INL/EXT-13-30117

Development of a Technical Basis and Guidance for Advanced SMR Function Allocation

Jacques Hugo
David Gertman
Jeffrey Joe
Heather Medema
April Whaley
Ronald Farris

September 2013

Idaho National Laboratory

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL/EXT-13-30117
SMR/ICHMI/INL/TR-2013/04

Development of a Technical Basis and Guidance for Advanced SMR Function Allocation

Jacques Hugo
David Gertman
Jeffrey Joe
Heather Medema
April Whaley
Ronald Farris

September 2013

Idaho National Laboratory
Human Factors, Controls and Statistics Department
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

EXECUTIVE SUMMARY

This report presents the results from three key activities for FY2013 that are helping to determine the definition of new concepts of operations for advanced Small Modular Reactors (AdvSMR): a) the development of a framework for the analysis of the functional, environmental, and structural attributes of AdvSMRs, b) the effect that new technologies and operational concepts would have on the way functions are allocated to humans or machines or combinations of the two, and c) the relationship between new concepts of operations, new function allocations, and human performance requirements.

A previous report described some of the principles involved in how AdvSMRs will use advanced digital instrumentation and control systems, and make greater use of automation. These advances not only pose technical and operational challenges, but will undoubtedly have an effect on the operating and maintenance cost of new plants. It is generally assumed that automation would be the most likely way to reduce the impact of labor on operating and maintenance cost. However, the effect of automation and other advanced technology on staffing requirements and safety standards has raised many questions and very little research has been conducted to date.

For example, the impact of AdvSMR designs on operational and regulatory considerations, such as workload, situation awareness, human reliability, staffing levels, and the appropriate allocation of functions between the crew and various plant systems that are likely to be highly automated is largely uncertain and will remain uncertain until empirical research data become available to support the development of sound technical bases. Experience with AdvSMRs outside of the US Navy is limited to a very few predecessor plants. In addition, existing human factors and systems engineering design standards are not current in terms of human interaction basics for automated systems, and there is a lack of good functional allocation and staffing models that take into account static or dynamic allocation.

Given these uncertainties and other issues, it is necessary to develop new Concepts of Operations models as well as new models of function allocation and human performance requirements. This report explains the relationship between these three requirements and how old paradigms and methodologies are no longer suitable for the analysis of evolving concepts. The report further explains how the development of new models and guidance for Concepts of Operations need to adopt a state-of-the-art approach such as Work Domain Analysis (WDA). The primary goal of this methodology is to identify and evaluate specific human factors challenges related to non-traditional concepts of operations, and the associated changes in the allocation of functions to human and system agents. This includes developing a framework for the analysis of AdvSMR functions, structures and systems using the WDA methodology, as well as the development of functional allocation principles as one of the primary decision criteria for staffing design and downstream design.

The results from this phase of the research indicate that the WDA methodology will provide a valid framework for the analysis of AdvSMR operating concepts, in spite of the lack of current design information on advanced designs. The basis for this conclusion comes from relevant operating experience that informs Concepts of Operations, a considerable amount of conceptual design information in published literature, and from a predecessor plant, the Argonne National Laboratory's Experimental Breeder Reactor-II (EBR-II). Given these sources of information, this research effort has made significant progress in developing a formalized approach to the analysis and definition of AdvSMR Concepts of Operations. This phase of the project has established the framework for the definition of operational strategies, determined requirements for and a basic model of function allocation, and identified a human performance requirements approach that can be used to address staffing requirements aspects of AdvSMR concepts of operations. The report further explains how the systematic application of the methodology will produce information essential to the formalization of this new AdvSMR Function Allocation methodology while also providing essential input for the development of new models of human-automation collaboration.

CONTENTS

FIGURES

TABLES

ACRONYMS

AC	Alternating current
AdvSMR	Advanced Small Modular Reactors
AIAA	American Institute of Aeronautics and Astronautics
ANS	American Nuclear Society
ANL	Argonne National Laboratory
ANSI	American National Standards Institute
AOO	Anticipated operational occurrence
AOP	Abnormal operating procedure
AdvSMR	Advanced small modular reactor (non-light water reactor technology)
ATWS	Anticipated transient without scram
BNL	Brookhaven National Laboratory
BOP	Balance of plant
CBP	Computer-based procedure
CFR	Code of Federal Regulations
COL	Combined License (NRC)
ConOps	Concepts of operations
COSS	Computerized operator support system
CNRA	Committee on Nuclear Regulatory Activities
CSNI	Committee on the Safety of Nuclear Installations
DC	Direct current
DCD	Design control documents
DiD	Defense-in-Depth
DOE	U.S. Department of Energy
EBR	Experimental Breeder Reactor
ECCS	Emergency core cooling system
EOF	Emergency operations facility
EOP	Emergency operating procedure
EPR	European Pressurized Reactor
ESBWR	Economic Simplified Boiling Water Reactor
FA	Function allocation
FBR	Fast breeder reactor
FRA	Functional requirements analysis
FSAR	Final Safety Analysis Report
GE	General Electric
HFE	Human factors engineering
HRA	Human reliability analysis
HSI	Human-system interface
HTGR	High-Temperature Gas-cooled Reactor
HVAC	Heating, ventilation, and air conditioning
ICHSI	Instrumentation and Control and Human Machine Interface
I&C	Instrumentation and control
IAEA	International Atomic Energy Agency
ICHSI	Instrumentation and Control and Human-Machine Interface

ICU	Intensive Care Unit
IEEE	International Electrical and Electronics Engineers
IIRP	Issue Identification and Ranking Program
INCOSE	International Council on Systems Engineering
INL	Idaho National Laboratory
INPO	Institute of Nuclear Power Operators
IPWR	Integral Pressurized Water Reactor
LD	Load Dispatcher
LMR	Liquid metal reactor
LWR	Light water reactor
MCR	Main control room
MWe	Megawatts electricity
NEA	Nuclear Energy Agency
NOP	Normal operating procedure
NPP	Nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NSSS	Nuclear steam supply system
O&M	Operations and maintenance (costs)
OCC	Outage control center
OCD	Operational concept document
OECD	European Organization for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
PCS	Process control system
PCU	Power conversion unit
PPE	Personal Protective Equipment
PRA	Probabilistic risk analysis
PSER	Pre-application safety evaluation report
PWR	Pressurized water reactor
RFI	Request for information
RPS	Reactor protection system
SAMG	Severe Accident Management Guideline
SEMP	Systems Engineering Management Plan
SEP	Systems Engineering Process
SMR	Small modular reactor (based on light water reactor technology)
SPDS	Safety Parameter Display System
SSC	Structures, systems, and components
TRP	Technical Review Panel
TSC	Technical support center
TSS	Task Support System
WANO	World Association of Nuclear Operators
WDA	Work domain analysis

Advanced SMR Concepts of Operations: Report on the Development of a Technical Basis and Guidance for AdvSMR Function Allocation

1 Introduction and Background

Modern small nuclear reactors currently being designed are all expected to be simpler, safer, and more economical. These plants will be characterized by unique plant structural and functional designs and also the ability to use excess heat for industrial applications such as hydrogen generation and sea water desalination. One of the more challenging aspects of the introduction of AdvSMR into the nuclear fleet involves the detailed description of how these plants will be operated and by whom. This requires consideration of the appropriate allocation of functions between the crew and various plant systems that are likely to be highly automated. This is challenging because operating experience with SMRs outside of the U.S. Navy is limited, existing human factors and systems engineering design standards are not current in terms of human interaction basics for automated systems, and there is a lack of a technical basis for plant operational staffing that takes into account static or dynamic allocation.

One of the aspects of the operation of the emerging reactor designs not well documented in the literature was the organizational and operational impact associated with implementing these new reactors, specifically the expected impacts on engineering, operations, instrumentation and control (I&C), and maintenance functions. This is especially true for multiple-purpose hybrid energy plants where the boundaries between processes may intersect and personnel may have dual roles. No information is currently available on the type of safety critical operational scenarios that might include AdvSMR interaction with other processes. Other less safety-significant issues, but important from an economic perspective, is the approach to a clear process for monitoring and resolving conflicts among the interconnected processes. This is particularly challenging because it seems clear that operators will be faced with new tasks due to the increased ability of multi-modular plants to load-follow, to distribute load demand among multiple units, and to transition among different product streams. This will be achieved through operational concepts that would include high levels of automation, advanced human-system interface technologies, computerized procedures, and on-line maintenance of multiple reactor units. All of these features will result in new challenges for the definition of plant concepts of operations, systems design, and staffing and training. It is expected that operational sequences will include failure phenomena such as high temperature excursions and other types of disturbances not associated with light water reactor designs. Past research has shown that the new generation of reactors will include a list of human performance issues associated with such conditions and that have not been empirically evaluated in detail.

To address these issues, the AdvSMR Program has established a critical Instrumentation and Control and Human-Machine Interface (ICHMI) research pathway, which includes the investigation of the human factors issues involved in AdvSMR Concepts of Operation (Wood, 2012 [59]).

A plant's Concepts of Operations document is a high-level description of the plant, its structure, systems and their functions, and how operating personnel will interact with the system to achieve the plant goals. AdvSMR plants will require detailed definition of the unique operating scenarios that will influence the design of systems and procedures and the interaction of humans with systems and the environment. This needs to be investigated and resolved in sufficient detail to enable designers to include the operational as well as human requirements in their concepts of operations definitions.

As explained in a previous report, functions can be assigned to a human or automation agent, or to a multi-agent team. In a subsequent step the high-level allocations must be transformed into design requirements for the automation system. To achieve optimal collaboration between human and system the identified functions must be implemented in the automation system in such a manner that it allows both human and system to perform assigned functions effectively and safely. The function allocation methods that have been applied in the nuclear industry in the past were appropriate for older technology but are no longer suitable for highly automated systems. These outdated principles need to be adapted for modern nuclear power plant (NPP) designs and advanced automation systems.

The focus of this phase of research was therefore to address the specific human factors challenges related to advanced concepts of operations, with the associated changes in the allocation of functions to human and system agents. This report describes the research performed to date, which consisted of three parts: a) development of a framework for conducting a Work Domain Analysis for a predecessor sodium-cooled plant, b) development of a new foundational model for Function Allocation, and c) description of human performance considerations for AdvSMRs.

2 Project Approach

2.1 Project Objectives and Scope

This phase of the project focused primarily on developing a framework for the application of Function Analysis (FA) principles to AdvSMR concepts of operation. As explained in previous reports (cf. [23]), the Function Allocation process forms one of the elements conducted by NPP designers as part of the Human Factors Engineering Program in conformance with the requirements of NUREG-0711 (Human Factors Engineering Program Review Model). It should be emphasized that FA is not a stand-alone process and would always be performed in association with either a power plant upgrade effort (for example control room upgrade) or as part of systems engineering for a new plant. This means that the development of the foundational FA model described in this report is also not a stand-alone effort and is in fact closely linked with the development of the framework for Concepts of Operations definitions and scenario analyses. The interdependence between FA and Concepts of Operations therefore required the use of a methodology that supports the progressive refinement of analyses and structuring of the resulting information in different levels of detail.

The overall approach in this phase of the project is to conduct an in-depth analysis of the characteristics and attributes of the concepts of operations of future AdvSMRs, how the operation of these plants might be influenced by the need to integrate human factors principles in the design, and, conversely, how the role and function of humans in the plant might be affected by advanced technologies as part of the need to reduce operations and maintenance O&M costs.

These objectives are an extension of the work reported in the April 2013 milestone with emphasis on the following activities and tasks:

1. Extend the previous exploratory Work Domain Analysis (WDA) based upon a generic AdvSMR design by applying the method to a selected predecessor sodium-cooled reactor. This includes developing a framework that will allow extrapolating the information from the predecessor plant to a modern sodium-cooled reactor to allow analysis of its structural and functional characteristics.
2. Develop a foundational model and theoretical basis for allocation of functions to humans and systems for AdvSMRs. This will use insights gained from the extended WDA (task 1) and include the following subtopics:
   - Analysis of the changes needed to traditional FA models to accommodate the needs of AdvSMRs;
   - Definition of the principles of dynamic function allocation for AdvSMRs;
   - Requirements for the application of the foundational FA model to inform decision on human-automation collaboration and human-system interface design.
3. Description of the human performance criteria derived from the analysis of selected operating scenarios as part of the WDA. The main objective of this activity is to identify the human factors considerations for specific AdvSMR operational conditions and could therefore be used to identify the human performance requirements and conditions that could contribute to the likelihood of failure of humans to achieve a needed response.

These topics are interdependent and also form a logical hierarchy of detail. Concepts of Operations can be seen as the 'umbrella' that incorporates several levels of detail where each higher level contains information that serves as input to the lower level. Conversely, each lower level provides the requirements that can be used to validate the higher level. In combination, all levels of information provide essential design and implementation for downstream design, such as the automation system and HSIs.

As in previous project phases, the emphasis is on determining the means to identify human decisions, actions, interfaces, and staffing-related aspects that could impact the success of achieving critical system functions. This information will be determined largely through the WDA activity that will continue until March 2014. As indicated before, part of this process will identify how a system is to be used, where it is located, how it fits into operational sequences, and operator performance requirements in conjunction with that system. This will help to determine the impact of operators failing to meet performance requirements. The methods and procedures developed by the INL research team will specify how human performance information can be used to inform or supplement the process for addressing issues of function allocation for Concepts of Operations, and also how this information may be used by the Human-Automation Collaboration project.

