INL/EXT-14-32939
SMR/ICHMI/INL/TR-2014/04
Revision 0

A Framework for Human Performance Criteria for Advanced Reactor Operational Concepts

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EXECUTIVE SUMMARY

This report presents research results from the review and investigation of open source material supporting the development of Operational Concepts for Advanced Reactors, including guidance for Operational Concepts and relevant human performance criteria models and frameworks.

Advanced reactors will use advanced digital instrumentation and control systems, optimize use of automation and passive components, and integrate new design configurations. When compared with current reactor designs, the emerging designs will have different allocation of functions, new operator roles and responsibilities, as well as different requirements for operator knowledge, skills, and abilities, all of which will lead to new operational concepts. Many of these emergent designs are first of a kind (FOAK) and will require up-to-date human factors techniques such as work domain analysis, cognitive task analysis and human performance modeling. Many emerging concepts are speculative and will remain so until empirical research data become available to support the development of sound technical bases, for example, expected shifts in 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. This research has extrapolated the effect of these concepts from existing sources including other domains that have experienced a shift toward automation.

Existing human factors standards and regulatory guidance such as NUREG-0711 [10] and NUREG-0700 [9] do not completely address the role of automation or changes that are associated with FOAK. The standards and guidance allow for the integration of operating experience in the design and review process, however, save for the experience with sodium reactors gained at EBR-II, there is little operating experience to include in the genesis of a framework for advanced operational concepts.

The objective of this research is to establish the technical basis for human performance criteria frameworks, models, and guidance for operational concepts for advanced reactor designs. This work recognizes and accounts for predicted non-traditional operational concepts, staffing requirements, level of automation and changes in the allocation of functions to human and system agents.

This report includes the following important research areas: (1) operating principles for advanced reactors, (2) human performance issues and the requirements for human performance based upon previous work domain analysis and current regulatory requirements, and (4) consideration for the development of general human performance criteria.

To inform the required analysis, this report draws from available information on two advanced reactor designs, namely sodium fast reactors (SFRs) and high temperature gas reactors (HTGRs) as a starting point from which to build a framework.

The major findings and key observations to date are that some operating experience from the Experimental Breeder Reactor-II (EBR-II), a best-case predecessor design, helps to inform operational concepts for the baseline designs, Sodium Fast Reactors (SFR) and High-Temperature Gas-cooled Reactors (HGTRs). These are not mainstream designs and operating experience with digital control of these systems and other technology advancements are not available, which makes the development of human performance criteria and operational concepts all the more challenging.

This report summarizes the progress to date on work to determine the theoretical and operational foundations for the development of a framework and model for human performance criteria that will influence the development of future Operational Concepts. The report also highlights issues associated with advanced reactor design and clarifies and codifies the aspects of technology and operating scenarios that were identified.

Reader’s note: It is assumed that readers are familiar with previous milestone reports, hence some important background information that would have added substantially to the bulk of this report has been omitted. References to previous reports are included where relevant.

Acknowledgements

The success of this project depends upon the experience, knowledge and insights of several highly respected individuals. We are especially indebted to the late Dr Julius "J" Persensky whose extensive knowledge and experience in Human Factors, nuclear power, and the regulatory environment was unsurpassed, and to John Forester who during his brief tenure with INL was a welcome contributor. We are also indebted to members of INL who are experts in either HTGR or EBR-II with whom we conferred during the writing of this report.

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ACRONYMS

AC	Alternating Current
AdvNPP	Advanced Nuclear Power Plants
AFR	Advanced Fast Reactor
AOO	Anticipated Operating Occurrence
ART	Advanced Reactor Technologies (program)
ATWS	Anticipated Transient Without Scram
CFR	Code of Federal Regulations (U.S.)
EBR-II	Experimental Breeder Reactor II
EOF	Emergency Operating Facility
EOP	Emergency Operating Procedure
FOAK	First-of-a-kind
HFE	Human Factors Engineering
HSI	Human-System Interface
HUPESS	Human Performance Process Evaluation Support System
HVAC	Heating, Ventilation and Air-Conditioning
HTGR	High-Temperature Gas-Cooled Reactor
IAEA	International Atomic Energy Agency
I&C	Instrumentation and Control
INPO	Institute of Nuclear Plant Operations
iPWR	Integral Pressurized Water Reactors
LOCA	Loss of Coolant Accident
LMR	Liquid-Metal Reactor
MCR	Main Control Room
Na	Sodium (chemical symbol)
NOP	Normal Operating Procedure
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission (U.S.)
OCC	Outage Control Center
LWR	Light Water Reactor
PCU	Power Conversion Unit
PPE	Personal Protective Equipment
PSF	Performance Shaping Factor
RSF	Remote Shutdown Facility
SAMG	Severe Accident Management Guidelines
SFR	Sodium Fast Reactor
SMR	Small Modular Reactor
TSC	Technical Support Center
WANO	World Association of Nuclear Operators
WDA	Work domain analysis

Framework for Human Performance Criteria for Advanced Reactor Operational Concepts

1 Introduction

U.S. Department of Energy (DOE) and the nuclear power industry are partners in America's energy future and are exploring alternatives to meet the future United States energy demands. As part of this mission, they provide planning for the energy demands of current and future generations and as part of that ongoing process are examining the social, political, and economic feasibility of Advanced Reactor Designs. These next generation designs are by definition evolutionary improvements to today's reactor fleet and with these improvements and refinements in technology come changes in the way future advanced nuclear power plants (AdvNPPs) will be operated. As we discuss in this report, these differences are not only in terms of level of automation, efficiency, plant configuration, use of passive systems, fuels, maintenance, the degree to which they are tolerant or resistant to operational upset; they can fundamentally change the workload, roles, and responsibilities of the operator and crew. For example, some future designs may consider improved capability for load-following or have the capability to provide excess heat for industrial applications.

The impact on operations and requirements for operators to understand the duties of and interact with grid operators, other grid suppliers and industrial end users is not well characterized and this has been the focus of the Operational Concepts project for the past three years. The DOE has performed reviews in the past considering near term advanced light water reactor (LWR) designs. This report is focused upon longer-term plant designs using advanced technologies and coolants other than water that are likely to become available after 2020. When the become operational, these plants will still rely on human interaction for supervision, system management, and operational decisions. More importantly, operators will still be regarded as the last line of defense should failure of the automation system prevent automatic plant protective measures from actuating. Regardless of the specific reactor design, all AdvNPP designs will employ advanced digital instrumentation, controls, and human-system interfaces (HSIs), which consist of technology that is significantly more advanced than current analog systems in the LWR fleet. Although it has been argued that the role of the human will be primarily supervisory in nature, there are a number of concerns about the impact of new and advanced technologies on human performance in advanced plants.

A plant's operational concept is generally understood to be a high-level description of the plant, its systems and their functions, and how operating personnel will interact with the system to achieve the plant goals. AdvNPPs will require new operational concepts to address the unique operating scenarios associated with new coolants, new materials, multiple product streams, and advanced automation. The overall purpose of the Advanced Reactor Operational Concepts project is to investigate the impact of these advances on human performance, and, conversely, the impact of human abilities and limitations on the safe operational design of AdvNPPs (Hugo et al. 2014 [5])). A crucial aspect of any operational concept therefore involves incorporating human performance criteria in the overall engineering design. This report serves to document research performed to date on human performance criteria as it pertains to AdvNPP Operational Concepts, particularly in terms of the specific human factors challenges related to non-traditional concepts of operations associated with advanced reactor design.

1.1 Goals, Objectives, and Scope

The DOE Advanced Reactor Technologies (ART) program includes consideration of designs such as advanced sodium fast reactors (SFRs), Advanced Fast Reactors (AFRs), liquid-metal reactors (LMRs) and high-temperature gas-cooled reactors (HTGRs). The current engineering work for these advanced reactors aims to demonstrate the capability to produce electricity and process heat for industrial use. The human factors engineering (HFE) work necessary for these new designs is challenging because operating experience with these reactors is limited. Existing HFE and systems engineering design standards are also not current in terms of human interaction principles for automated systems. In addition, there is a lack of a good technical basis for identifying human performance criteria, measurement techniques and methods, and an associated framework to support engineering design.

The primary objective of the present phase of the project is to continue the analysis of the characteristics and attributes of Operational Concepts for advanced reactors, how the operation of these plants should manifest in terms of human performance criteria, and, conversely, how the role and function of humans in the plant might be affected by advanced technologies as part of the need to ensure effective, efficient and safe operations.

