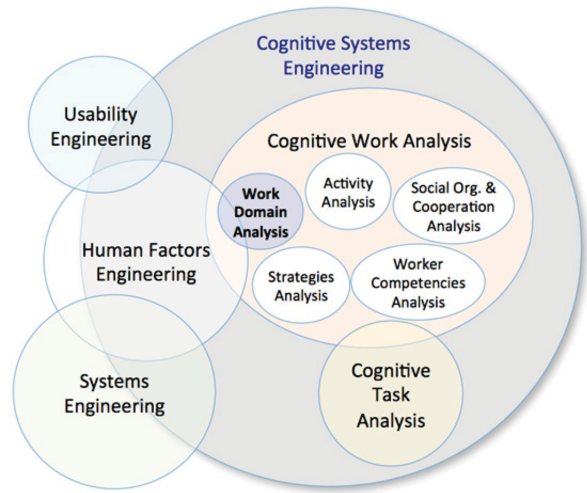


Figure 1: Cognitive Systems Engineering Relationships

There is ample evidence in the literature that the cognitive aspects of tasks have been typically neglected in system design, even in methodologies that are supposedly human-centered, such as Usability Engineering. The research at INL is demonstrating that significant value is added to existing system development methodologies by including a focus on cognitive functions and how they relate to actions and operations.

As Militello et al. (2009) point out, it is possible to design advanced systems without considering the value added by engineering approaches such as CSE or HFE. Many have done so. All it takes is for the design team to simply ignore the human requirements for the systems they are specifying, and direct their energy towards meeting the physical specifications. At best, designers would make assumptions about human requirements and extrapolate their own experience to anticipate the needs of the workers. Occasionally their assumptions are correct. But then we hear about cases where such assumptions were dramatically wrong (e.g. Perrow, 1999, whose analysis of the Three Mile Island accident in particular highlighted the complex relationship between human perceptions, system design, and precursors to human error). We are not the first to note that automating whatever you can and handing the leftovers to the human is a recipe for disaster.

One factor that will have a significant effect on future plant operations and thus on the role and function of the operating staff, is the design of the automation system and procedures to handle the range of new missions and tasks that might be required by the SMR designs. While the primary mission of the plants would still be to safely generate electrical power, some AdvSMRs may be designed to accomplish additional missions, such as producing high-temperature steam for hydrogen generation and other high-temperature industrial applications. It can thus be concluded that automation system design has to be informed by results from a comprehensive CSE process, in particular, WDA followed by the remaining phases of CWA, as explained below.

APPLICATION OF THE CWA FRAMEWORK

Based on the definition of OpsCon above, AdvSMRs 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. This 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 first-of-a-kind designs, it is incumbent upon the designers to assemble these definitions, structures, functions and scenarios and make them available for the CWA. Without the CWA, and especially the WDA, as described below, there is uncertainty that the evolving design will be highly usable by operators. WDA is the foundation upon which everything else is built. As a general rule, and even more so for FOAK engineering such as the design of a multi-unit AdvSMR, engineering efforts that skip WDA and only perform functional requirements analysis, activity analysis or task analysis will fall short of the mark in delivering a viable system that supports optimal human performance.

In his work on CWA, Lintern (2009) emphasizes the need to understand the work that must be supported for a new system and also the constraints of the work environment. That knowledge must then be represented or summarized in a form that supports the design effort. For a new system, and particularly a first-of-a-kind (FOAK) design, this is very difficult primarily because of the lack of well-documented predecessor designs and the immaturity of the new design. The technical aspects of this are difficult enough for Systems Engineering, but for Human Factors Engineering it is almost impossible to start designing HSIs until the engineering design is mature enough. In addition, Systems Engineering is not concerned with operational requirements until the system design is stable enough to allow integration and consideration of instrumentation and control requirements. The knowledge elicitation and knowledge presentation phases of CWA, which are not well known in Systems Engineering, can offer early ideas and operational considerations that have the potential to strengthen systems design and ultimately efficient and safe operations.

