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Idaho National Laboratory
Idaho Falls, Idaho 83415

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Towards An Operational Concept for Advanced Nuclear Power Plants

Jacques V. Hugo[1] and Ronald Farris

jacques.hugo@inl.gov; ronald.farris@inl.gov
Idaho National Laboratory, Idaho Falls, ID, 83415 USA

Abstract

Advanced nuclear power plants currently being designed are characterized by structural, functional and operational features that are uncommon in the current generation of plants worldwide. Due to the long worldwide hiatus in the development of new nuclear power plants most of these issues and the implications of new operational concepts have never been evaluated in detail. This paper is a summary of the results of a four-year project at the Idaho National Laboratory to develop a systematic process to analyze the operational requirements of new plants. The paper describes a method to produce reliable information for the design of robust and resilient systems that allow dynamic collaboration between operators and plant systems. It also provides examples of the application of this method to the development of an operational concept for advanced nuclear power plants, with examples from sodium fast reactors (SFRs).

Key Words: Advanced Nuclear Power Plant, Operational Concept, Concept of Operations, Human Factors

1. Introduction and Background

Advanced nuclear reactors currently being designed are all expected to be simpler, safer, and more economical. These plants are characterized by unique structural and functional designs, unconventional processes, materials, structures, and 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 used by older nuclear power plants (NPPs).

It should be noted that some newer light water reactors (LWRs), like the Westinghouse AP1000 and the NuScale multimodular plant, are also regarded as "advanced reactors", but as indicated already, water-cooled reactors are specifically excluded from this review. The type of plants discussed in this paper are regarded as "advanced" primarily because of non-water coolants and the advanced structures, systems, components, materials, processes, and operations associated with such coolants.

Advanced nuclear power plants (AdvNPPs) face new challenges that will impact their overall technical design in general, but their operational design in particular because of new technologies and materials. This includes, for example, the ability to load-follow, different product streams with reconfigurable balance of plant systems, high levels of automation with humans in supervisory roles, integration of advanced human-system interface technologies, computerized procedures, new challenges for staffing and training, on-line maintenance for multiple reactor units, and many more. The human factors considerations that result from advanced automation will influence workload, situation awareness, human reliability, and staffing levels. This means many changes to how operators manage and interact with the plant.

The changes in operational concepts are primarily due to very different automation schemes, compared to older LWR plants. Operating practices in older plants include, for example, different start-up and shutdown regimes, many manual actions required by discrete analog devices, such as manual generator synchronization, many checks and tests because of a lack of self-diagnostic systems, and many more. All of these actions are governed by extensive procedures and typically require a full operating crew per reactor, consisting of two reactor operators, a senior reactor operator, shift supervisor, and shift technical advisor. In addition, the crew is supported by engineering, maintenance, and safety personnel. The U.S. Nuclear Regulatory Commission (NRC) currently regulates NPP staffing through federal regulations and several guidance documents. Control room staffing has become an important aspect of the design of new plants, especially with the emphasis on reducing operating and maintenance costs. When considering the expected reductions in plant staffing, based on the size, simplicity, and level of automation of AdvNPPs, operating staff could be much smaller in proportion of the total staffing than for existing plants.

All of these anticipated changes imply that new design and operational guidance is needed for new plants. Although many of the operational principles for older plants may still be valid, they have not been documented in a way that supports new designs. O'Hara et al (2004) pointed out that at present there are

[1] Corresponding Author,
jacques.hugo@inl.gov, +1 208 201 6447

only a few advanced reactors in operation, of which none are found in the U.S. Operating experience with plants like the BN-600 and BN-800 sodium-cooled reactors in Russia is limited and not available in the general literature. For reactor designs that have yet to be built, information concerning their concept of operations or the design of their control rooms is limited at best, and non-existent at worse. Historically, Operational Concept documents were not developed for the existing fleet of NPPs and the only operational information available is contained in operating procedures, and to some extent, the Conduct of Operations document, which does not contain the information described in this paper (see section 2.2). For this project, we therefore needed to examine operational concepts for new reactors in terms of the impact of current technological developments and to make projections into the near and longer-term future.

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 AdvNPPs, not only into the U.S. nuclear fleet, but in the rest of the world. The detailed examination of these issues will include the development of Operational Concepts for AdvNPPs to inform system, functional, and operational design and licensing basis. This requires the analysis of the impacts of, for example, unique operational conditions and scenarios, operational requirements of various product streams (steam, process heat, electricity), the increased use and reliance on passive safety systems, high levels of automation with humans in supervisory roles, remote surveillance and on-line monitoring, and reduced use of local control stations. Much of the difficulty in analyzing these challenges is due to the lack of operating experience and valid technical bases for the operation of new reactor designs. 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. The U.S. Department of Energy has recognized that the new design efforts in the nuclear industry required a detailed examination of these issues. An extensive research project was launched at the Idaho National Laboratory (INL) to develop a framework that would enable developers to define a new plant's operational requirements and characteristics. The resulting Operational Concept would help to inform the plant's system, functional and operational design, and also the development of design certification documentation.