These objectives are pursued in this project through the following activities and tasks:

1. **Identify and describe advanced reactor operational conditions**. This includes conducting a Reference Work Domain Analysis (WDA) for a selected SFR design. This work was started in 2012 with the preliminary WDA for EBR-II and will continue in FY2015 with an advanced SFR design. This analysis will include an overview of the basic operational concepts of known SFR designs and analysis of how these proposed concepts (for example, staffing design and advanced HSIs) would contribute to future engineering and operational design. Any available information on HGTR designs and operating experience will also be considered.
2. **Identify human performance criteria.** This includes definitions and criteria for human performance for AdvNPPs and their contribution to the development of Operational Concepts. In order to provide a human performance perspective to Operational Concepts, a number of other considerations must be addressed. These include the level and qualifications of staffing proposed for normal and disturbance conditions, different approaches to automation, detailed operating scenarios, expected team dynamics, and proposed HSIs that will be used. The function allocation and automation aspects have already been addressed in a previous milestone report and also forms part of the associated Human-Automation Collaboration project.
3. **Identify human performance measures.** The identification of human performance measures will adopt the Human Performance Process Evaluation Support System (HUPESS) model to develop measures of personnel task performance and teamwork. This includes post-test subjective measures to evaluate cognitive workload and situational awareness and the evaluation of the impact of anthropometric and physiological factors on plant performance and personnel task performance. (Ha and Seong, 2007 [1], [2]).
4. **Develop a preliminary human performance framework for advanced reactors design.** This includes the identification and analysis of the performance demands and associated elements for characterizing human performance in complex socio-technical systems.

This report summarizes progress to date on reviews of literature on human performance issues, performance criteria, human performance measures, and the development of an overarching framework to aid the HFE and engineering design process. In the context of applicability to AdvNPPs, this work establishes HFE design principles and identifies design criteria as input to the design life cycle for AdvNPP design and operation.

Note that Operational Concepts are mentioned throughout this report, but a full discussion of this topic is outside the scope since it has already been addressed in previous milestone reports (see Hugo et al. 2013 [6]).

1.2 Assumptions and Constraints

As explained in previous reports, at present there are no operating AdvNPPs in the U.S. to provide concrete design information or operating experience. The only predecessor plant that could provide useful information was the Experimental Breeder Reactor-II (EBR-II). Other pertinent information was obtained from publicly available documentation on the GE-Hitachi PRISM, the Toshiba 4S and the Argonne National Laboratory AFR-100 designs.

2 Overview of Advanced Reactor Characteristics

To establish context for the discussion on human performance criteria, it is necessary to reiterate and summarize the characteristics of advanced reactors described in previous reports.

The following table has been compiled from various sources to highlight characteristics that are likely to have an impact on operational concepts as well as human performance (see references [4], [5] and [6]).

Table 1: Operational and Human Factors impact of AdvNPP design concepts

Typical AdvNPP systems characteristics	Operational and Human Factors Impact
No active safety injection system required. Core cooling is maintained using passive systems.	No operator intervention required for safety injection. No need for manual or mental calculations. Fewer emergency operating procedures (EOPs) required. Ability to remove core heat leads to significant safety enhancement.
No safety-related pumps for accident mitigation. No need for sumps and protection of their suction supply.	No operator action required for coolant pump failures or leaks. No need for leak calculations.
Passive design does not require emergency alternating current (AC) power to maintain core cooling. Core heat removed by heat transfer through vessel.	No operator action required for loss of AC power, except to monitor condition.
Automatic reactor shutdown system. Reduced need for manual scram.	Even if automatic system fails, reactor will automatically shut down due to negative power coefficient of reactivity.
No active containment heat removal system or spray systems required because of passive heat rejection out of containment.	No operator action required to activate containment systems to reduce steam pressure or to remove radioiodine from containment.
Simpler and/or passive safety systems require less testing and are not as prone to inadvertent initiation.	No or very few operator actions required to activate safety systems or to monitor cooling systems. Simpler operation, less prone to inadvertent operator actuation or other human error.
Ability to remove core heat without an emergency feedwater system.	No operator actions related to feedwater or emergency cooling water supply. Removing core heat without an emergency feedwater system is a significant safety enhancement and reduction of operator workload.
Smaller reactor designs may allow load-following.	Load-following entails more transitions to enable the plant to increase or decrease both reactor- and turbine-power in response to the external demand. Also, multi-modular plants may require startup and shutdown of individual modules to meet large changes in load demand. Load-following will require more actions from operators, and increased monitoring of the response of the automatic systems. Hence, there is more opportunity for equipment failures and operator errors. This may have to be mitigated through resilient designs and automation.
Integral designs eliminate the need for seals.	Reduced need for inspection and maintenance, leading to potential reduced human resource requirements.
Variable modular plant configurations: AdvNPP designs may be configured with different combinations of reactors and power conversion units (PCU), for example:	Different configurations will have different effects on operations and human factors. Also, the different plant modes and states for these configurations will require non-traditional definitions of operator and maintainer

Typical AdvNPP systems characteristics	Operational and Human Factors Impact
• multi-reactor, single PCU • single reactor, multi-PCU • single reactor, single PCU, etc. In addition, different combinations of reactors and process heat plants are possible.	roles and functions.
AdvNPP designs are passive and reject heat by conduction and convection. Heat rejection to an external water heat sink is not required.	Fewer operating procedures required for normal operations. However, displays are required to keep operator informed.
The plant design minimizes or eliminates the need for safety-related control room cooling. Safety-related control room HVAC system and associated closed water cooling systems can be eliminated.	No operator action required for emergency control room ventilation.
Large heat capacity inherent in AdvNPP design. Heat-up events would tend to be slow and allow for time to unblock air flow pathways, associated with convection cooling in liquid metal-cooled Reactor (LMR) designs.	Reduced need for operator intervention during start-up.
Automated grid protection systems: AdvNPPs are expected to employ technologies that provide protection from grid disturbances through automated functions like turbo-generator protection, etc.	Automated protection systems will mean significantly different operating scenarios and anticipated operational occurrences (AOOs) for AdvNPPs. As with several other AdvNPP technology innovations, this will reduce the need for operator intervention and thus potentially reduced procedural complexity and lower workload.
Coolants: AdvNPP coolants include molten salt, lead-bismuth, or gases like helium, nitrogen or carbon dioxide. For some molten salt reactor designs, the fuel is dissolved in the molten fluoride salt coolant as uranium tetrafluoride. The coolant makeup systems of AdvNPP differ significant from those of LWRs. For example, HTGRs are characterized by a predictable helium leakage of ~0.01% per day; a helium makeup system is required that will replenish coolant to maintain pressure. In contrast, LWRs require a primary coolant makeup system to handle losses during a loss of coolant accident (LOCA). Similarly, different systems are required to handle coolant chemistry and makeup systems for LMR designs.	Sodium leakage would be a concern, requiring new defense-in-depth measures and new EOPs. Of particular importance is the use of argon to cover the sodium to prevent contact with air. This remains a key safety concern for sodium-cooled reactors because the argon purging processes and monitoring associated with maintaining the argon cover imposes an additional operator workload that may be justification for advanced automated systems. Both liquid metal and gas-cooled designs pose serious environmental and safety hazards for field operations. For example, for HTGRs the high temperatures and leakage of helium will prevent field operators from accessing many areas inside the plant during operations. Many surfaces of pipes, ducts and components will be too hot to work on and will require long cool-down periods before maintenance work can be done. Liquid sodium and molten salt leakages are equally hazardous and will require special vigilance in areas where human contact might occur. These environmental constraints are very likely to lead to design requirements that will ensure operator safety as well as environmental and investment protection. Results from this research will help to provide the technical bases for non-traditional function allocations, and decisions for on-line monitoring, diagnostics, and automation. This will also lead to unconventional