This phase of the research includes the development of a framework for the application of WDA as an analytical method to inform the development of non-traditional concepts of operations. In addition, a foundational model is developed for the application of FA principles for generic AdvSMR plants. Both the WDA and FA framework will produce an essential input for AdvSMR designers to conduct task analyses and at the same time, provide input to the design of the automation system.

2.2 Significance

The April 2013 milestone report [23] described how the innovative design concepts expected for AdvSMR plants will require new approaches to the analysis and definition of human factors requirements. Of particular importance is the need to achieve more efficient and cost-effective operations, not only in the control room, but also for the plant as a whole. All innovations will have a significant influence on the role and functions of operating personnel. To define the human performance requirements for the new generation of multi-modular plants, research is required to provide technical bases for designers to incorporate these principles in their designs. It is very likely that non-traditional operational concepts and requirements that depart from traditional light water reactor approaches will arise from new processes and technologies like advanced automation systems will include the need for smaller operating crews to achieve one of the key economic requirements for SMRs: reducing the cost of O&M.

This project addresses a number of topics that will have an impact on DOE strategies for the funding and future deployment of AdvSMR plants. This includes investigation of decision criteria[1] needed to create a framework for the development of generic as well as design-specific concepts of operations, models for FA of advanced automation schemes, criteria for designing human-centric automation systems, and criteria for staffing design.

All of the above issues form part of a plant's concepts of operations, not only as a conceptual description of the plant's operational characteristics, but also as the basis of a technical document that describes and guides the development of structures, systems and components (SSC) throughout the life cycle of the new construction project.

An end goal of this phase of the research is the development of a framework for the formalization of a Concepts of Operations document for AdvSMRs, as described in the April 2013 milestone report. The results from this phase will demonstrate the importance of a structured approach to the analysis of a large amount of information necessary before designers can proceed with confidence to design actual SSC for the plant. This report also demonstrates the critical importance of integrating human factors considerations into the systems engineering process throughout the project lifecycle.

---

1 The development of decision criteria for the design of human-centric automation systems and criteria for staffing design will form part of work planned for FY 2014.

2.3 Assumptions and Constraints

The constraint described in the April 2013 report must be reiterated here: the only predecessor plant that could provide useful design information and operating experience for the purpose of this project was the Experimental Breeder Reactor-II (EBR-II), shut down in 1994. Since this sodium-cooled reactor was operated successfully for thirty years, it was assumed that its design and operation would provide a valid basis for some of the operating concepts for modern reactors. This task was made easier by the EBR-II operating procedures, drawings and system descriptions that became available to the authors. It was further assumed that current human factors literature would provide a rich and valid theoretical basis for the development of a conceptual function allocation model as well as direction for the determination of human performance criteria.

2.4 Methodology

The method followed in 2013 was an extension of the studies initiated in 2012, the aim of which has been to determine the functional, structural and operational characteristics of AdvSMR designs. The current report summarizes the extended literature reviews, leverages the findings of the April milestone report and synthesizes new information from the relationship between the WDA and FA.

Additional literature was reviewed on operator roles, responsibilities, and performance requirements in environments that employ advanced technologies. The review and evaluation of the FA literature was performed in the context of applicability to AdvSMRs, and establishes human factors engineering (HFE) design input to the design life cycle for AdvSMR design and deployment. It was confirmed again that the development of the next generation of HSIs for the next generation of operators working in concert with advanced automation systems is a key aspect of the technical basis for new concepts of operation and a robust function allocation strategy. The most recent publications (e.g., Naiker, 2013 [35], Sanderson et al., 2012 [52], and Woods & Hollnagel, 2006 [60]) emphasize that the only rational approach to incorporating human considerations in the development of first-of-a-kind power plants is to follow a formal, structured methodology that supports the analysis and description of the environmental and functional constraints that would be placed on human actors by the new design. In particular, these sources highlight the importance of making a distinction between design decisions that are mandated by the physics of the process, and those that are subject to analysis and optimization by considering a large number of factors, such as cost, complexity, available technology, and human abilities and limitations.

The review confirmed the previous finding that any strategy for the development of future AdvSMR concepts of operations would not be possible without first conducting a WDA. This report describes how the results from the WDA would help not only in informing the development of non-traditional concepts of operations, but would also provide essential information for the analysis of the requirements for allocating functions to humans, machines or a combination, and ultimately for the design of the automation system and other systems that require human involvement.

3 Work Domain Analysis as Organizing Framework for Concept of Operations Analysis and Design

3.1 Methodology Review

It was explained in the April 2013 milestone report that Cognitive Work Analysis (CWA) is a structured framework for the analysis and development of complex socio-technical systems. The framework leads the analyst to consider the environment within which operational functions and tasks take place and the effect of the imposed constraints on the system's ability to perform its purpose. The framework guides the analyst through the process of answering the question of *why* the system exists; *what* activities are conducted within the domain as well as *how* this activity is achieved and *who* is performing it (Jenkins et al., 2008 [25]).

CWA focuses on identifying properties of the work environment and of the workers themselves that determine possible constraints on the ways that humans might interact with systems in the environment, without explicitly identifying specific sequences of actions (*formative modeling*) (Hassall & Sanderson, 2012 [16], Naiker 2013 [35]).

CWA can be broken down into 5 phases, each with a defined outcome that serves as input to the next phase [57]. (The blue text highlights this project's emphasis on WDA):

Table 1: Cognitive Work Analysis Phases

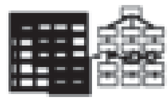
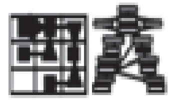
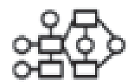
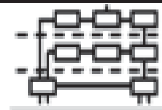
Phase	Product
Work Domain Analysis	Abstraction-Decomposition Framework and System Decomposition
Activity Analysis	Decision Ladders
Strategies Analysis	Course of Action, Information Flow Map
Social Organization and Cooperation Analysis	Combination of previous
Worker Competencies Analysis	Skills, Rules, Knowledge Inventory, high-level function allocations

WDA is the foundation upon which everything else is built. As a general rule, and even more so for first of a kind engineering such as the design of multi-unit AdvSMR, efforts that skip WDA and only perform activity analysis or task analysis will fall short of the mark in delivering a viable human factors product. Analysis of the work domain and its functional and structural characteristics identifies a fundamental set of constraints on the actions of any actor, thus providing a solid foundation for subsequent analysis and design phases. 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 (Naikar et al. 2005 [34], Naikar, 2013 [35]). Therefore, the work system environment that the task is conducted in has the potential to significantly affect the task and ultimately the entire plant operation. CWA, and specifically WDA, is particularly suitable as an organizing framework for analysis of the key principles of AdvSMR operation.

The next table shows the contents of the various phases through all phases of the project lifecycle[2]:

[2] Adapted from Vicente (1999) [57] and Sanderson at al. (2012) [52]

Table 2: The contribution of different phases in CWA to activities and needs at different points in the system life-cycle

				*Annotation of other diagrams*	
Phases of CWA:	**WDA**	**Activity Analysis**	**Strategies Analysis**	**Social Organization Analysis**	**Worker Competencies Analysis**
Content of phase:	*Purpose and Structure*	*Control Tasks and Coordination*	*Course of action*	*Roles and teamwork*	*Skills, Rules, Knowledge*
Requirements	Develop				
Specifications	Develop	Develop			
Concepts of Operations	*Develop*				
Design:					
Hardware, software	Define				
Control Tasks		Define			
Dialog support			Define		
Actor Roles and Function Allocation				*Define*	
Automation System Functions				*Guide*	
Interface formats					Define
Design Evaluation	characterize/ evaluate/ compare	characterize/ evaluate/ compare	characterize / evaluate/ compare	characterize/ evaluate/ compare	characterize/ evaluate/ compare
Implementation	guide				
Test	judge match	judge performance	judge process	judge roles	judge workload
Operator selection (Staffing)				*guide*	*guide*
Operator training	guide	guide	guide	guide	guide
Routine use	describe	describe	describe	describe	describe
Non-routine use	describe	describe	describe	describe	describe
Maintenance	describe				
Upgrades & modifications	model effects	model effects	model effects	model effects	model effects
Decommissioning	judge shortfall	judge shortfall			

Both tables above highlight WDA as the first phase of CWA and the method used during this phase of the project to analyze and define the task environment for AdvSMRs. Table 2 also indicates (in red italics) the crucial contributions of CWA to this project: inputs to Concepts of Operations, FA, Automation System design, and Staffing.

3.2 Integration of Work Domain Analysis with the Systems Engineering Process

Integration of human factors in engineering processes is not new. It is regarded as best practice by most military forces worldwide, and also by large organizations, like Ford Motor Company, Lloyds Register, the Human Factors Integration Defense Technology Center, the UK Health and Safety Executive, NASA, the aviation industry worldwide, and many other reputable organizations. Hugo (2013 [24]) points out that all of these organizations integrate human factors in their engineering processes to combine the broad ranging concerns of human-centered system design and align these with the focus of the engineering activities. Organizations like the International Council on Systems Engineering (INCOSE) and the Institute of Electrical and Electronics Engineers (IEEE) emphasize that the systems engineering process should be guided by a formal plan for human factors integration that is used concurrently with the system development plan. A human factors integration plan typically establishes the guidance to be followed by the project to implement the best-practice human factors methods, as well as the principles involved. It describes the project organization, methods, processes and controls necessary over the entire life cycle of the system from the concept phase through to commissioning and operations.

According to Hugo (*ibid.*), much of the same is true for the nuclear industry. The large body of literature (textbooks, regulatory guidelines, standards, processes and methodologies) that has evolved since the Three Mile Island accident has implicitly had the intention of providing guidance for controlling human factors activities and ensuring that they are integrated with the mainstream of engineering development. Whatever type of system is being developed, the appropriate action is suggested by some underlying principles of good human factors practice. As described in this report, there is ample evidence that WDA constitutes a best-practice approach, especially for mission-critical projects.

Translating the union of all the engineering and human factors elements into an integrated systems engineering process is not a trivial undertaking and representing this process visually is difficult. However, it is possible to simplify this as a high-level overview. The simplified process map (Figure 1) illustrates a generic Systems Engineering Process (SEP) with the human factors inputs and outputs. This diagram highlights the place of WDA and FA in the process as well as the most important feedback loops for verification and validation.

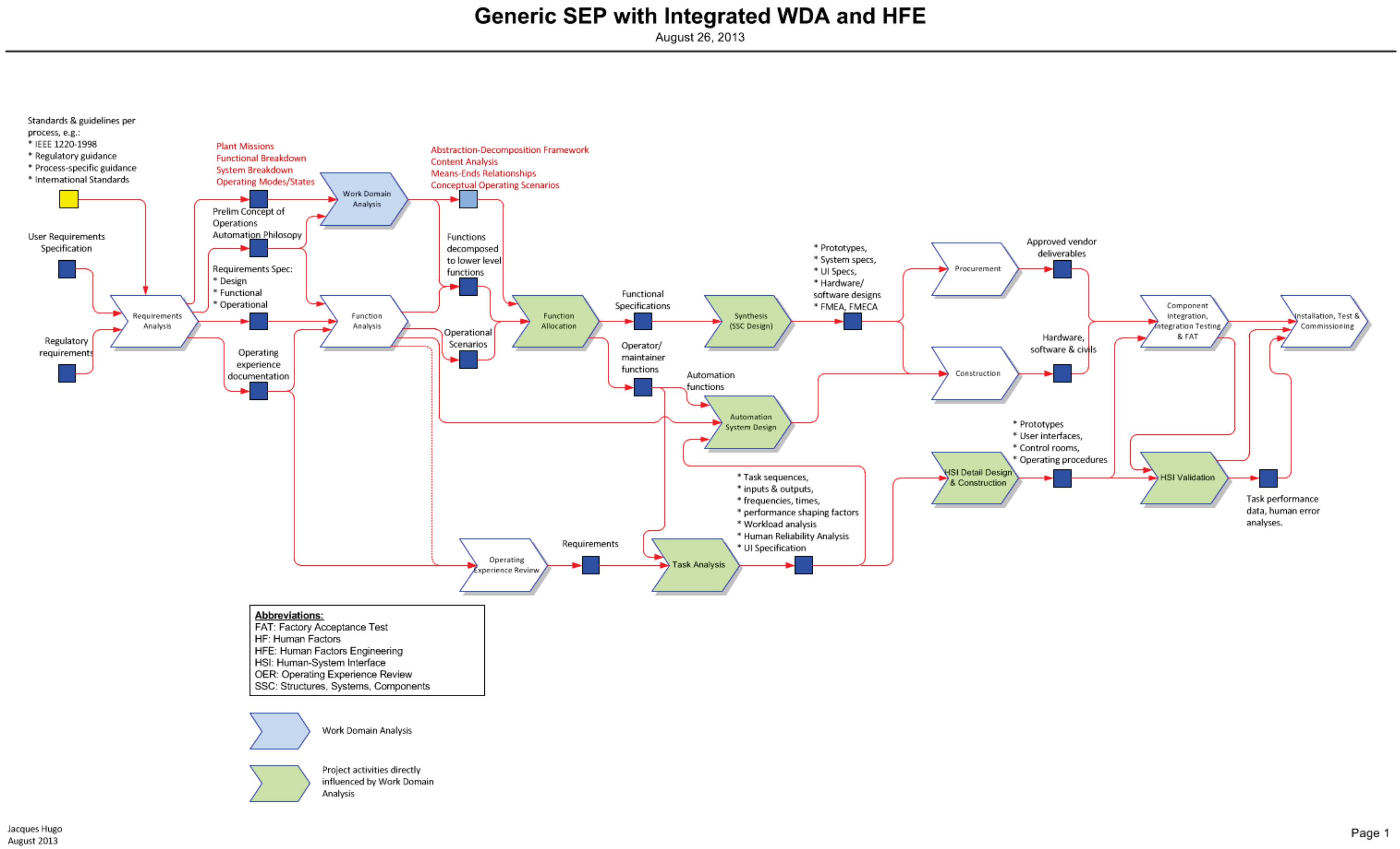


Figure 1: Integrated Systems Engineering Process with WDA

As shown in Figure 1, in combination, the goals and purposes of the work domain define the fundamental problem space of workers and include the values, priorities, and functions that must be achieved by a work system with a given set of physical resources. However, within these constraints, workers have many options or possibilities for action in the work domain. This becomes the basis for the further allocation of functions to humans or systems, the analysis of tasks, determination of skills, rules and knowledge involved in those tasks, the definition of operating principles and requirements, and ultimately the design of human-system interaction tools to enable operators to perform the identified tasks effectively, efficiently and safely.