The research project was concluded in September 2015 with guidelines and examples for the preparation of an Operational Concept Document for an AdvNPP (Hugo & Farris, 2015). A generic sodium fast reactor was chosen as a model for this report, due to the relative maturity of this particular design, but the general principles can be applied to the development of any system. The concepts presented should be sufficient to inform certain decisions regarding the design of AdvNPPs. The information should help DOE and various industry stakeholders to identify operational concepts that may affect the further design of AdvNPPs.

2. Development of Operational Concepts

2.1. What is an "Operational Concept"?

The operation of a nuclear power plant is described in a document called an Operational Concept, sometimes also called a Concept of Operations, commonly abbreviated as "OpsCon" or "ConOps." This document is a statement of an organization's assumptions or intent in regard to the operation of a specific system or a related set of specific new, existing or modified systems. It is best developed as part of a system engineering or acquisition program.

The International Council on Systems Engineering (INCOSE) defines the term as follows in the INCOSE Systems Engineering Handbook (INCOSE, 2012):

"*…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.*"

The operational concept is intended to give an overall picture of plant operations, using one or more specific systems, or set of related systems in the enterprise's operational environment from the users' and operators' perspective. It is a high-level description of the functional and physical structure of the plant, which includes its main systems and their functions, and how operating and maintenance personnel will work and interact with system resources to fulfil their roles and responsibilities. It includes the user description and summarizes the needs, goals, and characteristics of the system's user community.

From a licensing perspective, the content of an operational concept document generally conforms to the definition in NUREG-0711, the Human Factors Engineering Program Review Model (Revisions 2 and 3). 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.

For an AdvNPP, 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.
- An overview of operational procedures, including instrumentation and control (I&C) architectures, automatic

and manual operations, outage management, normal and emergency operating procedures, alarm handling, etc.

- 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.

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.

2.2. Purpose and scope of the OpsCon

While several new nuclear power plant (NPP) designs have emerged in the past few years, the issues and implications of innovative operational concepts that will inevitably result from new technologies employed by AdvNPPs have not been evaluated in detail. These new plants will require definition of non-traditional operational concepts to address unique operational scenarios that are expected to have an effect on human performance and reliability, leading to new challenges for system design, staffing and training. A particular operational characteristic of new NPPs is that automation is expected to decrease complexity and workload, and also improve team coordination requirements for operators and crews. This has led to one of the most urgent goals for new NPP operational concepts: addressing the economic imperative of reducing the dependence on large operating crews when possible, thereby reducing operating and maintenance costs.

As a guidance for managers, engineers and designers, the OpsCon document (also referred to as the OCD) aims to provide answers to the questions that are specific to an Operational Concept:

- WHAT: The structures, systems, components, and their top level capabilities that perform the necessary system functions, including provisions and facilities such as the control rooms, human-system interfaces (HSIs) and operator workstations, local control stations, communication equipment, procedures systems, etc. This information is obtained partly from a Work Domain Analysis that should ideally be conducted prior to, or at least in parallel with, the development of the OpsCon.
- WHO: A description of the interaction among various human elements and also with the various systems and external interfaces. This includes a high-level description of how operating personnel will work and/or interact with various resources to fulfil their roles and responsibilities. This also describes concepts for the coordination of team members' activities, such as the interaction between different types of operators, and the coordination of maintenance and operations personnel, and the relationship between operating personnel and plant automation, such as the responsibilities of operating personnel for monitoring and interacting with automatic systems.
- WHEN: A high-level description of the functions, activities, tasks, flows, precedence, and concurrent or sequence-related elements necessary to achieve mission objectives in various operational modes and conditions. This includes high-level descriptions of requirements and provisions for operating and maintenance procedures.
- WHERE: These are concepts related to the plant or system's geographical and physical siting, layout, and external interfacing systems.
- WHY: This includes the technical, political, economical, environmental, or social reasons for the existence or particular functional characteristics of specific systems or the plant overall. This also describes the various constraints that may affect design decisions.
- HOW: An overview of the requirements for system usage, operation, and maintenance in a given environment. This includes principles that will enable designers to develop automation concepts, alarm system and protection system principles, and do initial assignment of automatic versus manual controls (i.e. function allocation and level of automation) and remote (e.g. Main Control Room) versus local control (including the type of local control such as at the component, at a permanent or portable control station, etc.)

The purpose of the OpsCon can be summarized as follows:

- Align various stakeholders (e.g. utility, regulator, safety analysts, system engineers, etc.) on key plant operational principles and concepts.
- Support development of requirements, design specifications, and design details.
- Support development of procedures and operational documentation (e.g. training, operating, maintenance, etc.).
- Serve as high-level requirements input to specialty engineering disciplines, including systems engineering, I&C, human factors engineering (HFE), maintenance, etc.

2.3. OpsCon Development method

The early phases of this research highlighted the need for a formal framework within which the operational characteristics and associated human factors requirements for an AdvNPP could be analyzed and defined. Because of its emphasis on the relationships and dependencies between operational purposes, measures, functions, processes and systems in the plant, the Work Domain Analysis methodology (Vicente, 1999; Naikar, 2013) proved to be an exceptionally appropriate way to identify and describe all relevant attributes of the new plant and document it in such a way that it can be easily incorporated in the OpsCon. In this respect, the use of a well-defined framework and methodology like Work Domain Analysis is a significant departure from any previous approach to defining operational concepts, and regarded by the authors as the most significant contribution to the ability of current designers to produce a coherent and cogent OpsCon.