Typical AdvNPP systems characteristics	Operational and Human Factors Impact
	measures, such as advanced visual plant monitoring displays and communication systems, to keep operators in the control room informed of conditions inside the plant.
Operating pressures and temperatures: In contrast to PWRs, most AdvNPPs will operate at low or moderate pressures. LMR reactors function much like a PWR in terms of efficiency, and do not require much high-pressure containment, as the liquid metal does not need to be kept at high pressure, even at very high temperatures. HTGRs operate at high temperatures (typically between 850°C and 950°C) and low pressure within the pressure boundary (~58 psi to ~116 psi, or 400 kPa to 800 kPa).	As in older NPP designs, operating temperatures and pressures are two performance parameters that will require constant monitoring and control also in AdvNPPs. However, it is expected that the passive safety systems of AdvNPP will reduce the need for operator action for nuclear safety purposes. Several designers are proposing no reactor intervention for up to three days in the event of a loss of coolant accident. This is because inherent properties of the reactor design regulate nuclear power so no electrical power, coolant flow or any other active systems or operator actions are required to limit nuclear power levels and fuel temperatures under any condition. Instead, it is more likely that advanced automation systems will enable the operator to optimize the power conversion efficiency of the reactor.
Fuel: Small size (50 to 150MWe) modular-type sodium-cooled reactors are expected to employ uranium-plutonium-minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in facilities integrated with the reactor. Thorium based fuel offers an alternative to fast sodium reactor fuel or current fuel for LWRs. The thorium can act as a breeder, however; it needs a moderate, not fast neutron environment, so some technical challenges still exist for thorium designs.	Operators need to avoid boiling instabilities where sodium boiling can occur as a result of condensation and evaporation in the sodium upper plenum.
Core Design: Sodium cooled reactors are highly sensitive to sodium void reactivity excursions that may induce positive reactivity feedback in some core zones (especially in case of large cores).	LMR AdvNPPs have a much smaller core cross-section and the potential for sodium void and the need for rapid automation or operator intervention is therefore greatly reduced. Additionally, increased visualization for operators regarding core status will further lessen the risk associated with this failure mode.
Non-proliferation: LMRs including sodium reactors close the fuel cycle. Also, a closed fuel cycle results in less radioactive waste management issues.	Different fuel handling regimes may introduce unfamiliar tasks and operating procedures. This may have an impact on training and operator licensing requirements.
Shutdown requirements: Most AdvNPPs have a negative temperature coefficient of reactivity and lower shutdown margin. This helps to avoid power excursions, means less need for active safety systems, and enables the reactor to shut down automatically in the unlikely event of a LOCA and resulting rise in temperature.	No safety-related operator intervention required for reactivity incidents.
Siting: AdvNPPs can provide power for applications where large plants are not needed or sites that lack the infrastructure to support a large unit. This would	• Expected AdvNPP siting is such that many systems will be located underground. While this may produce improved safeguards for non-

Typical AdvNPP systems characteristics	Operational and Human Factors Impact
include smaller electrical markets, isolated areas, smaller grids, sites with limited water and acreage, or unique industrial applications.	proliferation purposes and provide improved protection from external threats, it may make access and egress problematic. • The siting of many AdvNPP systems underground leads to enhanced ability to withstand seismic event. For example, the spent fuel pool may be sited underground. Operational impacts may include accessibility to distributed facilities and time needed for response teams. Also additional training for operators, maintenance and response teams.
Physical plant layout	• The anticipated compact footprint of AdvNPPs is likely to affect worker access and egress in certain areas.
Plant Mission	• Electrical production and potentially process-heat applications would extend the traditional role of the operator. This does not necessarily mean more workload, but implies a broader range of responsibilities and thus more or different training. Some parts of AdvNPP plants may employ technology with minimal predecessor plant experience, especially those systems and subsystems employing advanced automation systems, non-traditional materials, or digital displays.
Off-normal Operations	• New operating modes introduced by non-electrical operations (e.g. process heat applications) will require new operating procedures. • Design of the technical support center (TSC), emergency operations facility (EOF) and outage control center (OCC) will have to consider integration with connected non-electrical operations. • Most safety systems are passive and require no operator intervention. The emphasis in emergency operations will rather shift to investment protection.
Normal Operations	• AdvNPP designs use non-light-water reactor technology (for example, liquid-metal-cooled or gas-cooled) that might pose new operational requirements. • Load following as well as base-load operations. • A single crew or operator may manage multiple units and additional missions from a single control room. • Individual reactors may be in a variety of states (e.g., shutdown, startup, or refueling, and various types of maintenance and testing) and running at various power levels. • Additional units can be added when needed and while other units are operating. • Fewer operator hold points for start-up and shut

Typical AdvNPP systems characteristics	Operational and Human Factors Impact
	down. • Novel approaches to refueling, such as on-line refueling, and physically relocating reactor modules to a dedicated servicing area for refueling.
Hazards	• Operational, industrial or environmental hazards might be introduced by new technology, for example, hydrogen, liquid-metal (such as sodium and lead), and much higher operating temperatures/pressures, and the use of high temperature gas and graphite in the core. The hazards must be understood, and then addressed in those safety systems that monitor and mitigate the hazards, the HSIs that personnel employ to monitor the plant, the procedures they use to address hazards, and operator training. • The reactor design is considered as failed safe, that is, it fails to a safe configuration and condition without the need for operator intervention. • A single unit can trip without affecting adjacent units that remain at power. Operators can scram a single unit individually.
Maintenance	• Novel approaches to maintenance, such as moving reactor module to a dedicated location in the plant or to the factory for servicing. • There are many new maintenance practices and potential hazards, due to different materials, compact plant layout, different product streams, advanced monitoring and measurement instruments, automated diagnostics, remote surveillance, and even robotic systems. • Advanced HSIs and special tools will be used for maintenance, diagnostics and materials and fuel handling.
Procedures	• Some level of automated procedures or procedures checking system is anticipated. This will simplify operator actions and potentially reduce workload during upset conditions.
Roles and Responsibilities	• Role and function changes are anticipated, for example concurrent responsibility for multiple product streams, such as electrical production, process heat and hydrogen production. • Single crew members may be responsible for multiple modules. • Extensive use of automation, sometimes complex, for operations may introduce a level of complexity that will require more abstract information representations in the control room and more training.
Staffing	• Staffing levels are expected to be below requirements stated in 10 CFR 50.54(m). This will require license

Typical AdvNPP systems characteristics	Operational and Human Factors Impact
	applicants to request exemption in terms of NUREG-1791.
Technology, Plant Configuration and Construction	• Modular approach to constructing plants. • Some AdvNPP designs use shared systems; some are shared across many units. • Lower power levels associated with AdvNPPs (< 300MWe) will result in lower probability for higher levels of radionuclide release. • Automatic turbine warm up, synchronization and integrated control between the NSSS and turbine during operations. Feedwater, condensate, and steam control is likely to be automated. This will simplify NOPs as well as EOPs and thus reduce operator workload during evolutions.
I&C and Human-system interaction	• A high level of automation is anticipated and digital (computer-based) controls and displays are used in the control room. Only safety-critical systems like diverse actuation systems may still be hardwired. • Monitoring tasks will rely increasingly on trends and smarter alarms, and diagnostics will provide early warning of potential problems so action can be taken earlier. • HSIs include large flat panel displays for group view functions, as well as smaller flat panel monitors for individual operator use. Operators will monitor the process using large overview display panels, plus workstation displays designed to provide both functional and physical views of the process and systems. • Indications and displays will be task-centered to support all conditions, including evolutions like start-up, shutdown, and system line-ups. • Control rooms are centralized to maximize coordination between units. • Advanced HSI will also be used for diagnostics, maintenance, communication and surveillance. • HSIs provided for plant evolutions of multiple units, and also for monitoring and control or other missions.
Containment	• AdvNPP designs typically reduce the level of challenge to the containment vessels and building by means of an integral primary system. By integrating the reactor, steam generator and primary cooling systems in the containment, catastrophic loss-of-coolant accidents are eliminated. This has important implications for EOPs and the range of operator actions that would normally be credited in older designs.

2.1 Notable AdvNPP Safety Concepts during Operation

As shown in Table 1 above, there is an emphasis on 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(s) 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 coolant (Na) to come in contact with water or steam. The design of containment is leak-tight and serves as a barrier against uncontrolled release to the environment.
- Shared structures for efficiency and economics, reviewed to determining that sharing will not impact accident response.
- Separation of protection and control systems.
- Protection from reactivity control malfunctions (achieved through redundancy and diversity) and ability to automatically initiate operation of systems including the reactivity control system.
- Improved shutdown heat removal.
- All protection systems are designed to 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.
- 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 system.

3 Human Performance Criteria for AdvNPPs

3.1 Operational Considerations for SFRs

Due to the amount of publicly available design information, SFRs are chosen as the basis for the analysis of human performance criteria. Although these reactors have some design and operational characteristics that are unique to sodium-cooled reactors, they nevertheless share many characteristics with the family of advanced reactors. These general characteristics include extensive automation, use of modern materials and systems, the ability to load-follow, the ability to provide excess heat for industrial applications, and extensive use of passive safety systems.

SFRs have efficient heat transfer systems and operate at low atmospheric pressure and their operating characteristics are well understood. As stated by the International Atomic Energy Agency (IAEA) (2007) "Among the fast reactor systems, the sodium-cooled reactor has the most comprehensive technological basis as result of the experience gained from worldwide operation of several experimental, prototype and commercial size reactors."