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

As explained in the September 2012 and April 2013 milestone reports [22],[23], WDA has never been applied in the development or analysis of concepts of operation in the nuclear industry. Previous efforts in various industries to standardize the format and the process of developing concept of operations documents have also not paid much attention to human factors issues. Nevertheless, examples in the literature (Roth, Patterson and Mumaw, 2012 [51]; Bisantz and Vicente, 1994 [1] and Kim 2011 [29]) suggest that WDA is the most systematic and structured method for this purpose.

Several other authors also make a strong case for not relying on paradigms that might have applied thirty or forty years ago when control system technology was primitive compared to today's advanced automation systems and human-system interfaces:

> "*If we design based on pre-existing behaviors and mistaken mental models, we are designing for failure and not for improvement or innovation*". (Katopol, P. 2006 [27]; 2007 [28]).

This does not mean that AdvSMR designers should try to innovate just for the sake of innovation; rather it means that we should recognize that new technology often requires not just new design techniques, but also new mental models. This will enable us to cross the chasm between the old, often ineffective paradigms, and advanced design approaches that are not just different, but add significant value in both human and technological terms. The extensive literature on CWA and WDA suggests that the nuclear industry is in serious need of a methodological makeover, especially with regard to the way operating concepts are designed and the roles of humans are defined.

3.3 Selection of a Reference Design

Molten-salt reactors are currently regarded as one of the most prominent AdvSMR designs and the design most likely to be licensed within the next ten to fifteen years. However, none of the reactor designs currently in progress (e.g., Toshiba 4S, GE PRISM, Korean SMART, etc.) is mature enough to have design information available for analysis. It was therefore decided in 2012 to conduct an exploratory exercise using information from a predecessor sodium-cooled reactor. The subject matter and relevant information was derived from the design of the EBR-I and EBR-II reactors. A subject matter expert who was an operator on EBR-II is currently assisting with the analysis. The results from the FY12 exploratory analysis of EBR-II confirmed that WDA is a powerful method to structure a large part of the research planned for the next phase of the project. The primary focus for FY13 was thus on developing a framework for the application of relevant aspects of WDA to EBR-II. This methodology was verified by extending the previous exploratory exercise with additional EBR-II information. This included a brief survey of EBR-II operating modes and states captured through the Contextual Activity Analysis part of the WDA. Information like this, combined with human performance criteria, could also be used to assess the crew performance aspects associated with the identified operational concepts. These results helped to define a framework for a full WDA that will be used to extrapolate EBR-II operating principles to a more modern sodium-cooled reactor design, based upon various assumptions, such as modularity, plant layout, and higher levels of automation. The ultimate aim is twofold: a) to produce a set of unique AdvSMR operational scenarios for at least one candidate design and b) to formalize and document the methodology for future application by AdvSMR designers and human factors analysts.

3.4 Phase 1 Work Domain Analysis Results for EBR-II

Following the analysis of literature on CWA, the research team collected and analyzed the following documents from the EBR-II archives:

- Operating Instructions, Vol 1 – 7
- Technical Specifications
- System Design Descriptions – Primary and Secondary Systems
- Emergency Procedures
- Probabilistic Risk Assessment – Sections 1 – 14
- Reactor System Training Manuals Vol 1 - 5

From these documents a high-level WDA was conducted for the following scenarios:

- Normal Power Operation (Steady State)
  - Plant Startup
  - Hot standby
  - Cold Shutdown
  - Restricted Fuel Handling
  - Unrestricted Fuel Handling
- Abnormal Operations: Secondary Sodium system
  - Water to sodium leak (H_2O – Na)
  - Minor earthquake
  - Major sodium leak in reactor outlet piping
  - Reactor scram (auto or manual)
  - Loss of normal electric power.

The following state-transition diagram (Figure 2) was developed and used in conjunction with the documents listed above as the basis for identifying important normal and abnormal operating conditions.

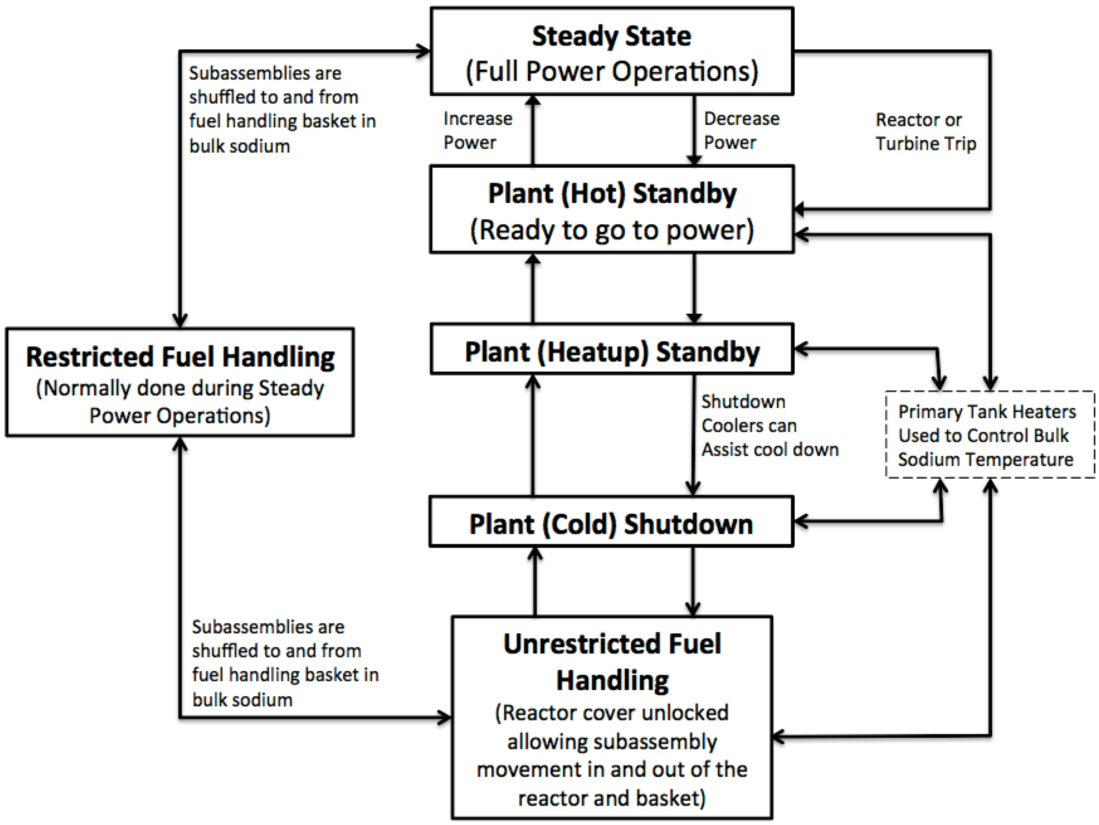


Figure 2: EBR-II State Transition Diagram

3.4.1 EBR-II State Matrices

This state transition diagram was further elaborated in a preliminary state matrix for normal and abnormal operating conditions (fault modes) (Table 3 and Table 4). These matrices describe the operating conditions for the following major systems:

- Reactor cooling system
- Control rods and safety rods
- Secondary sodium system
- Emergency shutdown coolers
- Turbine generator
- Condensate and feedwater system
- Main steam system
- Evaporators and superheaters
- Fuel handling and associated equipment
- Electric plant

Table 3: EBR-II State Matrix for Primary Systems and Normal Operations

EBR-II - Normal Operations State Matrix						
System/Mode	**Unrestricted Fuel Handling**	**Plant (Cold) Shutdown**	**Plant (Heatup) Startup**	**Plant (Hot) Standby**	**Power Operation (Steady Power)**	**Restricted Fuel Handling**
	(This is typical fuel shuffling with the reactor shutdown)	**(Typical plant shutdown for maintenance)**		**(A condition of readiness – ready to go to power)**		**(Steady Power Operations – Allows for subassemblies to be removed from/placed into the fuel basket only)**
Reactor Cooling System	RCPs: S/D Aux Pump: S/D Primary Flow: 0 gpm Bulk Na Temp: Core cooling: N/A Rx Power: 0% Cover Gas: 6-7 psig Primary Tank Heaters: Energized	RCPs: S/D Aux Pump: S/D Primary Flow: 0 gpm Bulk Na Temp: 350-695 F Core cooling: S/D Coolers Rx Power: 0% Cover Gas: 6-7 psig Primary Tank Heaters: Energized	RCPs: 32 – 98% Flow Aux Pump: 100% (575 gpm) Primary Flow: 100% (9000 gpm) Bulk Na Temp: 350-695 F Delta Temp: 2 F/min Rate (max) Core cooling: IHX Rx Power: 0-100% Cover Gas: 6-7 psig Primary Tank Heaters: Deenergized at 700 F Bulk Na Temp Limitations: RCS H/U Rate 10 F/Hr Max	RCPs: 100 % Aux Pump: 100% (575 gpm) Primary Flow: 100% (9000 gpm) Bulk Na Temp: 695 – 705 F Delta Temp: 183 F Core cooling: Rx Power: 0% Cover Gas: 6-7 psig Primary Tank Heaters: Energized – Variable output based on Bulk Na Temp	RCPs: 100% Flow Aux Pump: 100% (575 gpm) Primary Flow: 100 % (9000 gpm) Bulk Na Temp: 695 – 705 F Delta Temp: 183 F Core cooling: IHX Rx Power: 100% (62.5 MWt) Cover Gas: 6-7 psig Primary Tank Heaters: Deenergized	RCPs: 100% Flow Aux Pump: 100% (575 gpm) Primary Flow: 100 % (9000 gpm) Bulk Na Temp: 695 – 705 F Delta Temp: 183 F Core cooling: IHX Rx Power: 100% (62.5 MWt) Cover Gas: 6-7 psig Primary Tank Heaters: Deenergized
Secondary (Sec.) Sodium (Na) System	Sec. Na Pump: S/D Sec. Na Temp: N/A	Sec. Na Pump: S/D Sec. Na Temp: N/A	Sec. Na Pump: Variable gpm to maintain bulk Na temp 695-705 F Argon Press: 6-7 psig	Sec. Na Pump: Variable gpm to maintain bulk Na temp 695-705 F Sec. Na Temp to Steam Drum: 866 F	Sec. Na Pump: 86 % / 5160 gpm Sec. Na Temp to Steam Drum: 866 F	Sec. Na Pump: 86 % / 5160 gpm Sec. Na Temp to Steam Drum: 866 F

EBR-II - Normal Operations State Matrix

System/Mode	Unrestricted Fuel Handling	Plant (Cold) Shutdown	Plant (Heatup) Startup	Plant (Hot) Standby	Power Operation (Steady Power)	Restricted Fuel Handling
	Press: N/A Argon Press: N/A	Press: N/A Argon Press: N/A Note: If system is drained for maintenance both Primary and Secondary Na temp should be less than 350 F		Sec. Na Temp From Steam Drum: 588 F Argon Press: 6-7 psig	Sec. Na Temp From Steam Drum: 590 F Argon Press: 6-7 psig	Sec. Na Temp From Steam Drum: 590 F Argon Press: 6-7 psig
Emergency Shutdown Coolers	Operationally Ready	Operationally Ready	Operationally Ready	Operationally Ready	Operationally Ready	Operationally Ready
	Note: S/D Coolers can be used to assist plant cool down (dampers open)	Note: S/D Coolers can be used to assist plant cool down (dampers open)				
Turbine Generator	Offline	Offline Note: Turbine Generator will be unloaded at Rx Power 18-20 MWt	Turbine warm-up in progress	Condenser providing steam dump	Turbine Generator: Loaded	Turbine Generator: Loaded
		Condenser providing steam dump			Power Output: 20 MWe	Power Output: 20 MWe
Condensate and Feedwater System	Offline. Typically drained for work on much of condensate and feedwater system	Offline. Typically drained for work on much of condensate and feedwater system	Filled and vented. Perhaps being recirculated by operating condensate pumps to clean piping and water to acceptable purity and low oxygen levels Startup Feed Pump or Emergency Feedwater Pump maintaining steam drum level.	Filled and vented. Being recirculated by operating condensate pump Startup Feed Pump or Emergency Feedwater Pump maintaining steam drum level and circulating yard lines. Feedwater Temp.	Condensate and Feedwater Systems in normal operational modes Hotwell Level: 26-29 in. Feedwater Temp: 550	Condensate and Feedwater Systems in normal operational modes Hotwell Level: 26-29 in. Feedwater Temp: 550