Results from the research (Hugo, 2015; Hugo and Oxstrand, 2015; Hugo and Farris, 2015) provide detailed descriptions of a modified work domain analysis (WDA) method that was developed specifically to serve as guidance for developers of AdvNPPs. It presents the WDA methodology as a system of broad principles and guiding rules from which specific methods or procedures may be derived to analyze or interpret multidimensional requirements and constraints within the scope of AdvNPP operations. The practical application of the derived methods forms a generic framework that can be broken down into subprocesses that may be combined or performed in different sequences. The reports also outline the strategy for undertaking a WDA during the design phase of a new AdvNPP and the methods to use in the development of the various phases of the analysis. This includes a description of the application of the basic principles in the preparation of operational concepts for a new AdvNPP.

3. Operational Characterization of Advanced Nuclear Power Plants

3.1. Functional and Safety Characteristics

There are similarities among AdvNPP designs, but also some important differences, especially between liquid metal-cooled reactors (LMRs) such as molten salt, sodium/potassium or lead/bismuth, and high-temperature gas-cooled reactors (HTGRs). This section provides a short example of operational concepts derived from information available on sodium-cooled reactors.

The Sodium Fast Reactor (SFR) design utilizes liquid sodium as the reactor coolant. The liquid sodium allows the reactor to function at near-atmospheric pressure, high power density, with a high fast flux profile. The sodium is contained in the reactor vessel in an inert atmosphere (oxygen-free), thus preventing corrosion and obviating the need for high-pressure boundaries. The sodium also allows for high temperature operation with outlet temperatures in the range of 500-550°C. This is well below the boiling point of sodium, 882°C. This high boiling point creates a reasonable margin of safety as it relates to temperature and provides for thermal inertia against overheating. Additionally, this allows the SFR to take advantage of a higher thermodynamic efficiency than that of water-cooled reactors.

The SFR design offers cost-competitiveness with other means of electricity production and a variety of market conditions, including highly competitive deregulated markets. Lower overall life-cycle cost offers advantage over other energy sources. Other design measures to reduce cost that can be adopted in the design are compact reactor structure, shortening of piping, reduction of loop number, integration of components, high levels of automation, use of remote surveillance and diagnostic technologies, and the potential reduction of staff numbers. All of these features could help to reduce operating and maintenance cost.

SFRs can make use of reprocessed fuel and plutonium fuel, allowing the industry to greatly extend the existing uranium-235 fuel source. Weapons-grade plutonium has over 93% Pu-239 and can be used, like reactor-grade plutonium, to fuel a SFR for electricity production. This means that an important function of a SFR could be to support nonproliferation of nuclear weapons grade fuel or disposal of surplus weapons grade material.

Other operational considerations include using an intermediate sodium system that creates a barrier between the radioactive sodium in the primary system and the chosen energy conversion system. This greatly reduces radiation areas in the facility and subsequent cost of shielding.

SFRs are characterized by fewer engineered safety features and more passive safety systems, including emergency shutdown cooling systems to remove decay heat by natural convection and flow of ambient air. In addition, the secondary sodium loop is typically designed such that a severe reaction between sodium and steam would not endanger the reactor.

Like all nuclear installations, AdvNPPs will emphasize safety and reduction of human error in every characteristic identified. The following items are particularly important for advanced SFRs:

- Improved protection and resilience against natural phenomena such as fire, earthquake, flood, tornadoes, which is achieved by siting of the individual reactor module within its own silo.
- Protection from unintended sodium reaction through structure location, fire control systems implementation, and leak detection.
- Improved containment design to ensure that a single boundary failure of a passive system will not allow the primary sodium coolant to come in contact with water or steam. The design of the containment is leak-tight and serves as a barrier against uncontrolled release to the environment.
- Shared structures for efficiency and economics, but designed such that sharing will not impact accident response.
- Separation of protection and control systems.
- Protection from reactivity control malfunctions (achieved through redundancy and diversity) and the ability to automatically initiate operation of protection systems, including the reactivity control system.
- Improved shutdown heat removal, employing passive and natural convection methods wherever possible.
- All protection systems are designed to be fail-safe.
- Fuel storage will employ criticality safe geometry to prevent inadvertent criticality.
- In the event of accidents, operators will have more time to respond due to passive design features.

Regarding the interaction of operators with advanced automation systems, we know that one of the concepts for limiting operator burden is that startup operations can be streamlined by having the operators approve a series of hold points for an otherwise automated started up. Examples of digital control include computer control of the diverse and redundant reactor protection systems such that a severe reaction between sodium and steam would not endanger the reactor.

It must be emphasized that the unique operating characteristics and capabilities of the SFR will require the creation of human-system interfaces that will maximize the operator's ability to monitor and control the plant, and respond to off-normal and emergency events.