In terms of issues related to sodium-cooled AdvNPPs, several challenges are worth noting (as indicated before, most of these would also apply to other AdvNPP designs):

1. In a multi-unit plant, control systems may be able to manage multiple power conversion units (PCUs) in an integrated fashion. This could include systems that the units share in common, such as for circulating water or the ultimate heat sink for removing decay heat, and also systems for instrument air, service-water cooling and electric power. It may also include common control of systems that are similar but not shared between units, such as balance-of-plant systems. The integrated control of multiple PCUs 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 AdvNPP control rooms will be lower and thus supposedly allowing operators to handle more than one unit at a time.
2. The detailed design of HSIs (alarms, displays, and controls) to enable a single operator to effectively manage one or more PCUs will be an additional challenge. HSIs must enable monitoring the overall status of multiple systems and multiple reactors, as well as easy retrieval of detailed information on an individual unit.
3. Another 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 AdvNPP designs. While the primary mission of the plants would still be to safely generate electrical power, some AdvNPPs may be designed to accomplish additional missions, such as producing high-temperature steam for hydrogen generation and other high-temperature industrial applications.
4. Another general operational need for sodium reactors was exemplified in the EBR-II: an inert gas blanket is maintained over the sodium to ensure prevent sodium contact with air. This is essential in a pool-type reactor such as the EBR-II design. To maintain a low level of atmosphere contamination, a gas cleanup system was provided through which the argon could be re-circulated and purified. The argon system is also a covered gas monitoring system that allows for early detection of fuel failure. The argon system picks up the release and runs it through a gamma monitoring system. The constant covered gas monitoring system was alarmed in the control room, and trend information was presented to the operators. Unlike many of the issues found in the above designs, with a pool design sodium leaks in the primary system were not of concern. Within the heat exchanger a tube leak is picked up by a detection system, and it will be contained with tubes.

5. One of the aspects of the EBR-II that could have benefited by enhanced visualization or automation was the control rod maneuvering that could be automated. This was a mentally intensive activity where it fell upon the operator to continually monitor reactivity during rod control. A reactor operator and secondary coolant operator were required to jointly perform this task. Other operators included an electrical plant operator and steam plant operator, often the same person who formed part of the team. However, EBR-II was operating at a time when most controls were analog and the digital control systems readily available today were not options in terms of harnessing their capability to help run the plant.
6. New operational missions for SFRs as well as LMRs and HTGRs, such as exporting excess heat for industrial applications, would give rise to new operating modes, such as unplanned shutdowns, degraded conditions in one power module that may affect other modules, or off-normal conditions at more than one unit, will require new tasks such as load following operations, managing non-electrical processes, 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 Operating Procedures (NOPs) as well as EOPs for multi-unit disturbances.

3.2 Operational principles and the role of the operator

Emphasis in AdvNPP main control rooms (MCRs) would be on minimizing workload, while optimizing the ability to maintain situation awareness. It is expected that AdvNPP operations would be automated to the extent practical, but with due consideration of possible failure modes and consequential safety risks. Automated processes must be designed with due consideration of the need to reduce complexity and workload, but also to keep the operator in the loop and to maintain situation awareness. This is likely to cause some changes in the roles of operators, for example during normal operations operators are likely to perform more higher level tasks, such as production planning, and system optimization.

Like any other NPP, AdvNPPs must be operated in accordance with NPP procedures that reflect the plant design bases. 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 bases and support safe operation of the plant.

Very few situations would call for evacuation of the MCR. The only foreseen events that may initiate evacuation of the Control Centre (including MCR), would be an event internal to the Control Centre. Fire is considered the most likely of such events. Design of the automation system and MCR HSIs must ensure seamless transfer of control in such an event to a remote shutdown facility (RSF) before evacuation.

3.3 Staffing Concept

Staffing of the AdvNPP would be primarily influenced by the following:

1. Regulatory requirements: Staffing numbers will need to comply with all applicable NRC and Utility requirements. Where relevant, IAEA, INPO, NRC and WANO requirements would also be taken into consideration. Where designers anticipate reduced staffing as a means to reduce operating and maintenance costs, they will have to request exemption from the requirements of 10 CFR 50.54 (M)(i), in terms of the provisions of NUREG-1791.

2. The primary design and operating characteristics of the plant or specific systems: This includes consideration of mechanisms that enable or support operating personnel in monitoring, disturbance detection, situation assessment, response planning, response execution, and the management of transitions between automatic and manual control.
3. The overall operating environment and the nature and scope of HSIs to be used by operating personnel to perform tasks under different operational conditions.
4. The interaction of operating personnel with automated systems, including responsibilities for monitoring, operating, and overriding automated systems.
5. Verification of requirements imposed by the following design-specific criteria:
   - Operational conditions
   - Operating Experience
   - Functional analysis and allocation
   - Task Analysis and Workload analysis
   - Human Reliability Assessment
   - HSI Design
   - Knowledge, Skills and Abilities required per task
     - Skill-based tasks: Operators should have direct interaction with the display or interface
     - Rule-based tasks: Tasks with a one-to-one mapping between constraints in the work domain and the perceptual information displayed by the interface
     - Knowledge-based tasks: Interfaces should represent the given work domain hierarchically to match the hierarchical architecture of the automation system. Such a scheme would help to form an externalized mental model for problem solving (Vicente, 2002 [15]).

3.4 Human performance issues in Maintenance

The implementation of AdvNPP design for maintenance will take advantage of digital systems capability in a number of ways. Digital systems are expected to use sensor technologies that can identify when equipment is malfunctioning and when preventive or corrective maintenance is required. Smart systems will be able to diagnose equipment conditions such as malfunctions in level controllers or sensors and determine the associated maintenance activities, including equipment replacement. Failed sensors will mostly be alarmed and logged to support maintenance activities. Digital systems may also be able to confirm that equipment is in a safe state to be worked upon, with corresponding indications in the control room, thus reducing the potential for maintainer injury, such as exposure to electrical or radiological hazard. After tasking is completed, digital systems could be used to verify both the proper functioning of equipment as well as the configuration needed for startup. Truly advanced systems will be able to self-configure the equipment after maintenance. As part of the overall safety concept, a distributed control system may be able to ensure that systems with the potential for injury are not energized once personnel have begun to work on them.

A number of additional assumptions included in the concept for maintenance for AdvNPPs are that advanced digital systems, including online prognostics, can reduce, if not obviate, the potential for anticipated transient without scram (ATWS), and that out-of-service status can be automatically detected. This will have a significant impact on human performance and the reliability and quality of work. Digital systems may also be able to detect maintenance errors in real time and alert maintenance personnel in order to avoid damage to equipment. The AdvNPP is also likely to maintain a large set of databases that can be data-mined for trends to a greater extent than is now possible with the current LWR fleet. For example, there may be a database to support equipment tagging during outage control, a situation that is mostly handled in today's LWRs by paper-based methods. Advanced information and communication technologies now make it possible for MCR operators to be updated on ongoing maintenance activities through a combination of video feed, electronic statusing of equipment condition, and location of personnel through radio-frequency identification tags (RFID), instead of just by voice communication, which is now the predominant mode of informing the control room. Maintenance procedures and work orders for work to be performed outside of the control room are likely to be available on handheld mobile devices and verification may include video streaming of equipment status back to control room operators.

As a final consideration, various aspects of maintenance for AdvNPPs are expected to differ according to the type of reactor design. NUREG/CR-7126 notes that for Toshiba's 4S ("super, small, safe and simple") and GE's PRISM designs (both sodium-cooled), maintenance on the two external steam generators is hazardous and may entail specific training because operators must wear specialized personal protective equipment (PPE) and work in an inert gas atmosphere [8].

3.4.1 Human Performance Considerations for Advanced Diagnosis and Prognosis

Masys et al. (2013 [7]) present a number of problems in diagnosis and prognosis shared by the medical and nuclear industries, which may be even more pronounced for operators monitoring and control of multiple reactor modules and common systems. These problems can be summarized as:

1. Information overload and need to perform real time data reduction for emergent problems.
2. Problem diagnosis under conditions of sparse or conflicting data.
3. Optimal presentation of relevant data.
4. Understanding mechanisms of degradation (fuel, cladding, structures).
5. Effects of false positives on diagnosis.
6. Near real time requirements for diagnosis and prognosis of emergent problems.
7. Cognitive limitations for multi-tasking.