EBR-II - Normal Operations State Matrix

System/Mode	Unrestricted Fuel Handling	Plant (Cold) Shutdown	Plant (Heatup) Startup	Plant (Hot) Standby	Power Operation (Steady Power)	Restricted Fuel Handling
				320-330 F	F Condensate Pumps: 1 Pump in Run / 1 Stby Feedwater Pumps: 1 Pump in Run / 1 Stby	F Condensate Pumps: 1 Pump in Run / 1 Stby Feedwater Pumps: 1 Pump in Run / 1 Stby
Main Steam	Atmospheric Pressure	Atmospheric Pressure	Steam being dumped to condenser	Main steam lines being heated. Steam through Atmospheric Dump Valves or to condenser via turbine bypass system	Steam Pressure: 1250 psig Steam Temp: 820 F	Steam Pressure: 1250 psig Steam Temp: 820 F
Evaporators/ Superheaters	Offline. Typically drained for work on much of condensate and feedwater system.	Offline. Typically drained for work on much of condensate and feedwater system.	Maintain Superheater and Evaporator Shell Temps 0-50 F > Tube Temp	Maintain Superheater and Evaporator Shell Temps 0-50 F > Tube Temp	Fully Operational Na Temp from Evaporators: 590 F Na Temp to Superheaters: 866 F	Fully Operational
Fuel Handling & Associated Equipment	Small / Large Rotating Plugs: Heated to allow rotation Rx Vessel Cover: Up/Unlocked	Reactor Vessel Cover: Depends on work to be performed	Reactor Vessel Cover: Down/Locked	Reactor Vessel Cover: Down/Locked	Reactor Vessel Cover: Down/Locked	Small / Large Rotating Plugs: Frozen Reactor Vessel Cover: Down/Locked

Table 4: EBR-II State Matrix for Primary Systems and Normal Operations

EBR-II - Abnormal Operations State Matrix

System/Mode	Power Operation (Steady Power) Initial Condition for All Events	Sec. Na – Water to Na Leak	Earthquake (Minor)	Major Na Leak in Rx Outlet Piping	Reactor (Rx) Scram (Manual or Automatic)	Loss Of Normal Electric Power
Initial Indications	**N/A**	Hydrogen Meter Leak Detector (HMLD) alarm Cover Gas Meter Leak Detector (CHMLD) alarm Increasing Hydrogen (H_2) level Sec. Na High Sec. Na Press Leak Probe Detector alarms Sec. Na Relief Header flow alarm Sec. Na System Rupture Disk alarm SBB Evacuation	All rods on bottom (rod bottom lights lit) Earthquake alarms Full Rx Building Isolation Rx Building Evacuation SBB Evacuation	Increasing Bulk Na Temp Increasing primary tank cover gas temp. Decreasing IHX Sec. Na outlet temp Decreasing Rx Power Decreasing Rx Delta Temp Rx Building Evacuation	All rods on bottom (rod bottom lights lit)	Auto Rx Scram RCPs deenergized T-G Trips Sec. Na Pump Trips Sec. Na Recirc Pumps Trip EDGs auto start Primary and Sec. Heating lost Majority of electric pumps in plant deenergized
Control Rods and Safety Rods All rods on bottom (rod bottom lights lit)	Normal position for full power operations	Manual Rx Scram	Auto Rx Scram All rods on bottom (rod bottom lights lit) **Note:** Validating rods scrammed and did not bind /stick is extremely important	**Initial:** Bulk Na Temp = 720 F Anticipatory Rx S/D **Final:** If Bulk Na Temp = 725 F Manual Rx Scram	Auto or Manual Rx Scram All rods on bottom (rod bottom lights lit)	Auto Rx Scram All rods on bottom (rod bottom lights lit)
Rx Cooling System	Rx Coolant Pump (RCPs): 100% Flow Aux Pump: 100% (575 gpm)	RCPs: 100% Flow Aux Pump: 100% (575 gpm)	RCPs: 100 % Aux Pump: 100% (575 gpm)	**Initial:** RCPs: min. flow for 30 min.	RCPs: 100% Flow Aux Pump: 100% (575 gpm)	RCPs: deenergized Aux Pump: 100% (575 gpm) on battery

EBR-II - Abnormal Operations State Matrix

System/Mode	Power Operation (Steady Power) Initial Condition for All Events	Sec. Na – Water to Na Leak	Earthquake (Minor)	Major Na Leak in Rx Outlet Piping	Reactor (Rx) Scram (Manual or Automatic)	Loss Of Normal Electric Power
	Primary Flow: 100 % (9000 gpm) Bulk Na Temp: 695 – 705 F Delta Temp: 183 F Core cooling: IHX Rx Power: 100% (62.5 MWt) Cover Gas: 6-7 psig Primary Tank Heaters: Deenergized	Primary Flow: 100 % (9000 gpm) Bulk Na Temp: 695 – 705 F Delta Temp: 183 F and decreasing Core cooling: IHX Rx Power: 0 % Cover Gas: 6-7 psig Primary Tank Heaters: Deenergized	Primary Flow: 100% (9000 gpm) Bulk Na Temp: 695 – 705 F Delta Temp: 183 F Core cooling: Rx Power: 0 % Cover Gas: 6-7 psig Primary Tank Heaters: Energized – Variable output based on Bulk Na Temp	Aux Pump: 100% (575 gpm) Bulk Na Temp: 695 – 705 F and increasing Delta Temp: 183 F and decreasing Core cooling: IHX and S/D Coolers Rx Power: 100% (62.5 MWt) and decreasing Cover Gas: 6-7 psig Primary Tank Heaters: Deenergized **Final:** 30 Min. after Rx S/D or Scram secure RCPs	Primary Flow: 100 % (9000 gpm) Bulk Na Temp: 695 – 705 F Delta Temp: 183 F and decreasing Core cooling: IHX Rx Power: 0 % Cover Gas: 6-7 psig Primary Tank Heaters: Deenergized	power Primary Flow: Aux Pump only (575 gpm) Bulk Na Temp: 695 – 705 F and increasing Delta Temp: 183 F and rapidly decreasing Core cooling: IHX and S/D Coolers Rx Power: 0 % (0 MWt) Cover Gas: 6-7 psig Primary Tank Heaters: Deenergized
Secondary (Sec.) Sodium (Na) System	Sec. Na Pump: 86 % / 5160 gpm Sec. Na Temp to Steam Drum: 866 F Sec. Na Temp From Steam Drum: 590 F Argon Press: 6-7 psig	**Initial:** Press Sodium Boiler Building (SBB) Fire Push Button (P/B) Fire P/B cause trips Sec. Na Pump and Recirc. Pumps Sec. Na Pump: Deenergized (not restarted) **Final:**	Sec. Na Pump: Variable gpm to maintain bulk Na temp 695-705 F Sec. Na Temp to Steam Drum: 866 F Sec. Na Temp From Steam Drum: 588 F Argon Press: 6-7 psig	**Initial:** Sec. Na Pump: Pump tripped – off (Scram) **Final:** Restart Sec. Na Pump (alternate power) when Bulk Na Temp = 690 F Sec. Na Pump Variable gpm to maintain bulk	**Initial:** Sec. Na Pump: Pump tripped – off **Final:** Restart Sec. Na Pump (alternate power) when Bulk Na Temp = 690 F Sec. Na Pump Variable gpm to maintain bulk	**Steam Drum Level Indicated:** Sec. Na Pump: 0.1-0.3 % on Alternate Pwr Argon Press: 6-7 psig **Steam Drum Level Not Indicated:**

EBR-II - Abnormal Operations State Matrix

System/ Mode	Power Operation (Steady Power) Initial Condition for All Events	Sec. Na – Water to Na Leak	Earthquake (Minor)	Major Na Leak in Rx Outlet Piping	Reactor (Rx) Scram (Manual or Automatic)	Loss Of Normal Electric Power
		Dump Sec. Na to Sec. Na Drain Tank and allow to cool to ambient		Na temp 695-705 F Argon Press: 6-7 psig	Na temp 695-705 F Argon Press: 6-7 psig	Sec. Na Pump: Deenergized Sec. Argon Sys: vented Dump Sec. Na to Sec. Na Drain Tank and allowed to cool to ambient
Emergency Shutdown (S/D) Coolers	Operationally Ready	Operationally Ready	Operationally Ready	S/D Cooler Louvers Open when Bulk Na Temp = 710 F	Operationally Ready	S/D Cooler Louvers Open when Bulk Na Temp = 710 F Shut S/D Louvers if Bulk Na Temp <690 F
Turbine Generator (T-G)	T-G: Loaded Power Output: 20 MWe	T-G: Tripped Power Output: 0 MWe	Condenser providing steam dump	T-G: Tripped Power Output: 0 MWe	T-G: Tripped Power Output: 0 MWe	T-G: Tripped Power Output: 0 MWe
Condensate and Feedwater System	Condensate and Feedwater Systems in normal operational modes Hotwell Level: 26-29 in. Feedwater Temp: 550 F	FWPs: Deenergized Condensate and Feedwater System being S/D	Filled and vented. Being recirculated by operating condensate pump Startup Feed Pump or Emergency Feedwater Pump maintaining steam drum level and circulating yard lines.	**Initial:** Feedwater System in manual control to maintain steam drum level 30 inches Condensate Pumps: 1 Run / 1 Stby Feedwater Pumps (FWP): 1 Run / 1 Stby	**Initial:** Feedwater System in manual control to maintain steam drum level 30 inches Condensate Pumps: 1 Run / 1 Stby Feedwater Pumps (FWP): 1 Run / 1 Stby	**Steam Drum Level Indicated:** Emergency Feedwater Pump maintaining steam drum level and circulating yard lines. **Steam Drum Level <u>Not</u> Indicated:**

EBR-II - Abnormal Operations State Matrix

System/Mode	Power Operation (Steady Power) Initial Condition for All Events	Sec. Na – Water to Na Leak	Earthquake (Minor)	Major Na Leak in Rx Outlet Piping	Reactor (Rx) Scram (Manual or Automatic)	Loss Of Normal Electric Power
	Condensate Pumps: 1 Run / 1 Stby Feedwater Pumps: 1 Run / 1 Stby		Feedwater Temp. 320-330 F	**Final:** Condensate Pumps: 1 Run / 1 Stby FWPs: Secured	**Final:** Condensate Pumps: 1 Run / 1 Stby FWPs: Secured	Emergency Feedwater Pump: deenergized
Main Steam	Steam Pressure: 1250 psig Steam Temp: 820 F Generator Power: 20 MWe	Steam drum isolated on FW and Steam side Steam Dump Valve actuated: immediately drains Steam Drum to Steam Generator Water Dump System (SGWDS) Fill Steam Drum (water side) with Argon gas	Main steam lines being heated. Steam through Atmospheric Dump Valves or to condenser via turbine bypass system	Steam Pressure: 1250 psig and rapidly lowering Steam Temp: 820 F and rapidly lowering	Steam Pressure: 1250 psig and rapidly lowering Steam Temp: 820 F and rapidly lowering	**Steam Drum Level Indicated:** Main Steam Stop shut **Steam Drum Level <u>Not</u> Indicated:** Steam drum isolated on FW and Steam side Steam Dump Valve actuated: immediately drains Steam Drum to Steam Generator Water Dump System (SGWDS)
Evaporators/	Fully Operational	Rapid drain on Na and Water sides	Maintain Superheater and Evaporator Shell Temps 0-50 F > Tube	Fully Operational	Fully Operational	**Steam Drum Level <u>Not</u> Indicated:**

EBR-II - Abnormal Operations State Matrix

System/Mode	Power Operation (Steady Power) Initial Condition for All Events	Sec. Na – Water to Na Leak	Earthquake (Minor)	Major Na Leak in Rx Outlet Piping	Reactor (Rx) Scram (Manual or Automatic)	Loss Of Normal Electric Power
			Temp			
Superheaters	Na Temp from Evaporators: 590 F Na Temp to Superheaters: 866 F	Cooling towards ambient temperature		Na Temp from Evaporators: 590 F and lowering Na Temp to Superheaters: 866 F and lowering	Na Temp from Evaporators: 590 F and lowering Na Temp to Superheaters: 866 F and lowering	Rapid drain on Na and Water sides Cooling towards ambient temperature Dry layup
Fuel Handling & Associated Equipment	Rx Vessel Cover: Down/Locked Large & Small Plug seals frozen	Rx Vessel Cover: Down/Locked Large & Small Plug seals frozen	Rx Vessel Cover: Down/Locked Large & Small Plug seals frozen	Rx Vessel Cover: Down/Locked Large & Small Plug seals frozen	Rx Vessel Cover: Down/Locked Large & Small Plug seals frozen	Rx Vessel Cover: Down/Locked Large & Small Plug seal heaters power supply switched to emergency power
Electric Plant	Emergency Diesel Generators (EDGs): In Stby	EDGs: In Stby	EDGs: In Stby	EDGs: In Stby	EDGs: In Stby	EDGs: In Run and loaded supplying emergency electrical distribution panels

3.4.2 EBR-II Abstraction-Decomposition

When all the elements described above are broken down (decomposed) in terms of Total System (also called “Structures”), Subsystem and Components, the Abstraction Hierarchy and Abstraction-Decomposition Framework (in some literature also called the ‘abstraction-decomposition space”) are produced.