3.2. Structural characteristics

An SFR example can again be used to explain how the structural characteristics of an AdvNPP would be treated in the OpsCon, but it should be noted that most of these characteristics would apply to other AdvNPPs as well.

The major structural components of the typical SFR include the containment with the reactor vessel, guard vessel and reactor core, the reactivity control and shutdown system, the primary and intermediate heat transport systems, the energy conversion system consisting of the steam generator, steam turbine and generator, the decay heat removal systems, and all the instrumentation and control and auxiliary systems.

The physical plant can further be characterized in terms of the plant siting and layout, the buildings (which include the control center), and specific domains or areas where work is performed during the various plant conditions.

Of particular importance from an operational point of view are the structure and location of the areas where work is performed by humans. The operation of an advanced NPP may be better understood if it were characterized in terms of the 'operational domains' where operating staff will interact with each other and with various devices. These work domains are best identified and described through a Work Domain Analysis as mentioned earlier. It is important to define the nature of the work domain and its boundaries right at the beginning of the project. It is especially important to understand the interdependent relationships between the work domain, human abilities and limitations, and operational requirements: human factors requirements will influence certain design decisions, but human performance as well as operational efficiency will ultimately be affected by the physical and functional characteristics of the environment or work space within which work is performed. For example, the main control room is a physically benign environment, but cognitively very demanding. In contrast, high radiation areas or restricted spaces are physically hazardous, but cognitively less demanding.

Ten work domains are typically identified for most plants. Minor differences are introduced by the specific kind of reactor (e.g., LMR or HTGR) and the physical layout required for different configurations of the energy conversion systems (e.g., single reactor with multiple turbine-generators, multiple reactors with individual turbine-generators, etc.). These domains are the control center with the main control room, local control stations throughout the plant, remote shutdown facility, fuel handling facilities, work control center, outage control center, technical support center, emergency operations facility, operations support center, waste and materials handling, and maintenance facilities (workshops)[2].

3.3. The Main Control Room

Like in all other nuclear plants, the Main Control Room (MCR) of the AdvNPP will still be the nerve center of the plant. It is the central part of the Control Center complex that includes the operational domains described above.

A central control room is necessary as part of a strategy to coordinate plant operations, to minimize duplication of equipment, and to optimize the capability of automation systems. Central control rooms for modern plants are also designed to enhance communication between units, enable better coordination of plant-wide operations and maintenance and more effective response to upsets.

Traditionally, the main control room is located somewhere on the 'nuclear island,' which normally consists of the containment, including reactor, steam generator and primary cooling circuits. Because the nuclear island is seismically qualified and provides backup systems like electrical supply and heating, and ventilation and air conditioning (HVAC), this was, and is typically the choice for the location of the control room. This meets one of the strictest criteria for control room habitability. As indicated before, AdvNPPs will make extensive use of passive safety designs like negative temperature coefficient of reactivity, natural circulation of coolant, or less need for active controls and fewer active protection systems like forced cooling circuits. This means that requirements for seismic qualified control systems and HSIs may change so that the MCR may not need to be on the nuclear island. It should also be determined if the availability and reliability of wireless technology and fiber optics may allow certain types of remote operation. Other important considerations would be if the need for rapid operator response to certain events would still force location of the control room to be near the reactor. There may be significant cost benefits for an MCR that does not have to be on the nuclear island. However, due to the current strict NRC regulations (see NUREG-0696: NRC, 1980) proving these new operational concepts is likely to be an important challenge for designers.[3]

As the MCR makes use of modern computer-based technologies, a general design philosophy is to minimize hard-wired operator interfaces to the extent practical. It is also a design goal to limit the equipment in the MCR to only those needed for the HSIs directly associated with plant monitoring and control. This will reduce clutter in the MCR and also make it possible for maintenance personnel to perform as much as possible of the maintenance tasks without interfering with MCR operations.

The use of digital control systems, higher levels of automation and predominantly digital displays introduces an important departure from control room designs of older NPPs. Older control rooms (typically in the U.S.) are characterized by a large number of analog instruments and controls mounted on control boards that require operators to walk from location to

[2] A detailed description of these work domains is beyond the scope of this paper

[3] This is an important issue for plant design and operation but it still requires extensive investigation that is beyond the scope of this paper.

location in the control room and perform monitoring and control functions standing. In contrast, the AdvNPP control room is characterized by sit-down workstations where operators can perform all monitoring and control functions from one location. This implies that the layout considerations of older control rooms may not apply to AdvNPPs. However, the conventional left-to-right arrangement of consoles and HSI sections for a single-unit control room would likely still follow the nuclear industry conventions. In spite of that, the arrangement for digital HSIs would be flexible and could easily be changed to suit specific requirements. Normally the navigation requirements for digital HSIs would be determined during task analysis, but even then it would be possible for operators to call up any display on any workstation.

3.4. Constraints

A work domain analysis will show that all power plants and their functional and structural characteristics are associated with specific constraints placed upon the actions of any human or system agent. The goals and functions of the work domain impose constraints on workers by specifying the purposes that the work system must fulfill, the values and priorities that the work system must satisfy, and the functions that the work system must perform. Therefore, the work system environment within which the task is conducted has the potential to significantly affect the task and ultimately the entire plant operation. 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, Naikar (2013) explains that within these constraints, workers have many options or possibilities for action in the work domain. This becomes the basis for the 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.