Items 1 and 2 are opposite sides of the same coin: in the first instance, we have the capability to produce large numbers of measures of plant performance and equally large numbers of displays, and this has to be balanced or refined to support what is really crucial to supporting operations and the operator's role in plant management. In a highly digital operational environment the issue of conflicting data or sparse data is reason for concern. For example, when multiple units are being surveyed if there are conflicting data it is likely to tax the crews' information processing capability and situation awareness. Similarly, if only partial data are available for one unit and complete data are available for another, this may complicate the selection of the correct mitigative measures. Advanced prognostics and diagnostics can help to reduce uncertainty and aid in operator response.

By placing data presentation within the context of prognostics and diagnostics, the challenge of optimal data presentation (3) can be achieved. This assumes that diagnostics and prognostics can be context sensitive in terms of such factors as such operating mode, current conditions, and operating limits. One of the problems that will face operators of AdvNPPs is to understand the mechanisms of degradation and diagnostics keyed to temperature swings and partial sodium voiding. Advances in multiple robust sensors (4) combined with prognostics and diagnostics may greatly enhance the operator's understanding of plant degradation.

The presence of false positives (5) can produce confusion and thus greatly impair crew response. By running system models and performing automatic cross checking of data conditions, diagnostic and prognostic support systems will result in more accurate interpretation of actual plant and system conditions. Also, assisting crew identification of false positives will reduce cognitive workload. Emergent problems (6) are associated with complex emergency conditions, as has often been observed during the conduct of long-term outage work. AdvNPP operational concepts for simplification of the sheer number of systems to which the crew must attend and maintain may simplify outage work, but the complexity presented by the number of reactor modules simultaneously in service will produce relatively high levels of workload that can be reduced by real-time aiding and diagnostic evaluation of emerging conditions. Once an appropriate diagnosis has been performed, the automation can suggest or call up the appropriate procedures for response. Cognitive limitations for multi-tasking (7) particularly during busy times are a real phenomenon and advanced diagnosis and prognosis that support a collaboration among the crew or between the crew and smart systems can be used to lessen the effects of multi-tasking.

3.4.2 Human Performance in Beyond Design Basis Accidents

Severe accident management guidelines (SAMGs) were developed post-Chernobyl and embraced by the U.S. NRC and industry. Severe accidents involve fuel damage and/or damage to the reactor core, leading to radiological release to the reactor vessel, containment or the environment. One of the conditions leading to such an accident for LWR designs is uncovering the top of the fuel.

As was evidenced in Fukushima, there are a number of actions that operators may consider in order to try and protect the core and spent fuel pool including the use of portable generators and pumps, and alignment of various injection sources not typically part of control room or field evolutions. Although the design of SFRs and most other AdvNPPs will avoid any similar situation, more research to determine crew performance requirements at AdvNPPs for severe accidents is warranted. There are a number of safety features inherent in AdvNPP designs, but there still exists the potential for beyond design basis events. Three such beyond design basis generic events were evaluated for the PRISM reactor design: loss of primary flow, reactivity insertion through unprotected control rod withdrawal and extended loss of heat sink. Maximum transient effects occur at full power and calculations determined in the design must take this into account.

NUREG/CR-7126 [8] suggests that the automation system will play a key role in protecting the plant from leaks within the reactor vessel. The SFR design must therefore allow for sodium leak detection leading to automatic shutdown based upon the presence of detectors in the reactor vessel and in containment. The crew-system performance goal is to maintain cladding integrity and prevent radioactive release through control of the temperature, including both the surface temperature of the fuel and cladding temperature. Combined direct or indirect operator feedback on cladding temperature and coolant levels may be the sort of information needed in the control room and at the Technical Support Center during events.

In review of the available literature, it appears that most of the analysis for PRISM was performed in terms of the physics and structures and not on the basis of human performance requirements and ability of the crew to complete various SAMG procedures. If this design, or other AdvNPPs for that matter, were to be certified, the recent U.S. NRC Near Term Task Force Findings for Fukushima (2012) would have to be addressed, with particular reference to emergency power supplies at the site and loss of ultimate heat sink. Addressing these challenges for AdvNPPs may require training, new procedures for severe accidents, identification of portable equipment (pumps, generators), installation of specialized barriers to eliminate or reduce release of radionuclides, and extending simulation capability to extend to the severe accident realm. AdvNPP design requirements may include the configuration of reactor modules such that a severe accident would not be capable of spreading to adjacent modules and overwhelming common systems key to system safety.

Additional design information including response to transients mentioned in the referenced research is available in Slovik et al. (1990 [13], 1991 [12] and 1992 [14]).

3.5 The Nature of Human Performance Criteria

3.5.1 The Operational Context

Human performance in response to events can be considered a response to an operational context, that is, plant process or status conditions. Figure 1 presents a general stimulus-response flow for an operator. A context or upset condition is recognized, the context is mapped to previous successful response or responses, an action is taken, the effects of that action are evaluated and the operator then leaves that context or stays within it and continues to take action and evaluate until the context has changed congruent with operating goals, mitigative strategy, or return to normal conditions. A number of approaches exist to determine whether the context mapping is part of an exact match or part of a fuzzy partitioning of the context space and the action-execution space.

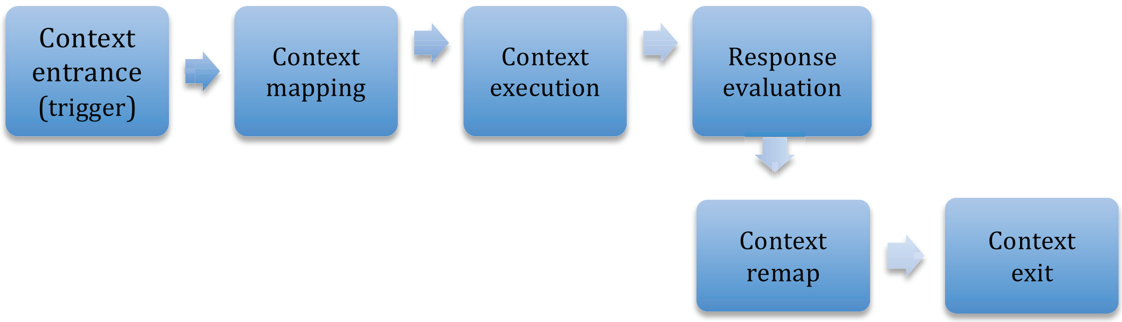

Figure 1: Relation of Context Interaction to Operator Performance

When conceptualizing operator performance in terms of response to events, i.e., to context or classes of context within the general framework of operational concepts for advanced reactors, it is useful to think not only of how the operator can meet performance requirements through context matching, but also to consider distinct operational conditions and operating modes.

This simple model illustrates only some of the large number of contexts that may exist. The context-driven response when some elements are similar can also vary widely. For example, the loss of a pump when the plant is at full power may have different implications for the operator and various processes than the loss of that same or similar pump during shutdown or cooldown conditions. It is the topology of context (which could be described as a unique instance of a defined operational condition) that lets operators account for the various processes from a general topological framework and plan their response accordingly.

Any strategy for consideration of human performance requirements for advanced reactor design must account for the variable demands placed on humans as well as systems during different operational conditions. The plant operating mode is also a crucial factor in terms of how unwanted conditions, that is, off-normal conditions, are to be mitigated. This is often just as important as the resources available to perform tasks or the operator's familiarity with procedures. Operating modes are also associated with regulatory practices and safety basis, including limiting conditions for operations. Many of the activities at NPPs are determined by the plant operating mode in conjunction with regulation and strategies of the work organization.

Understanding the effect of variable operational conditions on human performance assists in defining human performance criteria. In considering human performance criteria it is useful to think of the following broad set of plant conditions, i.e, contexts that are commonly represented in NPP operating procedures. Each of these conditions can be uniquely defined in terms of the performance parameters, operational limits (limiting conditions of operation as defined in Technical Specifications), dependencies, exclusions, procedures, and prohibited actions (Figure 2):

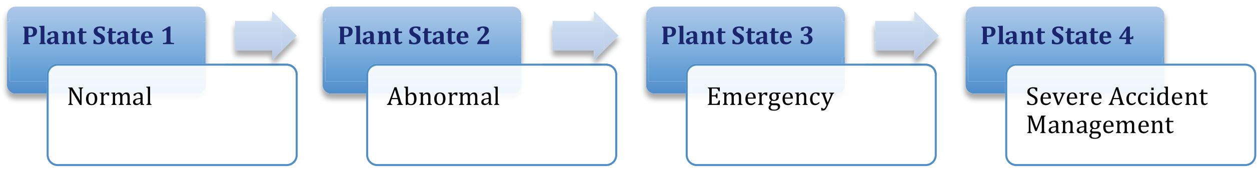

Figure 2: Plant Conditions by Procedures Category

It is clear that the accurate definition of operating modes and states for AdvNPPs will be of critical importance for several aspects of design - operational concepts in general, and automation system and HSI design in particular. For example, new modes such as load-following or monitoring of process heat may have new definitions and new performance requirements, some of which have yet to be defined. A generic set of operating modes that will have varying mode-dependent human performance requirements are listed below:

- Heat-up
- Start-up
- Steady-state power operations
- Shut down
- Standby/Cooldown
- Fuel handling
- Other special conditions, including load following, low power operation, multiple process/product stream support, and integration with renewable energy sources on the grid.