CWA can be broken down into 5 phases, each with a defined outcome that serves as input to the next phase:

Table 1: Cognitive Work Analysis Phases

Phase	Product
Work Domain Analysis	Abstraction-Decomposition Framework, and System Decomposition

Contextual Activity Analysis	Decision Ladders
Strategies Analysis	Course of Action, Information Flow Map
Social Organization and Cooperation Analysis	Combination of previous
Worker Competencies Analysis	Skills, Rules, Knowledge Inventory, high-level function allocations

The CWA framework guides the analyst through the process of answering the question of why the system exists; what activities are conducted within the domain as well as how this activity is achieved and who is performing it (Jenkins et al., 2008). 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 (formative modeling) (Hassall & Sanderson, 2012, Naiker 2013).

CSE and its various frameworks can make an important contribution to the design process by helping the design team as well as project managers to understand the human requirements of work and how technology can help or hinder operators in meeting those requirements. The method also offers a structured and systematic way to consider the role of humans in the process, to analyze design trade-offs and to specify requirements, based upon the assessed impact of various design choices for the execution of work allocated to systems, humans, or shared between both. The method is not limited to OpsCon for AdvSMR only, but is widely applicable to varied operational design situations where the operational concept is being defined or modified. For example, it would also apply to NPP plant upgrades and consideration of emergency response to long duration events such as extended station blackout.

The first step in CWA is to understand the problem space, including the work domain, the people involved, and the systems that are necessary to perform the work. WDA, the first phase of CWA as shown in Table 1, analyzes the work domain and its functional and structural characteristics and identifies a fundamental set of constraints that the work domain imposes on workers by specifying the purposes that the work system must fulfill. It also specifies the actions of any system or human agent, thus providing a solid foundation for subsequent analysis and design phases. (Naikar et al. 2005; Naikar, 2013).

Once the domain is well understood and described, designers need to determine who does what, when, with what, where, how people will interact with the system, and what the cognitive and physical requirements for the tasks are. The most important outputs of this framework are known as the Abstraction Hierarchy and the Abstraction-Decomposition Framework. These outputs describe the work domain in terms of a hierarchy consisting of the a) the overall functional purpose of the work domain, b) its values and priority measures, c) the functions of the systems within the domain, d) the processes they support, and e) the physical components that are required to support the various processes. The abstraction hierarchy developed through WDA can also serve as a knowledge-base, not only for the design of the HSI, but also for various other applications, such as development of diagnostic tools, computer-based procedures and operator training. This hierarchy is further used in later phases of CWA to determine how all of these components and functions influence the mental and physical performance requirements for the user’s task.

From a project management point of view, the appropriate use of CSE 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 CSE into existing project activities such as modeling, simulation, and prototyping can mitigate rising project costs.

THE ROLE OF MEANS-ENDS RELATIONSHIPS AND CONSTRAINTS IN WDA

In combination, the goals and purposes of the work domain define the fundamental problem space of workers and include the values, priorities, and functions that must be achieved by a work system with a given set of physical resources. However, within these constraints, workers have many options or possibilities for action in the work domain. This becomes the basis for 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 application of means-ends links between the levels of abstraction in the Abstraction Hierarchy is a very practical way to maintain traceability of the relationship between entities and also to identify the constraints and dependencies. The diagram below shows how, for each entity at each level, the Abstraction Hierarchy answers the question "why is this needed?" by the level above, and the question "how is this achieved?" by the level below. An example of this is shown in the Abstraction Hierarchy for EBR-II in Figure 3.

The main aim of WDA for AdvSMR OpsCon is thus to model the constraints that relate to the functional and physical context within which workers of a new generation of NPPs will perform their tasks. For example, the environmental, physical and functional requirements of an advanced plant will impose physical as well as mental constraints on workers. These constraints will determine the physical objects or tools that must be available to the operators to perform their tasks as well as the functional capabilities and limitations of those objects.