Our research results have demonstrated how the causal and intentional constraints defined by Naikar (2013) are exemplified in the structure, functions and dependencies of a complex sociotechnical system like a nuclear power plant. The constraints associated with the AdvNPP are influenced by the properties of the thermohydraulic process, materials and specific technologies. These are called *causal constraints* (defined by physical or natural laws). It is also influenced by regulations, company policy, market requirements, design conventions and many other intangible constraints. These are *intentional constraints*. The analysis of a system therefore depends upon the degree to which the behavior of the human and system agents within the system is influenced by the relationship and interaction between causal and intentional constraints.

It is important for the OpsCon to identify all constraints that may influence, or be influenced by, the design of structures, systems and components, and therefore operations and human performance.

There are seven categories of constraints that will have a major impact on plant design: environmental, human factors, organizational, regulatory, technical, economical, and political.[4]

3.5. Contextual activities and operational strategies

The constraints associated with what needs to be accomplished in the operation and the use of a system are modeled by an analysis of operational contexts within which various activities are performed. This analysis is called Contextual Activity Analysis and is performed as part of Work Domain Analysis. The operational contexts can be specific operational conditions within a defined scenario, such as upset conditions or transitions. The results of this analysis form an important part of the OpsCon since it identifies the correspondence between plant functions and operational conditions. In particular, the analysis provides the "course of action" basis for many subsequent decisions regarding operating practices and procedures and the associated control and monitoring artifacts.

Operational strategies described in the OpsCon will include responses to specific operational conditions, such as normal transitions between modes, response to anticipated operational occurrences, transients, and severe accident conditions. However, operational strategies may also be much more extensive and include strategies and plans for staffing, managing workload, and automation and human-system interaction.

The following table shows a practical way of analyzing and documenting contextual activities. The example is based upon operational (procedural) responses to typical upset events in a sodium fast reactor (Figure 1):

SFR Operational Concepts
Contextual Activities: Upset Events (End State conditions)

Functions \ Situations	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 1: Simplified Example of a Contextual Activities Template

[4] Space does not allow a full description of these categories - details are available in the referenced literature.

3.6. Operating Experience for AdvNPPs

Operating experience with AdvNPPs is obviously limited, since to date only a very limited number of new designs have been commissioned. Significant operating experience does exist for some reactors that are the predecessors of new plant designs currently underway. Most notable among these are the sodium fast reactor designs (SFRs). SFR proof-of-concept, that is, the viability of a sodium cooled fast reactor, with its non-aqueous reprocessing and fuel recycling technology, reactor safety, fast breeder (fuel production), fuel performance, fuel recycling and reprocessing, waste reduction, and electric generation, were achieved with the Experimental Breeder Reactor II (EBR-II) in the U.S. and BN-600 in Russia. In addition, irradiation and fuel testing for future fast reactors were proven in three U.S. test reactors: the Fast Flux Test Facility (FFTF), EBR-II, and the Clinch River Breeder Reactor Project (CRBRP).

Significant results were also achieved with operational safety tests at EBR-II where fuel and the plant were subjected to off-normal conditions such as operation of fuel with breached cladding and ultimately, anticipated transients without operator action or an automatic reactor scram.

As indicated before, an important function of a SFR could be to support nonproliferation of nuclear weapons grade fuel or disposal of surplus weapons grade material.

Predecessor plants like EBR-II also demonstrated decommissioning approaches, which yielded important information about the technology of sodium coolant processing for waste disposal.

Limited operating experience is available for high-temperature gas-cooled reactors, the most notable among these being the AVR (Arbeitsgemeinschaft Versuchsreaktor) and the THTR (Thorium High-temperature Reactor) in Germany, the Fort St Vrain and Peach Bottom plants in the U.S., the Dragon reactor in England, and the HTR-10 in China. Of these, only HTR-10 is still in operation. Its successor, the HTR-PM, is under construction, with commercial operation scheduled for 2016.

3.7. Typical operational strategies

Constraints and contextual activities form the basis of the definition of key operational strategies. Definition of operational strategies is a way to model one or more pathways (or strategies) from one system state to another. The strategies adopted under a particular situation may vary depending on the constraints within the given situation. The strategy applied will be determined by a number of variables, such as missions, experience, knowledge, training, workload, available tools, and whether it is a human or automated agent that performs the activity or some combination (shared automation) of both agents.

These identified strategies will result in decisions about the development of an operating scheme to handle the specific conditions and the transitions between them. Many of the operational conditions of AdvNPPs may not exist in LWRs, such as reduced power operations, novel refueling methods, on-line maintenance, unplanned shutdowns for sodium or argon leaks, or load following systems that automatically adjust power output. These modes and states will inevitably create complexities and require innovative treatments in the design and use of I&C systems, as well as appropriate HSIs. In order to guide decisions about automation and function allocation, it will be beneficial to define plant operation schemes in terms of a collection of discrete-event systems, that is, systems that perform discrete functions in uniquely definable operational modes and states.