3.5.2 The Human Context

At this point we have discussed human performance requirements in terms of context of the plant operational conditions – identification of context classes, plant procedures, and operating modes. To successfully define human performance requirements, however, we need to define human performance requirements from the operator perspective. There are broad classes of performance measurement and ways of defining response, for example, to perform within a certain time period and within certain tolerances and according to regulatory and safety bases. However, since one of the most difficult challenges facing designers is the nature of human-automation collaboration, identification of the performance criteria and their evaluation will serve us well. Even the most advanced automation within the nuclear industry will still require supervisory control on the part of the operator. The human performance requirements in terms of the mission effectiveness of the human-automation team may not be sufficient. Choosing performance criteria and the right class of metrics requires additional work and a comprehensive understanding of human perception and behavior in variable operational contexts. The selected criteria should not only target advanced human-controlled systems that are supervisory in nature, but also human performance in terms of the joint cognitive system, that is, the overall performance of the sociotechnical system. In this sense it is more prudent to consider human performance criteria from both perspectives: what is required of the system to support optimal operator performance, and what is required of the operator to effectively support the operational and organizational mission.

Supervisory control for an advanced automation system implies a hierarchy of operational information with a matching hierarchy of control. At lower levels of the hierarchy, human response latency, error and accuracy, productivity and efficiency in terms of resources and communications are typical human performance criteria. However, different components within complex tasks can have different functional priorities with respect to overall goals or temporal priority. Supervisory control associated with higher levels of automation entails vigilance on the part of the operator. Vigilance (and therefore situation awareness) is moderated by signal salience, uncertainty, and modality. Whether the vigilance is successive or simultaneous is another factor that can influence operator performance, for example, where the operator monitors two simultaneously operating systems under automatic control. If system A suffers an upset and B is relatively stable and performing to specification, the course of action is more straightforward than if system B enters an upset condition requiring intervention before system A has been placed under proper control.

At higher levels, criteria become more complex and include trade-offs in terms of making "safe" choices or choosing among competing goals and strategies. Attention sharing and dynamic modulation in response to changes in the immediate environment are potential requisite human performance criteria. People are expected to be able to maintain performance through adherence to procedures, which serves to add additional complexity to understanding or predicting the level of performance required by a concurrent task (a task concurrent to the task indicated by procedures).

As discussed above, in terms of system performance criteria needed to support operator action, the system criteria include presenting information to the operator regarding the current context, operational status (normal to severe accident status), and operating mode. To support situation awareness, status information should include alarms and displays that allow the operator to be able to comprehend current conditions, information on previous events to enable operators to understand the cause of an event, and trend information that allows the operator to predict near and long term future plant states. In addition, the system must also provide the means of control as well as the ability to provide immediate feedback to the operator on the result of actions taken.

Another performance criterion is the flexibility of the system to allow a degree of task scheduling and task control by operators when cognitive and resource demands are particularly high. Finally, all performance criteria need to consider the physical and cognitive limits to information processing by humans that should not be exceeded. Workload, task sequence, task duration, and levels of information uncertainty and precision can influence human performance. This is why the design of controls and displays design must be matched with the expected response and performance. In this regard, a number of human factors engineering standards can and should be referenced by designers.

3.5.3 Operator Performance Shaping Factors

Any analysis of human performance issues needs to include consideration of performance shaping factors (PSFs). In addition to the identification and description of technical and operational characteristics for the selected scenarios, PSF analysis is an important aspect of human reliability analysis (HRA) and should form an integral part of WDA to support the identification and determination of sound operational concepts for any operational environment. In a previous milestone report (Hugo et al. 2014 [5]), it was described how the use of PSF analysis as an adjunct to the WDA is a valuable approach in identifying areas of strength and weakness in the design and operational concepts. From an analysis of EBR-II operations, 11 PSFs were identified that could characterize emergency accident conditions:

1. *Procedures* - includes quality, availability, accuracy, relevance to context, and use of formal procedures in plant response.
2. *Training* – includes experience, expertise, and suitability of training to the scenario under review.
3. *Teamwork* - includes communications requirements and provisions for lock-out/tag-out expertise, and coordinated activities both within and outside of procedures.
4. *Fitness for Duty* – including aspects of fatigue, injury, exposure to heat or cold for long periods of time, fatigue factors.
5. *Cues and Feedback* – prominence of cues, i.e., the salience, quality, timeliness, availability of trend information, time from initiating event or other events until first alarm .

6. *Complexity* – presence of multiple faults, parallel tasking, difficult sequencing, masked symptoms.
7. *I&C and Ergonomics* – operator interface, need for plant protective equipment (PPE), special tools, ingress and egress.
8. *Operator workload* – includes stress, mental physical aspects or both including instance where crew has knowledge of impending time constrains.
9. *Timing* – includes time available and time required, travel time, drain down time, importance of timing in event progression and event response.
10. *Staffing and Resources* – including expectations that MCR staff is to be increased or decreased, or staff capabilities are likely to be stretched.
11. *Work Environment* – includes fire, flood, seismic, high temperatures, and inert gas environments.

Based on what is currently known about emerging AdvNPP designs, it is highly likely that the same PSFs would be generalizable to most advanced operational environments. In future analyses of human performance, these qualitative PSFs should be placed within the context of the physical and cognitive environment in which the operators would find themselves. This context should be defined in terms of what has to be done to protect the plant, what is required by procedures, and the expected availability of systems, information and communication channels.

3.5.4 Defining Human Performance Criteria

Based upon the performance principles described above, a number of high-level supervisory performance criteria can now be identified. These criteria would apply to normal as well as to abnormal or emergency conditions:

1. The ability to detect out-of-tolerance conditions. This will require the availability of appropriate operational information, as described in item 8 below.
2. The ability to adjust the system or stay on course as a function of plant conditions and various context topologies.
3. Maintaining the balance of goals and means for complex goal topologies.
4. The ability to perform goal and goal status assessments in a timely manner.
5. Conducting effective and accurate information search as required by conditions.
6. Successfully apply procedural guidance within regulatory bounds.
7. Intervene and override automation as required, and exercise control at various levels of systems performance
8. Adapt to varying levels of automation associated with various reactor systems (for example some automation will have hold points and others will be fully automated).

   The requirements for the automation system and the HSI to support human performance include such factors as:

   a) Visibility of operational information when and where it is required, including current operational condition, the required control action, and the consequence of the control action;
   b) Legibility of information under all operational conditions, including poor illumination;
   c) Matching the mental model of the operator;
   d) Avoiding complexity and information consistent with what the operator needs to perform the task, without undue manipulation and mental calculation;
   e) Provide consistent and effective system feedback, matched to the operator's expectation;

f) Ease of navigation of the entire information space and easy retrieval of information, with appropriate control of information and display density.