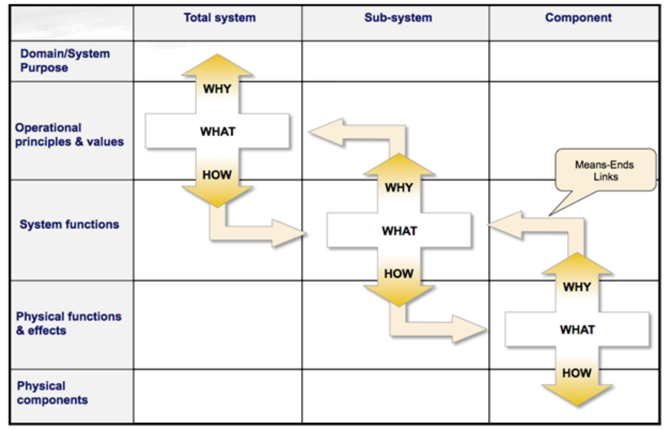


Figure 2: Means-Ends Links in the Abstraction Hierarchy

SELECTION OF A REFERENCE DESIGN FOR ANALYSIS

Liquid-metal reactors like sodium/potassium- or lead/bismuth-cooled designs are currently regarded as the most prominent AdvSMR designs and the designs most likely to be licensed within the next ten to fifteen years. However, none of the reactor designs currently in progress (e.g., Toshiba 4S, GE PRISM, Korean SMART, TerraPower TWR, etc.) is mature enough to have design information available for analysis. It was therefore decided in 2012 to conduct an exploratory exercise using subject matter and relevant information from EBR-II, which qualifies as a predecessor sodium-cooled reactor. In fact, the EBR-II reactor design is the basis for several of the current AdvSMR fast sodium-cooled reactor designs, in spite of its 1970s-era technology, including analog I&C. In considering emerging sodium reactor designs, we assume that across all operating scenarios there will be a high degree of automation, including the likelihood that operators will be able to take manual control of components, systems, and processes when necessary or appropriate. We also assume that the control rooms will employ advanced, digital I&C and HSIs. A subject matter expert who was an operator on EBR-II is currently assisting with the analysis.

At EBR-II, automation existed only at the component level, and manual control of systems and processes was the operational norm. The limitations were part of the original design and determined primarily by the limited automation and digital control capabilities at the time of construction. In AdvSMR sodium-cooled designs, it is expected that automatic control at the system and/or process levels will most likely be the norm, though dual control capability and the capability for manual control will be required (e.g., for off-normal or emergency events). Examples of the systems we expect to be under automatic control include reactivity control (automatic control rod drive system), primary and secondary sodium systems, steam plant systems, turbine control and fuel handling operations.

ANALYSIS OF EBR-II NORMAL OPERATING SCENARIOS

In an effort to determine major functions associated with EBR-II, interviews with previous EBR-II operators were integrated with our review of plant schematics, detailed normal operational procedures and emergency procedures. The abstraction hierarchy and the contextual activity analysis performed for normal operations identified four high-level functions that must be accomplished in normal operations:

- Maintain fast fission (functions required to convert potential energy to nuclear energy)
- Maintain reactor cooling (function to utilize sodium coolant to remove reactor heat)
- Drive the turbo generator (function to convert mechanical energy to electrical energy)
- Manage and control plant operations (function to manage the allocation of plant functions to operators and control systems)

Two plant operating states from EBR-II operations were selected and used as test cases in developing a framework for documenting operating crew responsibilities and performance requirements. Steady state and restricted fuel handling at EBR-II were selected and we then postulated operator responsibilities for the same operating modes in an AdvSMR sodium reactor plant. EBR-II fuel handling processes were complex and operators had a large amount of activity and strong safety-related requirements that demanded a high degree of situation awareness. We identified through this analysis that the high workload and potential for error that characterized this older EBR-II function will be sufficient justification for future automation.

Today's NPPs are considered as an electricity base load source; AdvSMRs break with that tradition by having the capability to load-follow more easily and economically. Load following can take the form of rapid response to grid demand, or pre-programmed variable load in agreement with the grid operator. In France and Germany there is already some degree of load following in larger plants via primary frequency control. Load following with newer generation plants, also referred to as maneuverability, is expected to pass safety studies and be an expected, explicit characteristic of AdvSMRs. As a result of the enhanced ability and corresponding expectation to load-follow, AdvSMR operators will likely have additional communication requirements and coordination with dispatch. The human performance requirements during load following will determine the level and type of workload experienced. However, if load following is under automatic control, the operator workload may not increase appreciably.

The EBR-II design required a significant amount of manual fuel handling and monitoring of sodium temperatures; in new designs this will be achieved by automation for steady state and restricted fuel handling operations. Performance requirements for operator manual use of the crane and control of fuel assembly movement in and out of the fuel basket during restricted fuel operations will be replaced by, for example, the operator initiating and monitoring robotic systems designed for that task. If there is a problem with the robotic manipulation the operator will intervene and take manual control. Also, in the EBR-II design the operator depended to a great extent on haptic senses (that is, tactile feedback) to verify that there has been a positive capture of the fuel subassembly. In an advanced SMR design, this verification is expected to be an automatic process.