Based upon the system breakdown, a set of high-level abstraction hierarchy diagrams, abstraction-decomposition frameworks, and contextual activity templates were developed for selected normal and abnormal operating scenarios. The diagrams show the abstraction (that is, described bottom-up in decreasing levels of detail) of the EBR-II work domain in terms of physical objects (systems and components) at the lowest level, object related processes, purpose-related functions, values and priority measures, and functional purpose at the highest level. It also shows the “why-what-how” means-ends links described in an earlier report.

The diagrams on the following pages illustrate the preliminary results as follows:

- Figure 3: Abstraction Hierarchy for EBR-II Normal Operations, showing the means-ends links for the primary systems.
- Figure 4: Abstraction-Decomposition Framework for EBR-II Normal Operations (Note that the system decomposition shown is conceptual only and will be refined durin g the detailed research, to be reported in March 2014).
- Figure 5: Contextual Activity Template for EBR-II Normal Operations
- Figure 6: Abstraction Hierarchy for EBR-II Abnormal Operations, showing the means-ends links for the systems involved in the selected scenarios
- Figure 7: Abstraction-Decomposition Framework for EBR-II Abnormal Operations
- Figure 8: Contextual Activity Template for EBR-II Abnormal Operations

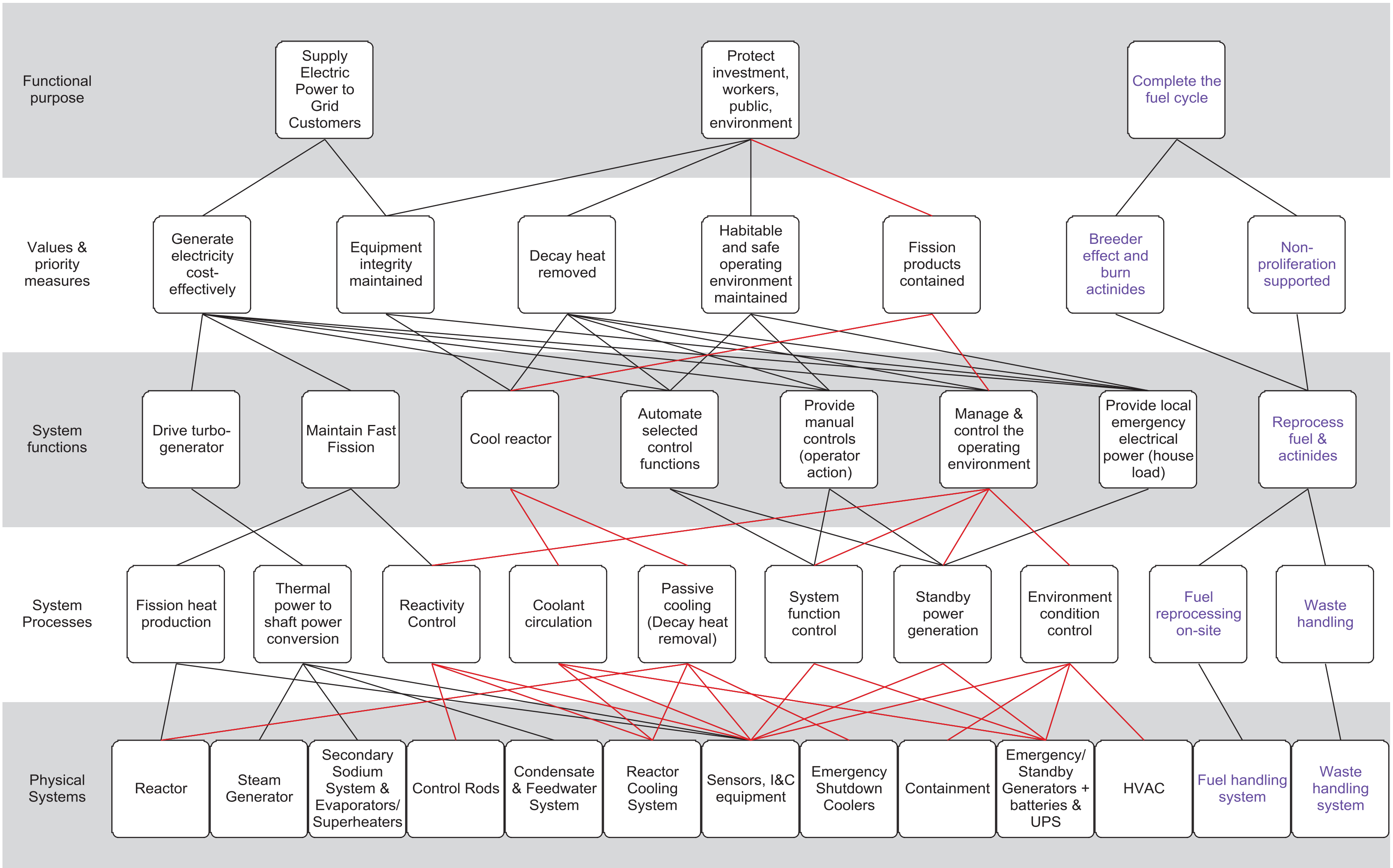


Figure 3: Abstraction Hierarchy - EBR-II Normal Operations

Abstraction \ Decomposition	Total System	Subsystem	Component
Functional purpose	Supply Electric Power to Grid Customers Protect investment, workers, public, environment	Complete the fuel cycle	
Values & priority measures	Generate electricity cost-effectively	Equipment integrity maintained Decay heat removed Habitable and safe operating environment maintained Fission products contained	Breeder effect and burn actinides Non-proliferation supported
System functions	Drive turbo-generator Cool reactor	Maintain Fast Fission Manage & control the operating environment Provide local emergency electrical power (house load)	Automate selected control functions Provide manual controls (operator action) Reprocess fuel & actinides
System Processes	Fission heat production Thermal power to shaft power conversion Passive cooling (Decay heat removal)	Reactivity Control Coolant circulation System function control Environment condition control Fuel reprocessing on-site Waste handling	Standby power generation
Physical Systems	Reactor Steam Generator Reactor Cooling System	Secondary Sodium System & Evaporators/ Sup Control Rods Condensate & Feedwater System Emergency Shutdown Coolers Containment HVAC Fuel handling system Waste handling system	Emergency/ Standby Generators + batteries & UPS Sensors, I&C equipment

Figure 4: Abstraction-Decomposition Framework - EBR-II Primary Systems and Functions – Normal Operations

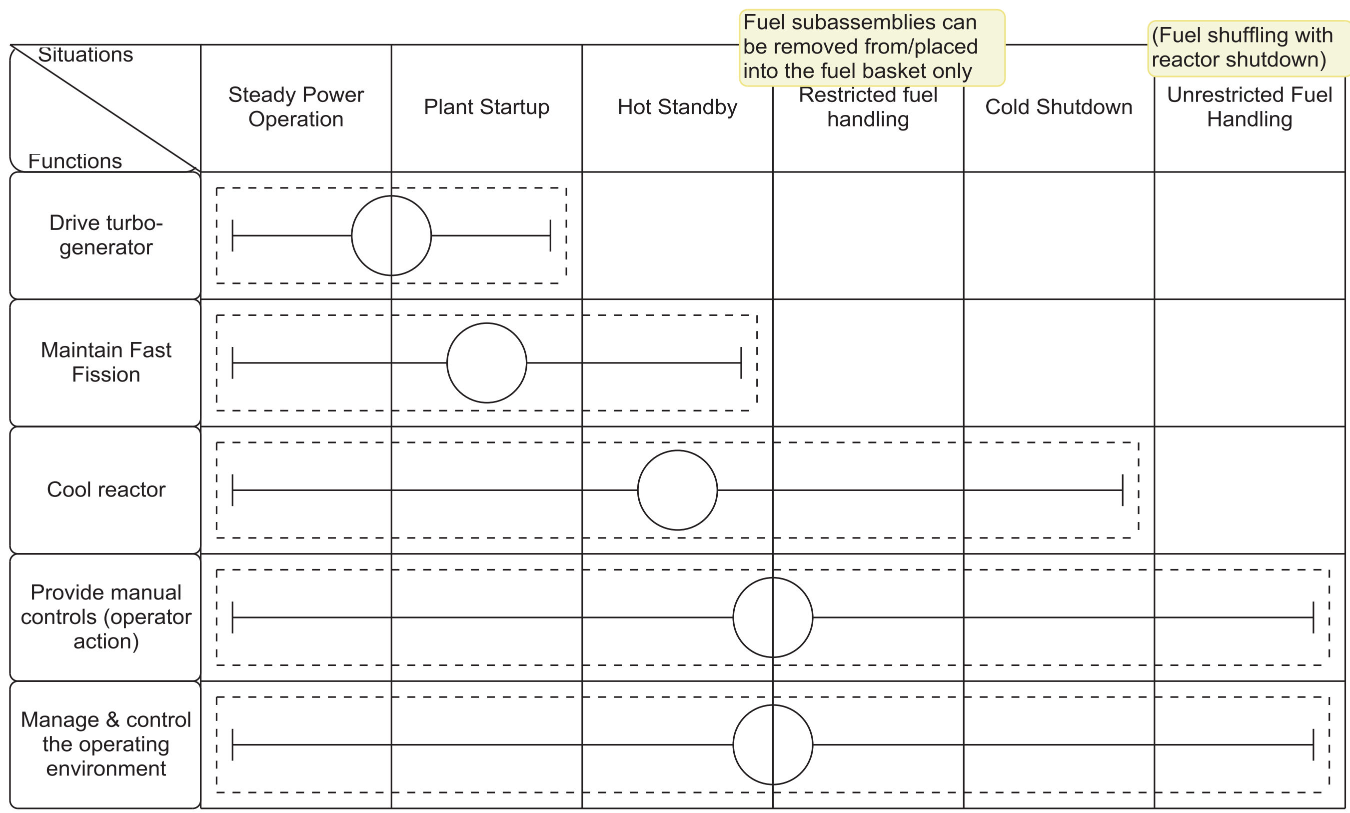


Figure 5: Contextual Activity Analysis for EBR-II Normal Operations

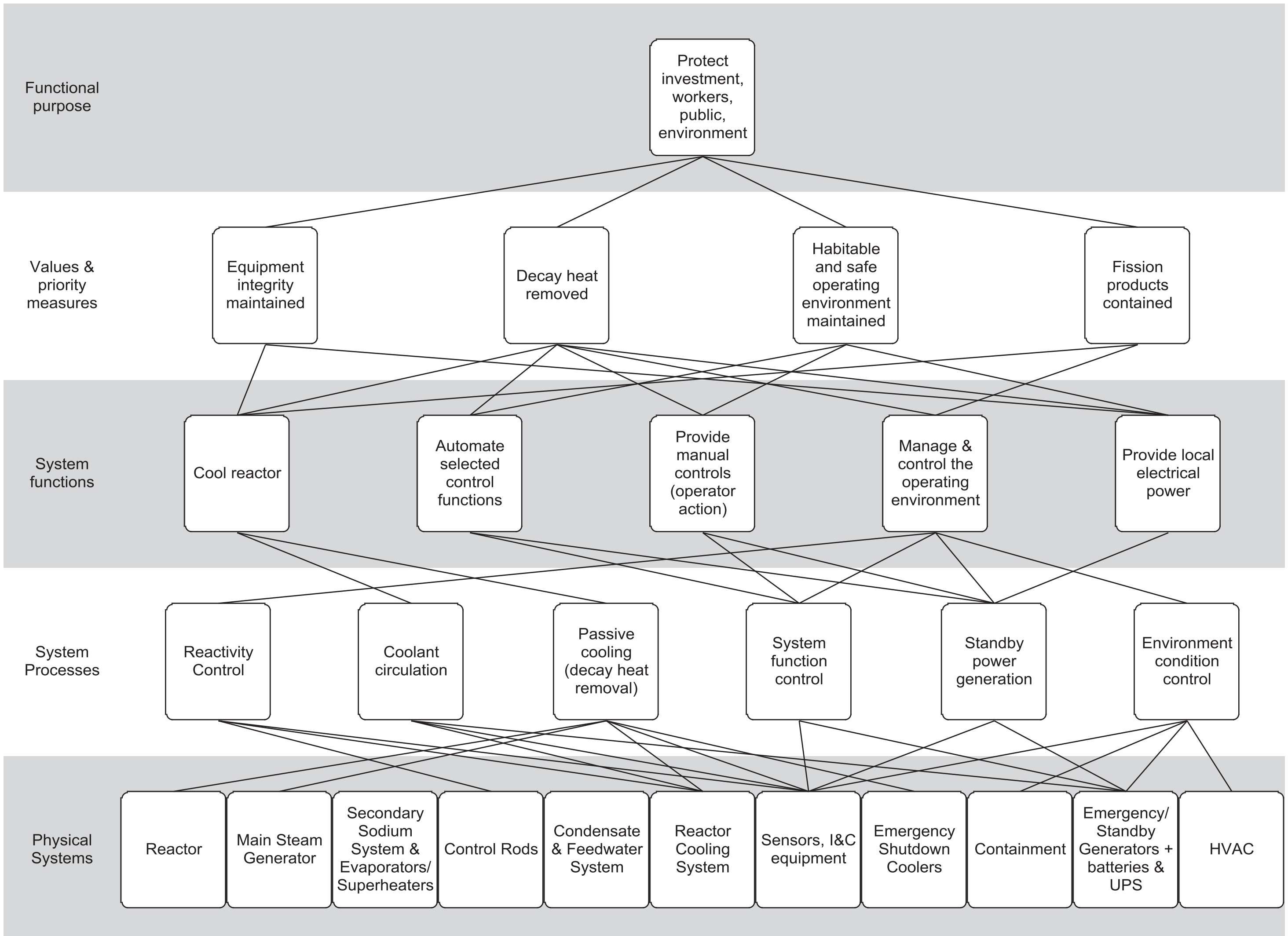


Figure 6: Abstraction Hierarchy - EBR-II Abnormal Operations

Decomposition / Abstraction	Total System	Subsystem		Component
Functional purpose	Protect investment, workers, public, environment			
Values & priority measures	Equipment integrity maintained	Decay heat removed		
	Habitable and safe operating environment maintained	Fission products contained		
System functions	Cool reactor	Manage & control the operating environment		Automate selected control functions
		Provide local electrical power		Provide manual controls (operator action)
System Processes	Passive cooling (decay heat removal)	Reactivity Control	Coolant circulation	Standby power generation
		System function control	Environment condition control	
Physical Systems	Reactor	Secondary Sodium System &	Control Rods	Sensors, I&C equipment
	Main Steam Generator	Condensate & Feedwater Syste	Emergency Shutdown Coolers	Emergency/ Standby Generators + batteries & UPS
	Reactor Cooling System	Containment	HVAC	