The following concept map summarizes the relationship and dependencies among the items above:

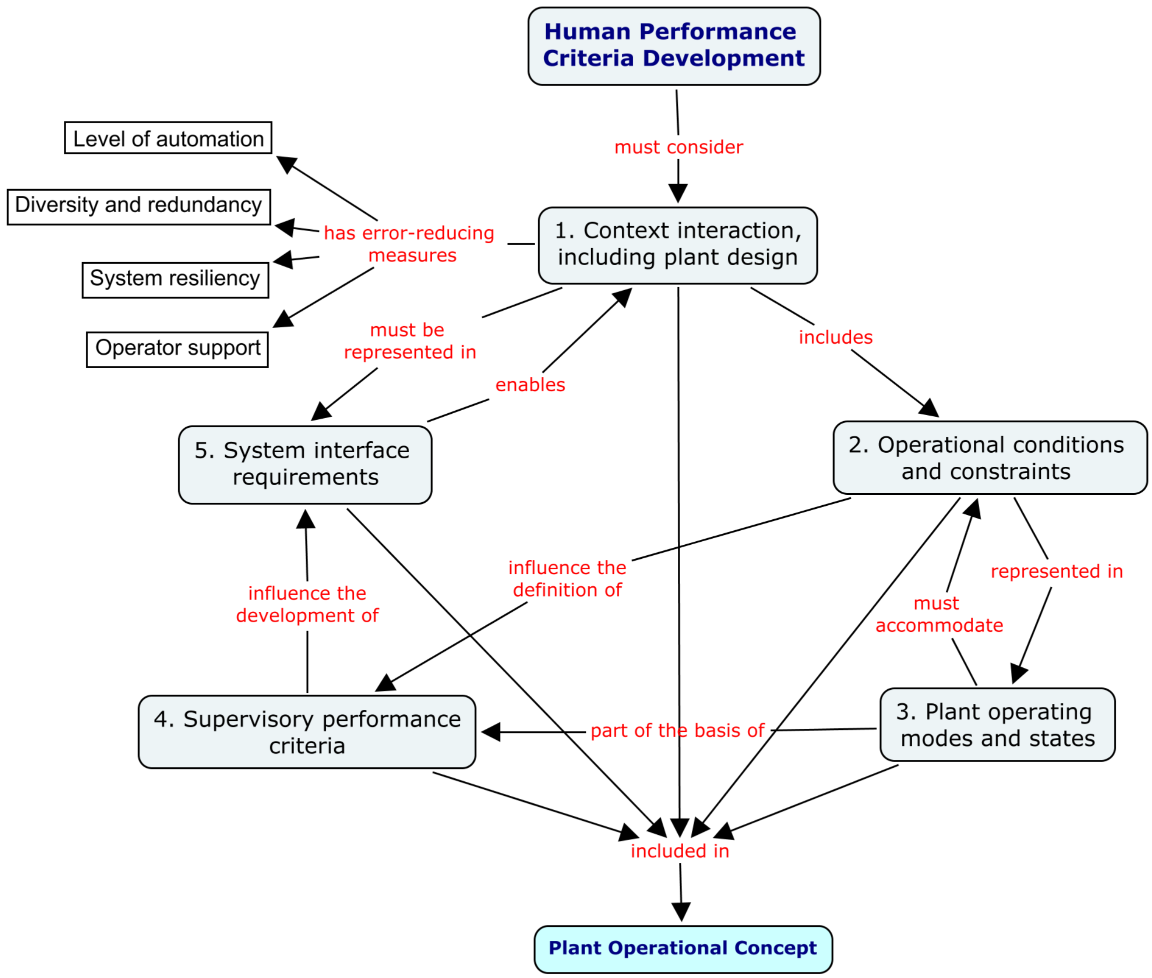

Figure 3: Elements supporting human performance criteria development

The diagram illustrates the five key elements that must be considered in the development of human performance criteria:

1. The context within which human interaction takes place, which also informs the development of error-reducing measures:
   - the level of automation commensurate with the function allocation principles,
   - provisions for diversity and redundancy of systems and controls,
   - provisions for resiliency and resistance to operator error,
   - provision for operator support under various operational conditions.
2. The operational conditions and constraints that shape a large part of operator perception and behavior;
3. The operational modes and states, which include the operating parameters that define operational conditions and constraints;
4. The performance criteria for supervisory control derived from the operating modes and states;

5. The requirements for operator control and interaction, including operational information requirements.

All of the items ultimately provide important information for the plant's operational concept.

3.5.5 Measures of Human Performance

Measures adopted from HUPESS, as described before, provide reliable and validated measures to evaluate complex process control systems involved with operating Advanced Reactors.

Figure 4 illustrates the six categories of measures that can be used to determined human performance under any of the operational conditions described before.

The summative measure of human performance in this model comes directly from the operating team's ability to accomplish plant goals. Personnel task performance must also be evaluated to improve diagnostic ability of individual operators' contributions towards team performance. Subjective measures like workload and situational awareness are typically assessed after a formal performance evaluation to determine cognitive workload, the operator's ability to acquire important information from the interface, the ability to comprehend the current state of the system, and the ability to predict the future behavior of the system. Teamwork must also be evaluated by subject matter experts to identify breakdowns of communication and other task performance based on cooperative work. In addition, physiological factors such as ergonomic and anthropometric data must be determined to evaluate the impact of workplace and display organization and contribution to personnel, team and plant performance.

Figure 4: Human Performance Measures required to evaluate process control (Adapted from Ha & Seong, 2007)

3.5.6 Specifying Human Performance Requirements

The role of the plant operator, maintainer, shift supervisor, and control room crew is impacted by the design of the plant, including its structures, materials, I&C, and general level of automation. In planning for operations it is crucial to understand from the perspective of the operator how the plant is to function and the expectations for human performance. Lack of understanding of the roles and responsibilities can have disastrous effects. It is therefore best to identify human performance requirements and criteria during the design process and as part of the plant's Operational Concept.

One of the ways of specifying human performance criteria is in terms of mission effectiveness. Mission success is summative, being based upon system functioning, processes, and task execution to defined requirements. Especially for first-of-a-kind (FOAK) reactor designs it is very beneficial to start with an analysis of the functional and structural architecture of the plant. As described in previous reports, the WDA method is particularly suitable for the early phases of plant design where many concepts are still being developed. This analysis also helps to define the operational conditions and constraints that will influence not only the operational design, but also the essential roles of humans and the interdependence between humans and various elements of the plant. The WDA will then serve as a framework for more detailed analyses of how to allocate functions to humans or machines or a combination of the two, and finally for the analysis of operator tasks and performance requirements. Specific task analysis methods are subsequently selected to support the identification of cognitive and physical performance requirements.

These analyses are important, not to determine what machines were good at and what people were good at, but to determine the requirements for human-centered automation. This, in combination with detail task analysis methods, will help to determine the requirements for team cognition and team collaboration as additional factors when developing human performance criteria. Particularly in situations where the context of situations dictates an inherent flexibility in work execution, rigidly designed devices or series of decisions and actions will fail to fit when called upon. In other words, when the context of the problem space demands it, the allocation of functions and nature of decisions and tasks is apt to change. An understanding of these contexts and interdependence will make it easier for designers to consider the impact of human performance criteria on system performance. This includes early identification of control and information requirements for all operational conditions. For example, a human performance criterion for alarms could be phrased as, "The operator is made aware through unambiguous means (- a constraint for the designer -) of the alarm and its priority." Or "Color coding of alarms is limited to the alarm and its significance, it is not used as a border, a background or means of functional grouping." Also, "Alarms are processed and presented at a rate that the operator can comfortably attend to". "The operator will be able to understand and use procedures that are made available for situations when the alarm status is not available."

These requirements are summarized in the following diagram: human performance is a continuous loop where specific inputs and contexts influence the quality of the output, which is compared to operational demands, and the results of the performance are fed back to the performer. This cycle is repeated until the operational mission has been completed, or a new mission is initiated.