All operational strategies will involve human involvement to a greater or lesser degree. This implies that the functions required for a particular strategy will be shared between humans and systems, as determined during the formal function allocation and task analysis phases of a project. The resulting strategies will therefore include well-defined definitions of the level of automation and the level of human involvement and can be classified as follows:

- Strategies for handling normal operational missions and transition between modes. These strategies will be determined by the capability of the automation system.
- Strategies for responding to anticipated operational occurrences. These strategies will define the conditions and criteria for sharing functions between humans and the automation system.
- Strategies for optimizing human performance. These strategies will define criteria for operator workload and situation awareness in the control room and how to reallocate functions when the operational demand exceeds human capacity.

Operational strategies can be described verbally, but often, especially during the early stages of developing the OpsCon, a graphical representation is useful to identify the alternative responses to an event and the information flows associated with each. Following is a simple example of possible responses to a water-to-sodium leak, a rare event, but one of the most significant events in an SFR that require rapid response.

This example shows three possible strategies that will prevent or mitigate the event (**Error! Reference source not found.**):

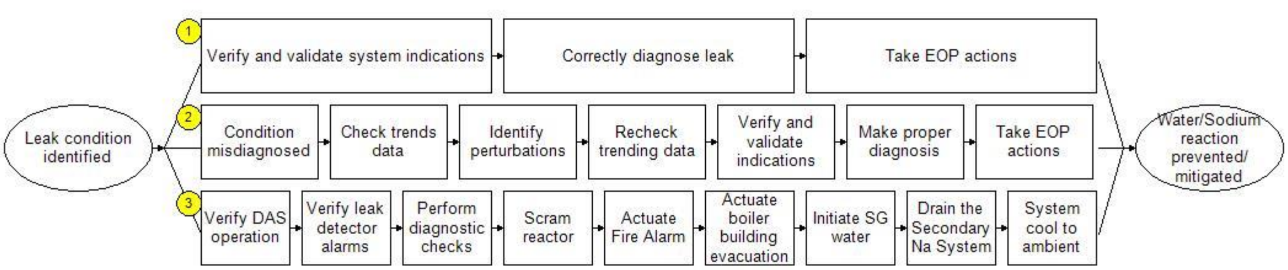

Figure 2: Strategies Analysis Example: Water-to-sodium Leak

4. Basic Operational Concept

4.1. Automation Concepts

As indicated before, AdvNPP operations are expected to be automated to a far greater extent than is currently possible in older plants, due to the state of technology. Recent experience during the modernization of control rooms (Boring and Joe, 2014) has shown that high levels of automation are possible, but that special attention must be paid to human factors and particularly operator response required to possible failure modes and consequential safety risks. Automated processes must have appropriate hold points where operator authorization is necessary to continue to the next step. Task analysis must ensure that operator actions during execution of Emergency Operating Procedures are supported by the design of the MCR and the HSIs.

A modern distributed control system (DCS) is designed to manage the safe and effective operation of a complex system like an advanced nuclear power plant. For the purpose of the automation system, the plant can be defined in terms of a collection of discrete-event systems, that is, systems that perform discrete functions in uniquely definable operational modes and states.

It is anticipated that the following typical operational sequences will be automated:

- Starting up and shutting down the Nuclear Steam Supply System (NSSS) (that is, reactor, primary and secondary coolant pumps, heat exchangers, steam generators, and associated piping needed to drive the turbine generator unit);
- Rolling, accelerating to speed, and synchronizing a turbine-generator;
- Transfer of primary system coolant to the coolant inventory tank;
- Reactor decay heat removal;
- Heat transfer from the steam generator to a passive decay heat removal system, etc.

These automated operational sequences will include predetermined holdpoints for operator verification of conditions and permissives to proceed to the next portion of the sequence and holdpoint. Supporting balance-of-plant and auxiliary and service system control are also likely to be automated. Where necessary, these systems will be put into service locally by field operators responsible for local control stations.

Automated monitoring and protective actions will be provided for systems and components to prevent operation outside defined operating envelopes. Where applicable, auto-start of redundant components will also be included. Process control of the operation of the plant in the normal power range will be completely automated, only requiring monitoring by the control room operators.

4.2. Operational Modes

NPPs have multiple operational states, most often referred to as “modes” or “modes of operation” that are characterized by conditions such as reactor power, temperature and condition of the reactor vessel. Different activities are allowed in different modes, for example, power increase or decrease, fuel handling, maintenance tasks, etc. The modes vary depending on the plant type. For example, there are important differences between sodium cooled reactors, high-temperature gas-cooled reactors, and LWRs. They all have unique modes that are driven by Technical Specifications and plant design. Unique systems, such as fuel handling systems, heat transport systems, and passive safety systems, impact the modes of operations and the activities that can be performed during a specified mode.

The typical operational states for an SFR are:

- Normal Power Operations
- Plant Startup (Heatup) to Hot Standby
- Reactor Shutdown
- In-vessel Fuel Handling and Refueling (unrestricted access to reactor vessel)
- Restricted Fuel Handling (Storage Basket to/from Fuel Handling System)

The OpsCon must provide a clear description of the different operational modes and how plant operations, including operating procedures and operator response to transients, are affected by them.