Figure 7: Abstraction-Decomposition Framework - EBR-II Primary Systems and Functions – Abnormal Operations

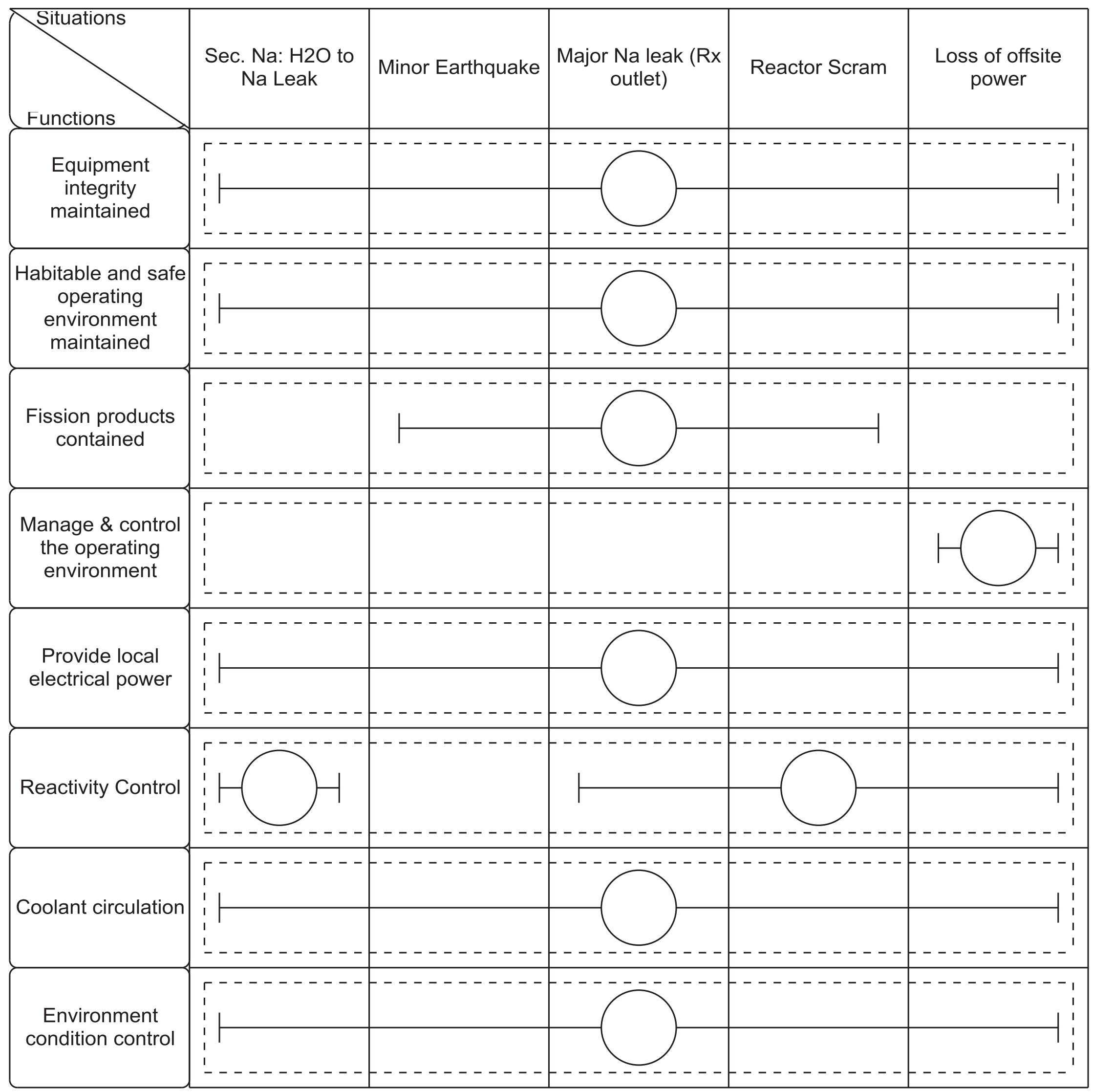


Figure 8: Contextual Activity Analysis for EBR-II – Abnormal Operations

This high-level analysis shows that three key functional purposes or goals can be identified for the EBR-II:

- Supply electric power to grid customers
- Protect workers, public, investment, and environment
- Complete the fuel cycle.

(Note that the systems and functions related to the "Complete the Fuel Cycle" mission shown in the abstraction hierarchy do not take part in power production – these elements are colored purple in the diagram. In the detailed analysis planned for FY14, this operating mission will be treated separately).

3.4.3 Scenario Analysis

Finally, one of the abnormal operating scenarios identified was analyzed in detail to establish a procedure for the second phase of the WDA, which would be the preparation for translating the EBR-II WDA to an advanced design such as the Toshiba 4S.

Table 5 represents the format for operating scenario analysis and the kind of information that would be used in the development of the WDA and ultimately also for other phases of CWA.

The table describes the thirty-two criteria that are necessary to describe a scenario, the systems involved, the primary roles of operators, start and end conditions, system performance parameters, and many more.

Table 5: Scenario Analysis Example: Secondary Sodium System - Water to sodium leak

Item	Item Name	Item Description
1	Scenario ID	Event 1
2	Name	Secondary Na System: Water to Na Leak
3	Type	Transient/Fault mode
4	Scenario Description	- Alarms are received on the Hydrogen Meter Leak Detector (HMLD) and/or Secondary Cover Gas Hydrogen Leak Detector (CHMLD) hydrogen level or rate-of-rise data on the plant computer. - The trend data for hydrogen will be on the rise. - All operating leak detectors should show upward trends within 5 minutes at full power operations for valid leak.
5	Related function	Related Events with similar actions: - Reactor Scrams for other events - Secondary Sodium Pump Leak event - Sodium Leak in the Secondary Sodium System event
6	Mode/state	Initial mode/state - Full Power Operations (Steady State with Turbine Generator providing power to the electrical grid). Final mode/state - Reactor shutdown, secondary sodium system drained and at ambient in draining tank, steam generator water and steam drained and back filled with argon, steam plant shutdown and cold, primary sodium normal state with primary tank heaters maintaining bulk sodium temperature.
7	Initiating conditions	Initial Event Alarms: - Hydrogen Meter Leak Detector (HMLD) alarm - Cover Gas Meter Leak Detector (CHMLD) alarm - Increasing Hydrogen (H2) level secondary sodium

Item	Item Name	Item Description
		- High Sec. Na Press - Leak Probe Detector alarms - Secondary Sodium Relief Header flow alarm - Secondary Sodium System Rupture Disk alarm
8	Start state(s)	Reactor: - Control & Safety Rods positioned for full power operations - Reactor Power: 100% (62.5 MWt) Electric Plant: - Normal Power available - Emergency Diesel Generators: In Standby - Turbine Generator: Supplying the electrical grid @ 20 MWe Primary Sodium Systems: - Rx Coolant Pump (RCPs): 100% Flow - Aux Pump: 100% (575 gpm) - Primary Flow: 100% (9000 gpm) - Bulk Na Temp: 695 – 705°F - Delta Temp: 183°F - Core cooling: Intermediate Heat Exchanger to Secondary Sodium - Primary Cover Gas: 6-7 psig - Primary Tank Heaters: Deenergized Emergency Shutdown Coolers: Operationally ready Secondary Sodium Systems: - Secondary Sodium Pump: 86 % (5160 gpm) - Secondary Sodium Recirculating Pumps operating normally - Secondary Sodium Temp to Steam Drum: 866°F - Secondary Sodium Temp From Steam Drum: 590 °F - Secondary Argon Press: 6-7 psig - Sodium Boiler Building Fire Pushbutton depressed: Operationally Ready - Secondary Sodium Drain Tank: Operationally ready Condensate and Feedwater Systems – Normal Full Power mode - Hotwell Level: 26-29 inches - Feedwater Temp: 550°F - Condensate Pumps: 1 Run / 1 Standby - Feedwater Pumps: 1 Run / 1 Standby Main Steam System: - Steam Pressure: 1250 psig - Steam Temp: 820°F Evaporators & Superheaters: - Fully operational - Sodium Temp from Evaporators: 590°F

Item	Item Name	Item Description
		- Sodium Temp to Superheaters: 866°F Fuel Handling and Associated Equipment: - Rx Vessel Cover: Down/Locked - Large & Small Plug seals frozen
9	End state(s)	Reactor: - Control & Safety Rods full down (manual reactor scram) - Reactor Power: 0% (0 MWt) Electric Plant: - Normal Power available - Emergency Diesel Generators: In Standby - Turbine Generator: Tripped by manual scram @ 0 MWe Primary Sodium Systems: - Rx Coolant Pump (RCPs): 100% Flow - Aux Pump: 100% (575 gpm) - Primary Flow: 100% (9000 gpm) - Bulk Na Temp: 695 – 705 °F - Delta Temp: <183 °F and decreasing rapidly toward 0 °F as decay heat dissipates - Core cooling: Ambient heat loses through primary tank - Primary Cover Gas: 6-7 psig - Primary Tank Heaters: Deenergized, to be energized as needed when primary temperature decreases Emergency Shutdown Coolers: Operationally ready Secondary Sodium Systems: - Secondary Sodium Pump: 0 % (0 gpm) deenergized (not restarted) - Secondary Sodium Recirculating Pumps deenergized (not restarted) - Secondary Sodium Temp to Steam Drum: rapidly decreasing to ambient - Secondary Sodium Temp From Steam Drum: rapidly decreasing to ambient - Secondary Argon Press: 6-7 psig - Sodium Boiler Building Fire Pushbutton depressed: Trips Sec. Sodium and Recirculating Pumps - Secondary Sodium dumped to Drain Tank and allowed to cool to ambient Condensate and Feedwater Systems - cold shutdown mode - Hotwell Level: N/A - Feedwater Temp: Ambient - Condensate Pumps: shutdown - Feedwater Pumps: shutdown

Item	Item Name	Item Description
		Main Steam System: - Steam Pressure: 0 psig - Steam Temp: 0 F Evaporators & Superheaters: - Drained on both sodium and water sides - Sodium Temp from Evaporators: rapidly decreasing temperature - Sodium Temp to Superheaters: rapidly decreasing temperature Fuel Handling and Associated Equipment: - Rx Vessel Cover: Down/Locked - Large & Small Plug seals frozen
10	Related system(s)	Steam Drum,
11	Personnel Involved	Shift Manager (SM) Senior Reactor Operator (SRO) Coolant System Operator (CSO) (1Roving and 1 Console) Power Plant Operator (PPO)(Includes Power Plant and Electrical Plant) Chemistry Technician (Chem Tech)
12	Operator role	The main role operators will be active in is achieving a safe condition that minimizes and mitigates for the sodium-water reaction(s) that will likely occur due to the sodium to water leak. (See section 14 for details). Secondary roles include: See section 16
13	Task Location	Main Control Room (MCR) and possibly area just outside Sodium Boiler Building (SBB)
14	Operator main functions	HMLD, CHMLD, and plant computer alarm monitoring. Diagnosis of alarms. Immediate actions: Shift Manager (SM), verify if any perturbations have occurred or changes in Secondary Cold Trap. Monitor Secondary Cover Gas Pressure (rising pressure will occur if valid). If all indications point to water-to-sodium leak perform following: SRO - Scrams Rx. Console CSO - Actuate Sodium Boiler Building (SBB) Evacuation Alarm form MCR. Or Roving CSO - actuates SBB Evac. Alarm from just outside the SBB entrance. SM - directs SSO or available operator to depress the SBB Fire Push Button (located in several locations outside and inside the SBB not in MCR). This action causes following automatic actions: Trips the Secondary sodium recirculating pumps and