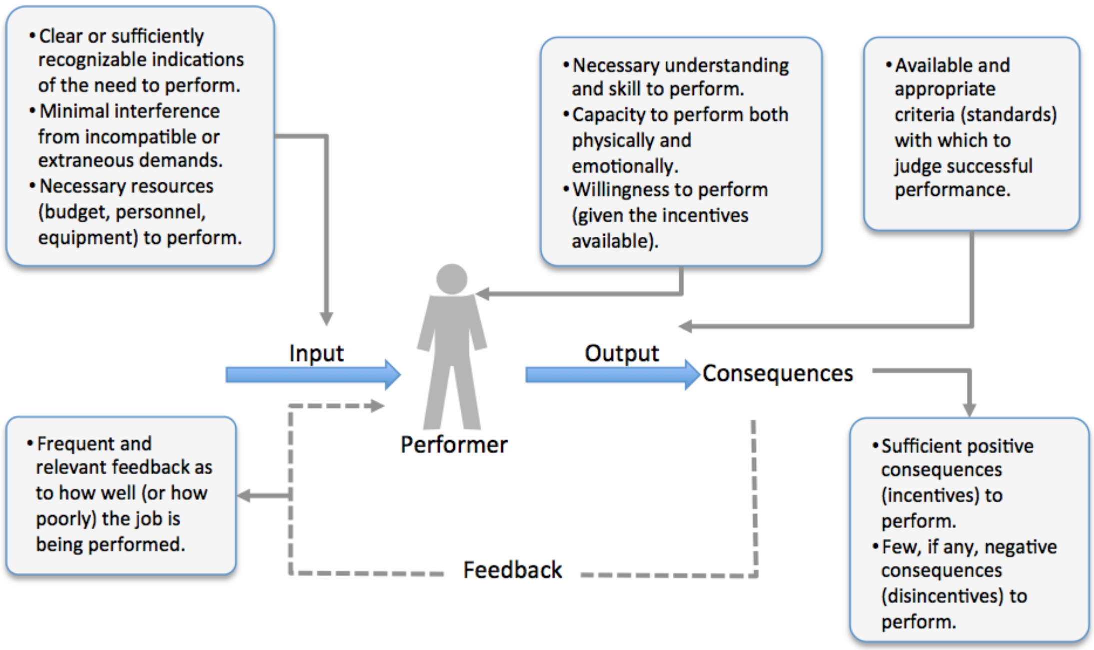

Figure 5: Generic Human Performance Requirements

3.6 Regulatory Aspects of AdvNPP Concept of Operations

Current U.S. NRC regulations were developed based on traditional large NPP LWR designs. However, AdvNPP designs differ substantially from traditional designs in a number of aspects, including size and number of reactors, inherent passive safety systems, fuel type, and coolant type, among others. These differences present unique challenges for licensing and regulation. Current regulatory requirements regarding human performance for AdvNPPs are immature, specifically with regard to the licensing process for AdvNPP designs. In preparation for pre-application activities for SMRs, the NRC has identified staffing as one of the most important parameters that play a role in developing a concept of operations (SECY-10-0034, "Potential Policy, Licensing, and Key Technical Issues for Small Modular Nuclear Reactor Designs," dated March 28, 2010"). It is expected that the same considerations would apply to other AdvNPPs. However, it should be pointed out that characterizing staffing as a single issue related to numbers of individuals in the control room ignores the complexities of human performance criteria and measurement. It is not just the numbers of individuals but also the plant design, the operational context, and operators' qualifications (training, education, experience, and certifications) that will affect performance. The HSI, level of automation, control room layout, procedure format, and number of units controlled all interact with the numbers of staff and have to be considered. It is expected that NRC regulatory guidance will be updated to better accommodate the changes to staffing requirements that may be appropriate for AdvNPPs. Early resolution of this issue, or identification of a clear path to resolution, is essential, both so that designers can incorporate appropriate changes during the development of their concepts of operation, designs, task analyses, and staffing plans before submitting a design review or license application, and to support the regulator's review of the design and license applications.

The primary issue that is expected to influence HFE aspects for AdvNPPs is the effect of increased automation and non-electrical operational missions on human performance. This is compounded with the issue of staffing discussed above since the current staffing regulation would not accommodate multi-unit or multiple product operations. O'Hara, Higgins, and D'Agostino (2012 [11]) reported on a study in which lessons learned from three different non-nuclear systems were reviewed. These three systems were unmanned aircraft systems, oil refineries, and tele-intensive care units. Specific AdvNPP operational and performance considerations arising from this study are summarized as follows:

1. Monitoring and controlling multiple units could be accomplished by a single operator or crew in a single control room, provided that a human-centric design approach is followed. This could include the use of enabling technologies that support operators to monitor multiple units or multiple processes:
2. Human-centric automation. Automation is a key enabling technology but it should be interactive and flexible. Training may improve operators' understanding and use of automation.
    - Advanced designs of HSIs and alarm systems
    - Control rooms that foster teamwork and communication
    - Procedures and HSIs that support the transition from normal to off-normal operations and to emergency management
    - Information technology support for troubleshooting
3. The effect of inter-unit differences on performance must be considered with care. Designing for such differences will be helpful in monitoring and distinguishing between units.
4. Clear responsibilities need to be defined for all staff. Allocating tasks to crew members is vital in terms of the performance of the overall team and integrated system.
5. Managing off-normal situations for AdvNPPs with multiple products requires crew flexibility. Significant organizational changes may need to be made to manage these situations. Additional staff may be needed for the disturbed unit or process and for some transitions, such as unit start-up or shutdown. Having a way to transfer responsibilities for reactors in off-normal states to a person or team specialized in dealing with them may be beneficial to AdvNPP operations. Communication between personnel is crucial for maintaining situation awareness during off-normal situations.
6. Designing the control room and HSI for multi-process monitoring and control is challenging. HSIs must enable monitoring of the overall status of multiple units or processes and the easy retrieval of detailed information on an individual unit. The design of alarms particularly must ensure operators are aware of important disturbances, thus minimizing the effects of change blindness and neglect. The organization of information is another critical HSI consideration, e.g., deciding on what information crew members need to access, both individually and as a crew, to support teamwork.
7. The design for multi-unit or multi-process management can be aided by detailed HFE analyses of staffing and operator tasks, via WDA, task analysis, human performance modeling, and operator-in-the-loop simulations.

It can be concluded that monitoring and control of multi-unit, multi-product facilities by a single operator or crew in a single control room may be possible. However, the successful accomplishment by a single crew of multi-unit operations in the commercial nuclear industry is yet to be demonstrated. The unique operational demands of different systems need to be addressed before conclusions about AdvNPP operations can be developed. The special demands of one industrial application may limit making generalizations to another. For example, while multi-unit operations may be routine in the petrochemical industry, it is proving a difficult challenge for unmanned vehicle operations, which, according to O'Hara (2012 [8]) is an appropriate analogy for an AdvNPP multimodule control room. The authors therefore recommend conducting more research on surrogate systems to answer questions, such as the impact of unit differences on monitoring.

The information obtained from these non-nuclear systems will help the understanding of the issues and human performance challenges associated with multi-unit operations and provide a technical basis to develop guidance for the design and safety review of the HFE aspects of AdvNPPs.

4 Conclusion

The engineering design of the emerging generation of advanced nuclear power plants differs considerably from existing water-cooled reactors. This will affect the operations and operator performance in ways that are currently not adequately addressed in either systems engineering guidance or HFE methods. Without explicit analysis of the operational conditions and constraints of this new generation of NPPs, it will be very difficult to ensure their optimal and safe operation. For example, new concepts in reactor design, fuel type, coolant type, and automation levels will inevitably change the human performance requirements and therefore the safety and risk impacts on the operator. Specific concepts associated with SFRs will require significant departures from conventional operating procedures. For example, SFR fuel handling is markedly different from refueling of LWRs and will place demands on the operator that have no precedent in the U.S. commercial nuclear industry. Similarly, some advanced SFRs will be capable of load following, and producing other commodities in addition to electricity in an economically competitive manner. Some are designed to be highly automated and require only a small operating crew in one central control room operating multiple units or multiple energy products. In general more automation will make the operator's role more supervisory in nature, but controlling multiple processes or power conversion units may introduce additional workload challenges. These changes to the mission of the AdvNPP may also affect the operator's performance. This report emphasized that such engineering design changes represent only some of a number of factors that can affect human performance in AdvNPPs. Ultimately, the role the operators play, their function and the tasks they perform, are going to change due to changes to the engineered design, planned use of automation, and change in plant mission.

The engineering changes and anticipated operational characteristics of AdvNPPs make it important to develop metrics of human performance that will ensure that the effect of these changes on the human operator can be measured and their performance implications assessed for future designs. This report presents a high-level analysis of the key operational characteristics of SFRs as the most prominent type of AdvNPP. Special emphasis is placed upon the anticipated use of greater levels of automation and the expanded mission of new plants, all of which will have significant risk implications for the human operator's roles, functions, and tasks.

In essence, this report answers the following questions:

- How are advanced SFRs different from LWRs?
- How will these differences affect the human operator and what demands will these differences place on human performance?

The human performance perspective presented in previous milestone reports considered the nature of function allocation and its contribution to reducing the risk of human error, as well as contributing to effective, efficient and safe operations. From that previous work, which included a WDA perspective on operations based upon an analysis of a predecessor sodium-cooled plant, it was clear that development of Operational Concepts for AdvNPPs must include the identification of human performance requirements. In general, the human performance approach that is taken for AdvNPP Operational Concepts development is to limit the conditions for human errors or human failures as far as possible. This report demonstrated how HFE principles and techniques can be applied in the identification and definition of human performance criteria, which will be used to inform the development of operational concepts. Ultimately, the early identification of human performance requirements and conditions could contribute significantly to reducing the likelihood of human failure to achieve a needed response.

As a critical part of the early HFE work, human performance analyses will determine the means by which to identify human decisions, actions, and interfaces, along with personnel-related aspects, that could impact the success of achieving critical system functions. This information will be determined largely through the WDA performed as part of the HFE work of an engineering project. This process includes identifying how a system is to be used, where it is located, how it fits within operational sequences, and operator performance requirements in conjunction with that system.

The results from this phase of the project will be merged with the final phase, which is aimed at providing a comprehensive methodology and framework for developing for Operational Concepts for AdvNPPs.

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