As indicated above, the EBR-II control systems essentially required the plant to be operated at a component level. This imposed many manual tasks on the operator that are likely to be automated for a modern sodium-cooled reactor design. For example, the automation will monitor system parameters and alarms and provide integrated data, trends, and displays to the operator. The automation systems will also perform data analysis, diagnostics and prognostics, and provide more integrated data and diagnosis information to the crew. This means that the operator's role is to anticipate required automatic actions, monitor automation, and verify necessary recovery actions occurred as expected and required.

This is a clear indication of the value of CWA, because this kind of information is very difficult to discover without a systematic analysis of systems, processes, functions, measures and purposes.

RESULTS OF THE PRELIMINARY WDA FOR EBR-II

This phase of the Operational Concept development project has documented the process for identifying the structural and functional characteristics and the human performance requirements in AdvSMR sodium reactor designs. The analyses that were required to prepare for the WDA included development of a state-transition diagram of the EBR-II operating modes, transitions and transients, a system breakdown of the main and subsystems, a state matrix that described the performance parameters of primary and secondary systems for normal operations and selected transients, and a detailed analysis of selected operating scenarios. These analyses are best performed by a team.

The decomposition of all the elements described above and subsequent analysis of constraints and dependencies in terms of systems, structure and components produced a set of the Abstraction Hierarchies and Abstraction-Decomposition Frameworks for EBR-II Normal Operations and selected design basis events (DBEs). These DBEs, available from the Probabilistic Risk Analysis, included a small sodium-to-water leak, a small seismic event, reactor scram, and a secondary sodium leak. Two diagrams are shown below as examples.