Item	Item Name	Item Description
		sec. sodium pump. PPO - secure Feedwater Pumps (FWPs), shut feedwater and main steam isolation valves. SM - directs SSO to dump Steam Generator (SG) water and drain the sec. sodium system. Roving CSO - depresses the SG water dump valve push button in MCR on Secondary Sodium Panel and observes open indication light. Depresses the Sodium Vent Valves Open push button this opens sodium-argon vent valves allowing sec.sodium to vent while draining without creating vapor lock. Shuts vent valves after waiting six minutes. Shuts SG water dump valve.
15	Supporting Task Analysis	N/A
16	Sub-functions	- Emergency Procedure compliance - Procedure place keeping - System monitoring for other abnormalities while monitoring plant parameters related to event - Plant personnel accounted for due to SBB evacuation
17	Execution/Performance requirements	- Intimate knowledge and understanding of severe consequences of water-sodium reaction. - Memorization of immediate actions and familiarity with sequent actions.
18	Timing	- Immediate Rx Scram is necessary to minimize time needed to drain Secondary Sodium System and potential water and sodium reactionary forces of plant systems - Also see timing instructions in section 14 associated with vent and dump valves
19	Sequence up/down	Rapid Down power due to Reactor (Manual) Scram
20	Information from system	Trend data from CHMLD, HMLD and plant computer
21	Information transmittal method	Alarms come in on plant computer screen, CHMLD or HMLD alarms in Sodium Boiler Builder main alarm panel or MCR alarm panel
22	Termination indications	- Secondary Na System drained and at ambient temperature. - SG feedwater drained and argon blanket placed on feedwater side of heat exchangers.
23	Potential Errors	- Misdiagnoses of alarms such as plant computer malfunctions providing false alarms or failed hydrogen leak detectors providing false alarms from flow and temperature upsets in leak detection system (these false alarms are more likely during Rx startup or shutdown). - Additionally, Changes in Secondary Cold Trap operations can also account for an increase in hydrogen level.
24	Source documents	Applicable Emergency Procedure
25	Cues to the Operator (for commencement of the action)	- Alarms are received on the Hydrogen Meter Leak Detector (HMLD) or Secondary Cover Gas Hydrogen Leak Detector (CHMLD) hydrogen level or rate-of-rise data on the plant

Item	Item Name	Item Description
		computer. - The trend data for hydrogen will be on the rise. - All operating leak detectors should show upward trends in 5 minutes at full power operations. - Validations from Chemistry Technician that Secondary Sodium Chemistry operations were not causal to the event
26	Diagnosis Required	Alarm validity and indication of faulty hydrogen detector or false information from plant computer malfunctions
27	Control and Display Sufficiency	- In this instance the controls used are Rx Scram button and - Sec. Sodium Vent Valve pushbutton and - SG Water Dump Valve push button
28	Feedback on the Operation	Post Emergency Action Indications: - Rod Bottom lights following Scram - Rapid decline in neutron production (Neutron Detectors indicate zero reactor power) - Turbine trip (from Scram) will indicate numerous associated alarms - Secondary Na System Drain Tank level and temperature rise - Secondary Na System piping temperature rapidly lowering - SG temperature, pressure and level readings rapidly lowering - CHMLD and HMLD levels trend down - Numerous steam plant alarms due to Feedwater and Main Steam systems rapidly drained
29	Recovery Opportunities if Omitted	No recovery likely if actual water-sodium reaction due to leak in system
30	Consequences of Failure/Non-recovery	- A water-to-sodium leak results in a reaction which generates heat and liberates hydrogen, causing rapidly increasing temperature and pressure in the affected Evaporator or Superheater. - The magnitude of the temperature and pressure increase depends on the size of the leak. - Localized high temperature and pressure can cause failure of Evaporators or Superheaters.
31	Recommendations	- Potential automation including Rx scram to be more conservative given the significance of such an event. - Consideration given to pushbutton actions to be automated upon hydrogen detection alarms (i.e. 3 out 5 sequence) with an alarm that is followed by automatic dumping of the sec. sodium system and SG water if operator action is not taken within a given time frame.

When the means-ends links from these high-level goals to lower levels in the hierarchy are examined, it is easy to see how a large number of new operating concepts could be identified for future advanced fast sodium-cooled reactor (FSR) designs. Each of those concepts (for example "on-site refueling of modules") could be associated with issues like FA, human performance, crew size, and many more.

Similarly, it is seen how the decomposition of the system into different levels would lead to non-traditional operating modes and thus non-traditional operating procedures. The ability of WDA to identify the need for non-traditional operating procedures is a critical output of the method; we know of no other means by which to systematically determine this type of procedural need prior to the build out of a multi-modular enterprise such as AdvSMR.

From this short exercise it was concluded that WDA would be a powerful method to structure a large part of the research planned for the next phase of the project. It will also provide a strong basis for verification and validation during the last phase of the project.

4 Development of a Function Allocation Framework for AdvSMR Concepts of Operations

4.1 Overview

One goal for this Concepts of Operations project is to develop a function allocation (FA) framework for AdvSMRs. The April 2013 milestone report of this project [23] documented a review of existing FA methods and models, and demonstrated that they still have some technical gaps. Therefore, some additional FA research has been performed in order to develop this FA framework properly.

A function is defined as the operation(s) that must be performed by one or more systems in order to meet the mission objectives of the system. These functions may either be executed by the automation, or initiated and performed by the operator through the human-system interface (HSI). FA is a HFE decision-making process and method that is used during the design life cycle of complex systems to distribute the roles and responsibilities to perform work functions among all human and automated machine agents in a team. The function can be assigned to a human or automation agent, or to multi-agent teams comprised of automation agent(s) and human(s), a team of human agents only, or a team of only automation agents. This definition explicitly uses the phrase "distribute the roles and responsibilities to perform work functions" versus other phrases, such as "assigning system functions" or "division of activities" in order to highlight the idea that FA is not an "either/or" proposition. As Jordan (1963 [26]) pointed out, the FA process needs to decide how the strengths of humans and automation can be combined to mitigate the weaknesses of the other, such that emergent team capabilities can be produced.

For the purpose of this part of the research, a "model" is defined as a simplified representation of a more complex process, physical object, phenomena, or system. Models are by definition not isomorphic with reality, but they include the most essential variables. Scientific models explain and predict how a process or phenomenon nominally occurs. Scientific models also try to explain why a process or phenomenon occurs by showing the causal mechanisms underlying the observed correlations among variables. These kinds of models are frequently the tools that researchers use to test (typically via experimentation and data collection) whether a hypothesis or theory explains the relationships between observed occurrences. More informally speaking, the term model is also used to describe the product of a researcher's thinking about a problem, and essentially represents how the researcher is "framing" the problem. These "analytical models" are a researcher's conjecture or supposition of how he or she believes the relationships between observable occurrences are organized. They are not as easily falsifiable as scientific models, but they can be judged on their utilitarian value. Additionally, because these analytical models essential "frame" the problem space, it can be argued that it is more appropriate to call them frameworks. This is why the Concepts of Operations project is developing an *AdvSMR FA framework*, and not an FA model. The AdvSMR FA framework presents a sensible way to frame the problem of allocating functions, and then as a logical extension of that perspective, it then provides useful guidance on the mechanics of how to perform the FA.

The previous milestone report explained how high-level FAs for a plant are transformed during the next step into design requirements for the automation system. This requires the application of design criteria for optimal collaboration between human and system – in other words, how the identified functions should be implemented in the automation system to allow both human and system to perform assigned functions effectively and safely. This is the topic of the Human-Automation Collaboration project, which is closely associated with the Concepts of Operations project.

This section of the report:

1. Describes the regulatory and HFE design/industry drivers for an AdvSMR FA framework.
2. Summarizes some of the more recent literature on FA that was not included in the previous milestone. Because this AdvSMR FA framework must address future working contexts, the report also summarizes the key literature on automated systems that provide assistance or support to

operators in control rooms (e.g., automated support systems, assistant systems, task support systems, and computerized operator support systems).

3. Specifies the principles for the development of a new foundational FA framework.
4. Presents the FA framework for AdvSMR Concepts of Operations.

4.2 Drivers for an AdvSMR FA Framework

Developing an FA method is an important contribution to the RD&D activities under the DOE ICHMI pathway for a number of reasons, but one important reason is that if an AdvSMR vendor wishes to receive an NRC license to operate their design in the U.S., the vendor must perform a functional requirements analysis (FRA) and FA to address a key part of the NRC's Human Factors Engineering (HFE) license application review (NUREG-0711, Rev. 3 [36]).

The goal of the FRA is to determine the functions that are associated with high-level operational goals and to create a framework for an understanding of the relative role of human, and/or system controllers. FRA also decomposes the high-level functions into a coherent set of executable functions associated with operational conditions or modes and specific systems and major components.

The FRA process that is typically followed as part of the HFE program analyzes all sub-systems of the plant to determine the HF content, applicability and plant control functional information. If sufficient information is available about the system function, it becomes a direct input to the FA process. That is, the designer and HFE analyst can apply the criteria derived from their FRA, combined with results from a WDA, to allocate the function to humans, an automation system component, or combinations of the two. If the level of the function is too high or it lacks operational control information, the FRA process would analyze the function in more depth to determine the following information:

- Sub-functions
- Role of controllers
- Operational limits and constraints
- Other characteristics of the function
- Operating scenarios that are applicable to the function.

According to NUREG-0711, Rev. 3, FA is the assignment of functions identified from the plant's functional requirements to personnel (e.g., manual control, automatic systems, and combinations of both). AdvSMR license applicants' submittals will be assessed in terms of the extent to which the design effectively combines human and automation capabilities in order to enhance, "The plant's safety and reliability, including improvements achievable through assigning control to these elements with overlapping and redundant responsibilities." (p. *x*). Unlike conventional NPP designs that could rely on a significant body of operating experience and well-defined system functions for making allocation decisions (e.g., as documented in the knowledge and abilities requirements for operator licensing in NUREG-1122 and NUREG-1123), many design decisions for AdvSMRs have very limited technical bases for human factors issues. Furthermore, given that higher levels of automation are envisaged in the operations of AdvSMRs, the definition of system functions and operator roles and tasks must be based on a *first principles* analysis of all the factors that may influence the behavior and performance of each.

As such, a FA framework for AdvSMRs must be developed, such that it can be a resource to AdvSMR designers as they prepare their designs for license review. In particular, early human factors analyses such as WDA performed in preparation for developing the plant's Concept of Operations must identify the functions that must be performed to satisfy the plant's safety objectives, that is, to prevent or mitigate the consequences of postulated accidents that could cause undue risk to the health and safety of the public. This analysis determines the objectives, performance requirements, and constraints of the design, and sets a framework for understanding the role of human and automated agents (i.e. controllers) in regulating plant processes. New and different functions associated with AdvSMR designs (such as passive safety features, design simplicity, increase in required response time, monitoring and control of multiple modules) need to be evaluated thoroughly.

Aside from the regulatory drivers, it is also worth noting that from the HFE design perspective (i.e., industry drivers, including national and international standards and guidelines such as the EPRI *Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification* EPRI 1010042-2005 [6]), a rational allocation of functions to operators, hardware, or software is necessary for optimal system design. FA provides the basis for subsequent efforts relating to crew or operator task analysis and description, operator performance analysis, instrumentation and control selection or design, HSI design, development, and evaluation. In particular, decisions for the allocation of functions will affect operator workload and have a significant influence on staffing levels, selection, and training requirements. FA is thus one of the industry's tools to identify how to reduce the number of human operators as a means to manage O&M costs, which is a very significant driver for the development of a new generation of nuclear power plants.

The analysis of operator functions is based upon the processes that are necessary to meet system requirements. Because refinement of such functions occurs progressively and iteratively, human factors engineers must ensure that the necessary iterations of FA are conducted to verify that all operator functions are included. Although operator functions such as supervision, monitoring, control, diagnosis and maintenance can be accurately defined only once FA decisions have been made, the form the execution of such functions should take in order to complement the operator's perceptual and cognitive capabilities has a major influence on the design of control systems. Analysts and system design engineers must therefore reiterate their FA decisions to include human functions.

As a secondary necessity, the need for a formal approach to FA lies in the probability of human error on the part of the designer. Just as operators make errors while performing tasks it is obvious that the human factors engineer, in collaboration with the systems engineer, may also make errors while allocating functions. Following a formal process and then implementing mechanisms that facilitate traceability in the allocation of functions can minimize designer errors.

An extensive review of FA methods and models, and a description of their applicability to the Concepts of Operations project can be found in the previous milestone report for this project [23]. However, for this report the research team included a few additional sources on FA. For the sake of thoroughness, a short summary of these additional sources is provided below[3].

Two studies by researchers studying FA for naval operations, Strain and Eason (2000 [56]) and Malone and Heasly (2003 [32]), are appropriate to mention in this report for AdvSMRs because they describe how existing FA methods are not particularly well suited for their operating environment or context. Naval operations have an imperative to reduce staffing levels (i.e., reduce manning). Like AdvSMRs, naval operations see a cost benefit to reduce staffing levels (as well as reducing the number of lives placed in harm's way), and they have come to the same conclusion that one way this can be achieved is through the increased use of automation. Furthermore, both Strain and Eason (*ibid.*) and Malone and Heasly (*ibid.*) are critical of Fitts' List (1951 [10]) as being too simplistic for the complex operating environment of a warship, and also of existing FA methods that attempt to optimize allocations between humans and automation, because optimization can run contrary to the imperative to reduce staffing levels. Consequently, both Strain and Eason and Malone and Heasly propose new FA methods that essentially have a techno-centric perspective that prioritize automating as many functions as possible. This techno-

[3] Other articles on FA were also found in the interim (e.g., Marsden & Kirby, 2005; Lupton, Lipsett, Olmstead, and Davey, 1991), but were deemed to be less important to summarize in the body of this report.

centric philosophy can be seen in Figure 9 from Malone and Heasly, which is a high-level depiction of their FA method and decision making process.