4.3. Operating Procedures

Like any other NPP, AdvNPPs must be operated in accordance with regulatory-mandated procedures that reflect the plant’s design basis. Clearly defined requirements for use of, and adherence to procedures, must exist and operators must be committed to perform procedures in accordance with the licensing basis. Operating procedures must be written to provide specific direction for the operation of plant systems and equipment during normal, postulated abnormal and emergency conditions, and surveillance and testing. Procedures will also exist for anticipated operations, evolutions, tests and alarm response. The adherence to procedures will ensure that operational activities are performed safely, consistently and correctly. These procedures must provide appropriate direction so that plants are operated within their design basis and support safe operation of the plant. To minimize the probability of operator error, measures must be implemented to ensure consistency in procedure format, content and wording. This will also help to ensure a uniformly high standard of operator performance.

5. Key Human Factors Considerations

5.1. Human-Automation Collaboration Concepts

The previous discussion explained that many AdvNPP operations would be automated to exploit the capabilities of advanced technologies, as well as human intelligence, but with due consideration of possible failure modes and consequential safety risks. Emphasis in AdvNPP MCRs in particular would be on minimizing operator workload and reducing error, while optimizing safety and optimizing situation awareness. This is likely to cause some changes in the roles of operators, for example during normal operations when cognitive demand is low, operators are likely to perform more higher level tasks, such as production planning, and system optimization.

Note that without evidence to the contrary, the need to maintain situation awareness and vigilance during automated process may challenge current assumptions that higher levels of automation will reduce workload in AdvNPP control rooms, thus theoretically allowing operators to handle more than one reactor unit at a time. This implies the need for special attention to human-automation collaboration; new approaches are needed to ensure that a technical basis exists for human-system function allocation and that personnel and automation are integrated to maximize productive, safe operation of the AdvNPP (Hugo and Oxstrand, 2014).

Automated system design must consider the need to reduce complexity and workload, but also to keep the operator in the loop and to maintain situation awareness. Automated processes will have appropriate hold points where operator authorization is necessary to continue to the next step. High levels of automation and long fuel cycles are expected to reduce complexity, leading to simpler procedures, less need for inspections and surveillance. As indicated earlier, ultimately, AdvNPPs may require smaller crews, but emphasis in AdvNPP MCRs would still be on minimizing operator workload and reducing error, while optimizing safety and the ability to maintain situation awareness.

Evidence from other industries suggests that advanced automation and new operational concepts may place significant demands on operator attention and activities. This implies that special attention must be paid to identifying opportunities to maximize operator efficiency and effectiveness with advanced digital technologies and computer-based procedures. This will include validating the use of technologies like mobile devices for operator situational awareness and limited plant control capabilities for AdvNPP support systems like plant auxiliary systems and for remote panel operations. Operational interfaces must be provided between the operator and the plant for the purpose of control and monitoring and also to provide the ability to shut down specific components, major subsystems, and if required, the entire plant. Provision must be made for control under both normal and accident conditions. This may apply especially to operations that may benefit from remote operator assistance in high activity periods like outages and accident/security events. This kind of human-automation collaboration will potentially allow offsite operators to remotely perform low safety-significant operational activities, freeing the control room operators to concentrate on safety functions.

In addition, advanced automation will affect control room protocols, communication, staffing, operator proximity, and control room management. These effects have not been studied in detail yet and designers should be aware of the burden of proof placed upon them by regulators.

5.2. Operator roles and responsibilities

Operator roles and responsibilities are derived from the generic nuclear power plant knowledge and abilities (K&As) as described in NUREG-1122 (NRC, 2007). Note: this NUREG refers to Pressurized Water Reactor operator knowledge and abilities, but may be considered generally applicable to LMR designs and other AdvNPP systems and operations. The four categories of generic K&As are:

- Conduct of Operations - daily operation of the facility, including routine administrative tasks, shift turnover or temporary modification procedures.
- Equipment Control - activities associated with the management and control of plant systems and equipment, including fuel handling, maintenance and temporary modifications of systems.
- Radiation Control - activities associated with handling of radiation hazards and protection (personnel, public and environment). This includes handling of significant radiation hazards or radiation work permits.
- Emergency Procedures and Planning - activities required to follow the emergency plan and procedures.

The OpsCon must describe these categories of K&As for each of four operational conditions:

- Normal Operations - this includes process control functions, monitoring functions, preventive and corrective functions, response to failures, faults and transients, diagnostic functions, mitigating and recovery functions, and remote shutdown functions.
- Fuel handling functions, during operations and during maintenance or refueling.
- Maintenance functions, including remote surveillance, diagnostics, tests, and support of maintenance staff.
- Routine control room functions, including all routine control and monitoring functions, administrative tasks, and communication functions.

5.3. Human-System Interface Concepts

Operational interfaces must be provided between the operator and the plant for the purpose of control and monitoring and also to provide the ability to shut down specific components, major subsystems, and if required, the entire plant. Provision must be made for control under both normal and accident conditions.