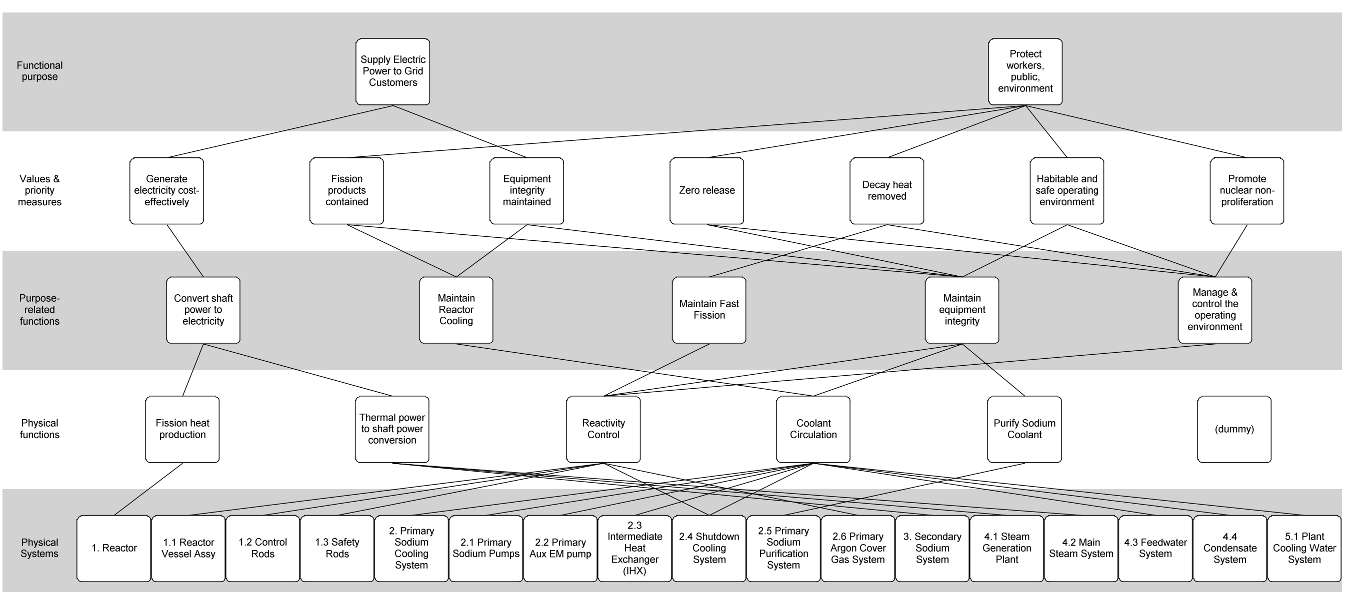
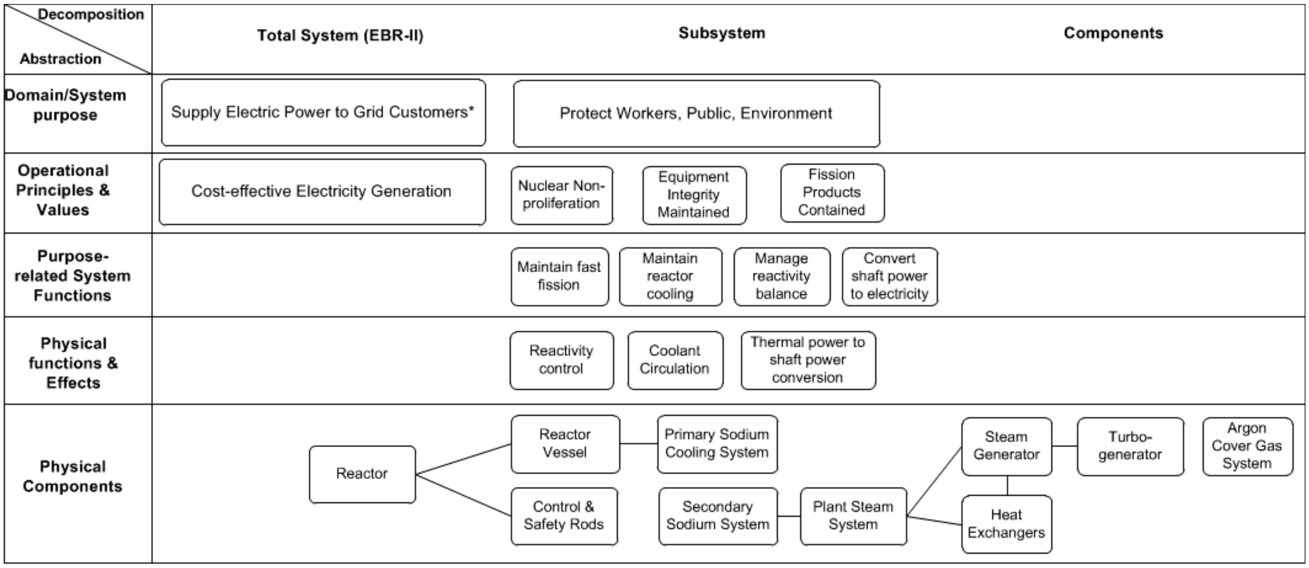


Figure 3: EBR-II Abstraction Hierarchy (simplified)



* EBR-II functions related to research, experimentation and fuel reprocessing are excluded from the analysis

Figure 4: EBR-II Abstraction-Decomposition Framework (simplified)

The diagrams show the abstraction (that is, described bottom-up in decreasing levels of detail) of the EBR-II work domain in terms of physical objects (systems and components) at the lowest level, physical functions and effects (i.e. processes), purpose-related system functions, operational principles and values, and domain or system purpose at the highest level. It also shows the "why-what-how" means-ends links described earlier.[2]

Using DBEs and procedures from EBR-II, we have also documented key operator responsibilities for selected abnormal/emergency operating scenarios and demonstrated how this could be extrapolated to future AdvSMR designs with higher degrees of automation and advanced HSIs. Based on this information, the main responsibilities of the operating crew were classified into six generic operator roles: Monitoring (of components, systems, parameters, automation, or HSI), Control actions, Diagnosis, Recovery/mitigation actions, Communication, and Configuration/setup functions. In addition, the normal and abnormal/emergency operating scenarios were evaluated based on these generic roles and specific functions that must be accomplished in normal and abnormal/emergency operations.