We can expect improved reliability, resilience, adaptability and information accessibility offered by the current HSI technology convergence and functional synergy. This could be one of the strongest driving forces in design decisions for AdvNPP control rooms and HSIs. The ability of these technologies to deliver text, audio, and video material over the same wired, wireless, or fiber-optic connections is rapidly making the conventional HSI devices of today's power plants obsolete. We can expect the operator of the future to be surrounded, inside as well as outside the control room, by a multi-level, convergent, media-rich world where all modes of computation, information presentation and communication are available to adapt to normal as well as emergency operating conditions.

Most I&C engineers assume implicitly that future plants will be highly automated. If we accept that technology advances (for example large-scale integration of networked intelligent sensors and control systems) will force higher levels of automation, then we can safely assume that the role and function of the operator will ultimately change. We can safely assume that operators will perform more supervisory functions and less hands-on control tasks. System engineers would be wise to plan ahead to avoid technology dictating this change. They should work more closely with human factors engineers than ever before to ensure that automation decisions are not based solely on the capability of advanced I&C technologies, but on a productive collaboration between humans and systems. In practice this means that functions should be automated only if it will improve reliability, efficiency and safety without compromising the operator's situation awareness and ability to intervene when necessary. This ability to intervene should be designed into the system in such a way that it will exploit those complex phenomena and capabilities that still make humans superior to machines: coping with uncertainty and conflicting indications, applying rules of thumb, rapid visual recognition of objects, or identifying and matching complex visual or auditory patterns and translating it into action. In contrast, operators should not be expected to perform complex mathematical calculations, to perform functions that humans perform poorly or with increased workload, or tasks that are too expensive or dangerous for human operators (Hugo, Gertman, & Tawfik, 2013).

5.4. Staffing Concepts

In order to match the system design and operational characteristics of the plant to the correct staffing levels, a formal process of analysis, design and verification of the required human capacity for plant operation must be followed. This process ensures that the required skills, knowledge and abilities are identified for all personnel posts and all operational conditions. Human performance requirements must be evaluated to determine the basic requirements for the number, qualifications and other personal attributes of operating staff. Recommendations to plant training personnel should include an assessment of nominal staffing and qualifications requirements, with consideration of applicable utility and regulatory requirements.

Crew composition will be determined partly by regulatory requirements and partly by the results of a task analysis. Although a high degree of automation may reduce the number of operators required in the control room, new missions beyond electricity production may actually increase the number of staff. This must be considered carefully in the function allocation, task analysis, and control room and HSI design. Specific human factors issues that must be considered in staffing design include regulatory requirements, cultural and social factors, task demands, communication requirements, organization structure, physical performance requirements, knowledge and skills requirements, training requirements, and operational conditions.

Minimum requirements for plant and control room shift staffing under different operational conditions are defined in 10 CFR 50.54(m)(i). However, these requirements have been defined for conventional light water reactors. Again, higher levels of automation and accompanying reduced need for local operations and inspection may lead to smaller operational crews needed to safely and reliably operate the plant. However, although AdvNPP operational practices may be similar to existing practices within the nuclear industry, reduced staffing numbers can only be confirmed through the Task Analysis process and Training Simulator studies. Such analyses, in conjunction with consideration of the criteria indicated above, may identify a shift staffing level that differs from that described above. In the U.S. such deviation from regulatory requirements must be justified in a request for exemption, as provided in NUREG-1791 (NRC, 2005).

6. Conclusion

This project highlighted most of the known operational conditions and characteristics that would be included in new non-light water reactor plants. However, OpsCon documents for such plants will focus primarily on the structural and functional aspects of work conducted in the Main Control Room and work domains associated most directly with the control room. Other considerations that were identified included the need for an overview in the OpsCon of the plant's main systems required for normal operations (details of these would be contained in system design documents). Information on the purpose and functions of such systems, in combination with operating experience and information on predecessor designs will be vital for all engineering disciplines. Designers also need early descriptions of the operational modes and states of the plant, basic considerations for staffing, operating requirements for facilities such as the control rooms, remote shutdown facility, HSIs, local control stations, communication equipment, and principles that will govern the monitoring, interacting, and overriding of automatic systems.

This paper provides an example of how the qualitative and quantitative characteristics of a new design, as well as its limitations and unique advantages, could be described as part of the input requirements for a new engineering project. These characteristics may be generic and technology-independent during the early or conceptual stages of the design, and become more technology-specific as the design matures. 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, emergency, and off-normal operating procedures for conditions not familiar to operators of conventional NPPs.

Finally, the project clearly suggested that a key element of an operational concept would be the formation of an interdisciplinary engineering team with a range of expertise that covers all important aspects of the system. The team members should be involved in the analysis and design of all plant operational characteristics and requirements for all operational conditions. Of particular importance during the basic design stages is the identification of undesirable operational impacts, conflicts with user assumptions, and other constraints. Such limitations may result from decisions taken during development or doctrinal inputs to the development activities. It is therefore vital that the OCD should be reviewed and updated periodically to ensure that it includes any adverse impacts on the environment, including the social, geo-political and economic environment. It should also anticipate the effect of those emergent characteristics that will arise from introduction and use of the system in the environment.

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