We have reviewed generic and domain-specific literature related to human performance with automation, advanced HSI and advanced design control rooms, and regulatory requirements for operator responsibilities to develop our preliminary list of human performance requirements. We also identified a high-level set of operator cognitive performance requirements, including basic skills, abilities, and knowledge that AdvSMR operators will need to possess, including knowledge of the plant physics and system interactions and dependencies, the ability to understand and integrate plant status information with plant processes, and manage multiple reactors. We are continuing these efforts by analyzing a complete set of normal and abnormal/emergency operating scenarios for EBR-II and the final output of the WDA will include a

2 A comprehensive description of the WDA and its models is beyond the scope of this paper. Readers are referred to sources in the References section.

competency matrix for operator roles and a set of human performance requirements.

The expected dynamic interaction between humans and systems in future plants will be a direct result of the design and architecture of distributed control systems, but will also be influenced by advanced design concepts resulting from new materials, multiple product streams, modular plant layout, etc. However, a large part of automation system design will be beyond the influence of human factors considerations. The reasons for this will be found in the reliability, accuracy and controllability requirements of certain physical processes, such as fuel handling, reactivity control, turbine control or synchronization to the grid. It is the purpose of the WDA to also identify those functions that are clearly beyond human capability.

WDA should ideally include the development of operating scenarios (iteratively derived from the Contextual Activity Analysis, which is part of CWA), and state matrices for the systems identified from the abstraction-decomposition for those scenarios. These analyses perform a bounding function and help to focus subsequent analysis and interpretation of findings. That is, the WDA and the rest of CWA produce input for detailed human factors analyses, which have to be completed in as much detail as possible before detailed HSI design can begin. The AdvSMR OpsCon project will perform its own validation of the various frameworks. Once the WDA and the rest of the CWA based on EBR-II 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 AdvSMR designs compared to EBR-II include the following:

a) New concepts in physical and functional plant layout 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. Compact plant footprints will make it difficult for field operators and technicians to reach certain areas; this will require increased attention to remote monitoring, surveillance, diagnostics and control.
b) The biggest change in the role of the operator 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 process in many cases, but this will be the exception to the rule. It is expected that an adaptive automation system may even monitor the operator's performance and take over when a potential error is detected.
c) Load following will involve reduced manual tasks, but increased communication with grid operators;
d) Different modules may be in different operational states at the same time, which will also require special HSIs and procedures.
e) The need to manage different product streams (i.e. electrical power and process heat) and will have design, licensing and procedural implications that are still unclear and require a lot of study.

CONCLUSIONS

CSE has value in creating a structured approach to OpsCon design that accounts for human performance, even for FOAK systems such as AdvSMRs. It must be emphasized that CSE is not only a way to facilitate systems engineering activities by showing how to incorporate cognitive work in systems engineering. CSE also can aid project managers by describing the systematic integration of human functions in the systems engineering process (Klein et al., 2008). Above all, an integrated CSE 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. CSE practitioners facilitate design discussions by describing the impact of various design choices on the execution of human work. In this way CSE supports the design process at different levels.

In going from an older design to a new FOAK design, the Contextual Activity Analysis part of the WDA outlined by Naikar, 2013, proved to be particularly valuable in helping us identify and characterize expected differences in responsibilities, roles, and automation likely to be present for normal and abnormal operations. Key assumptions, such as modularity, plant layout, and higher levels of automation figured in the analysis. For a new AdvSMR design, information like this, combined with human performance criteria, could also be used in forthcoming work to assess the crew performance aspects associated with identified AdvSMR operational concepts.

In practice, WDA, as the dominant component of CSE, can happen concurrently with automation system design, and in an ideal world there will be a lot of iteration, coordination and integration between the processes. Although the conduct of WDA can be considered to be consistent with the spirit of NUREG-0711, WDA has never before been applied (with the exception of small-scale academic studies, e.g. Bisantz & Vicente, 1994; Jamieson et al. 2007) in the development or analysis of concepts of operation in the nuclear industry. Examples in the literature (Roth, Patterson & Mumaw, 2012; Bisantz & Vicente, 1994, and Kim, 2011) suggest that WDA is the most systematic and structured method for this purpose. With time, we expect its use in the nuclear industry to become more widespread.

Several other authors also 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 (Katopol, P. 2006, 2007). This means that 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. The extensive literature on CWA and WDA and recent results for the AdvSMR OpsCon 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 designed and the roles of humans are defined.

While CSE may not be a magic bullet in Systems Engineering, our experience and results to date strongly suggest that the CSE approach in general, and CWA in particular, will add significant value in all new-build projects, especially those dealing with advanced reactor and automation technologies.

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