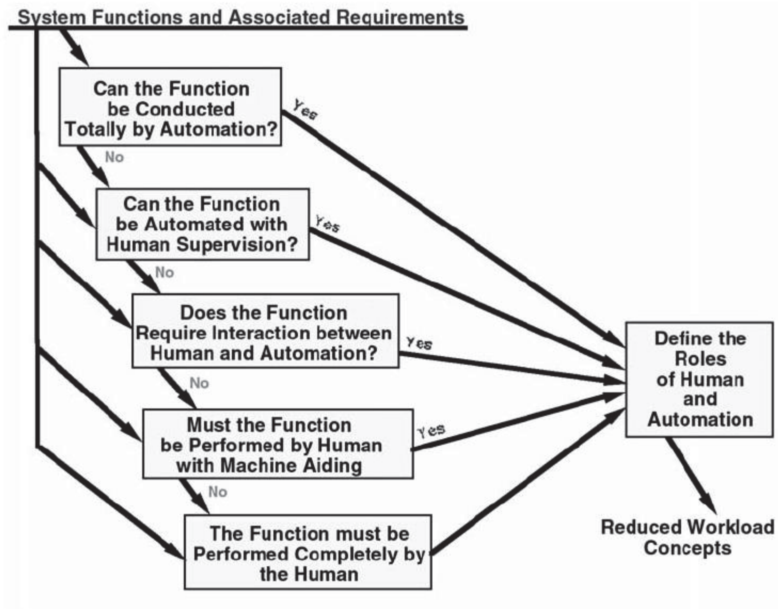


Figure 9: Malone and Heasly (2003) FA Decision Process

Specifically, the Malone and Heasly FA decision process, and in particular, the way in which the questions are posed and what order the questions are in, clearly shows a preference to try to automate the function in question first, and if it cannot be automated, to minimize human operator involvement, unless the function absolutely requires it. What is unclear about these new naval FA methods, however, is whether this approach, which biases the designer to automate as many functions as possible, still avoids well known issues for the human operator, such as the "leftover allocation" trap (Bailey, 1982 [1]), or creates a "brittle" automation design (Woods and Hollnagel, 2006 [60]).

More recently, a trio of articles by Pritchett, Feigh and Kim has elucidated a set of requirements for FA (Feigh & Pritchett, 2013 [9]), a modeling framework for FA (Pritchett, Kim, & Feigh, 2013a [45]), and a set of metrics to evaluate FA decisions or solutions (Pritchett, Kim, & Feigh, 2013b [46]). Feigh and Pritchett (2013 [9]) identify requirements that they argue are essential for effective FA involving humans and automation. The five requirements are:

1. Each agent must be allocated functions that it is capable of performing.
2. Each agent must be capable of performing the collective set of assigned functions.
3. The FA must be realizable with reasonable teamwork.
4. The FA must support the dynamics of the work.
5. The FA should be the result of deliberate design decisions.

The authors note, however, that these requirements are not meant to constrain their FA method, as they recognize that all operating contexts are different, and that FA needs to be customized for each context because no one FA is likely to be well suited (i.e., optimal or even sufficient) for all circumstances. To wit, the specific operating context this FA modeling framework simulates, and the metrics developed to evaluate this FA approach is for aviation, specifically model flight path management. In their FA modeling framework paper, four different FA solutions were proposed, which varied in how much taskwork was allocated to automation, to address four general flight path management scenarios (e.g., the nominal scenario, late descent, re-routing, and unexpected tailwind). The first solution, FA1 was defined as the highly automated allocation. FA2 was the mostly automated solution, FA3 was the mixed allocation solution, and FA4 was the mostly manual solution.

Pritchett, Kim, and Feigh (2013a [45]) use these five requirements as one of many inputs to the CWA and WDA they performed in order to develop their FA framework. WDA was used to build an abstraction hierarchy, which, as explained in Section 3.1 of this report, structurally decomposes the work domain, and identifies the information and work activities required to control the work process dynamics such that the system's mission goals are accomplished through clearly identified means and functions, and in a manner that is consistent with the designer's priorities and values. The result of the CWA and WDA efforts was the development of a computational simulation that can be used to model and evaluate the effectiveness of a given FA across humans and automated agents. By simulating the operating context, the FA modeling framework allowed designers to propose an FA solution, or if taking a 'dynamic FA' approach, multiple FA solutions, and then systematically test through their computer simulation the adequacy and effectiveness of those solutions. Like all other simulations, the ability to pose multiple "what if" questions and quickly test them gave this FA modeling framework a capability to not only formally analyze static FA solutions (i.e., work models), but also evaluate their effectiveness across the multiple scenarios within the operating context.

Pritchett, Kim, and Feigh (2013b [46]) address the next obvious question for this FA approach by describing ways to measure the effectiveness and appropriateness of the FA solution or solutions that have been tested in their FA modeling framework (i.e., simulation). The authors argue that up to eight different measures or metrics can and should be used to comprehensively evaluate the FA solutions. The eight metrics are:

1. Workload/Taskload
2. Mismatches between responsibility and authority
3. Stability of the human's work environment and mission performance
4. Coherency of a FA
5. Interruptions
6. Automation boundary conditions
7. System cost and performance
8. Human's ability to adapt to context

The Pritchett, Kim, and Feigh (2013a and 2013b) framework is interesting and a valuable contribution, but not beyond criticism. For example, the question is not whether there are interruptions or what the threshold for excessive interruption is, but whether the crew can deal with them in a seamless rather than disruptive fashion. Also, the notion that there could be a metric for adaptability is interesting. It is not clear if there is a range of conditions that would satisfy the nominal case and how one would know when operational context stretches the crew to the limit. Nevertheless, the authors demonstrate how the FA modeling framework and simulation could be used in conjunction with the eight metrics they developed to test the four different FA solutions they believed would effectively manage the four general flight path management scenarios described above. The results of the example presented in the Pritchett, Kim, and Feigh (2013b) paper showed that different FA solutions were more effective than others for a given scenario, but that the results also depended greatly on which of the eight metrics were being used to compare the performance difference. The lack of consistency among the metrics is not surprising, and highlights one of the fundamental challenges of FA – that there will always be some degree of mismatch between an FA solution and the scenarios within a given operating context. The important contribution these metrics make to the FA literature, however, is that researchers and designers now have 1) a means to characterize fairly comprehensively the nature and extent of the mismatch of a given FA solution to the scenarios and operating context to which it is being applied, 2) can identify, via 'low scores' on the metrics, the residual issues that will not be addressed with the FA solution, and 3) can then make a decision, using other criteria, regarding which of FA solution to use – presumably the FA solution that leaves the residual issues that can be mitigated most easily and cost-effectively through other means. Overall, these authors were able to show that there are pros and cons to every FA solution, which provides support for their initial claim that a single FA solution is unlikely to be optimal for all scenarios, and that multiple metrics are needed when evaluating multiple FA solutions. Furthermore, by posing and then using the requirements, modeling framework, and metrics in an integrated fashion, these researchers have presented a comprehensive and robust FA method that can be used to evaluate FA solutions. Their work contributes to the FA literature in ways that other methods that have been developed since the seminal contributions of NUREG/CR-3331, Price (1985 [43]), and Price and Pulliam (1988 [44]) have not.

These significant advancements in FA, however, are not without some issues with respect to the AdvSMR context and need. One pragmatic issue is transferring their FA framework from an aviation context to the AdvSMR operating context. A larger issue is the manner in which their 'dynamic FA' approach addressed the variable distribution of functions and tasks between the human(s) and automation. As mentioned previously, there were four FA solutions they tested (e.g., FA1, FA2, FA3, and FA4). These solutions were based on, "The fundamental requirements of information-passing and coordinated activities required to enable the teamwork," (p. 9), and varied in how much taskwork was assigned to the automation versus the human. Accordingly, FA1 – FA4 were defined as follows:

FA1: Automation of communication management (partial), trajectory management, and aircraft control (e.g., Highly automated).

FA2: Automation of trajectory management and aircraft control (e.g., Mostly automated).

FA3: Automation of aircraft control, with partial automation of trajectory management (e.g., Mixed).

FA4: Automation of only aircraft control (e.g., Mostly manual).

This 'division of labor' by allocating taskwork to different agents is a different approach to addressing the dynamic allocation of functions than other approaches proposed by Rasmussen and Goodstein (1987 [49]) and reiterated by Vicente (1999 [58]), Hugo (2009 [20]), and Flemisch, Heesen, Hesse, Kelsch, Schieben, and Beller (2012 [11]). These authors have proposed that the dynamic allocation of functions should be by information processing functions, which is not always the same as the tasks or taskwork to be performed. Furthermore, since taskwork is always context and domain specific, there is some inherent generalizability issues with this FA method, which means this approach is likely to require considerable time and effort to implement for each analysis as a way to provide a less labor intensive and more graded approach.

> Because the Pritchett et al. approach to FA has only recently become available for review and considerable development and testing would be required to tailor it to the nuclear domain, the AdvSMR FA framework will follow the information processing approach to FA.

This is not to say, however, that the tenets for effective teamwork as it relates to completing taskwork are unimportant or not applicable. Even in the simplest case of teamwork of two humans working together to complete a task, they will consciously or unconsciously enter into a negotiation (that is, an information exchange which may include certain compromises) that would result in one of the following work arrangements:

1. Where enabled by the context, both perform the task simultaneously, resulting in more effective completion (faster, more accurate, etc.).
2. One performs the task partly and then the other takes over.

3. One of them performs the entire task independently.
4. One selects to perform the task and the other monitors and verifies quality and completion.
5. One chooses to perform the task but the other provides an acceptable reason why he/she should rather perform the task and then takes over.
6. One starts performing the task but fails to complete and the other takes over.
7. Both agree to divide the task into two or more interleaved or interdependent parts and they proceed to perform the parts sequentially or concurrently, as allowed by the context.

It is conceivable that a similar negotiation paradigm would apply to a function allocation situation involving a multi-agent team consisting of human as well as system agents.

In more complex teams the work arrangements become more complex as well. Regardless of the complexity or simplicity of the team, all of these work arrangements require the team members to agree implicitly or explicitly on the mission, goals or objectives of the task in a defined context (i.e. the ground rules), which includes the constraints of the task environment. They also need to know how to determine when the task is completed and how to measure successful completion. Thus, any allocation of functions in this AdvSMR FA framework will need to effectively incorporate both the information process stages approach and tenets for an effective teamwork approach.

4.3 Summary of Recent Literature on Automated Support Systems

Virtually all published FA methods are very good examples of how to allocate functions statically, including shared functions. All existing methods, however, struggle to varying degrees to address dynamic changes in the system that affect the ability of agents to execute their assigned functions (i.e., anticipating and adapting to future working contexts). Furthermore, NPPs are high-risk and complex industrial process control systems whose functions are inherently dynamic not only with respect to their different modes of operation, but also with respect to hypothesized failures (e.g., design basis accidents). Seong et al. (2013 [53]) point out that different operating modes of NPPs have different allocations of functions between the human and automation, and that the Concepts of Operations of existing plants includes very formalized procedures that change which agent(s) are in control of functions when there are mode changes. This notion is depicted in Figure 10.

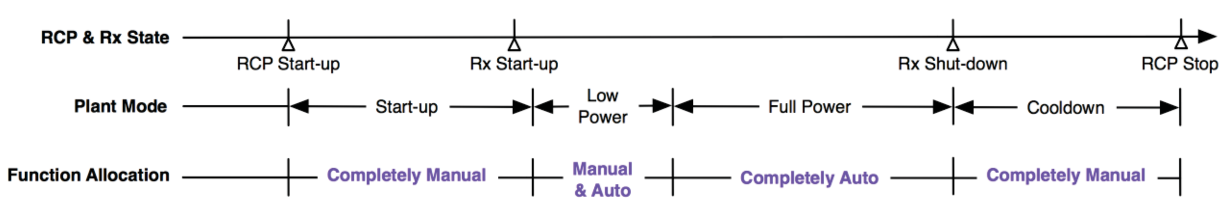


Figure 10: Typical PWR Modes of Operation and Corresponding Allocation of Functional Control (Seong et al., 2013)

Similarly, highly complex industrial process control systems, like AdvSMRs, have the potential to fail in many different ways. There are many different failures, or generic failure modes, for which the allocation of recovery functions to humans or automation should vary in order to ensure optimal recovery response. This idea is shown in Figure 10. According to Vicente (1999 [57]), for certain cases, such as a loss of coolant accident in a PWR, it would be better to allocate many of the primary recovery functions to the human than the automation (e.g., FM_c). Complete failure of the automation in an AdvSMR is another case where human will necessarily be allocated all control functions (e.g., FM_f). Other failure modes in an

AdvSMR that lead to an automatic shutdown obviously dictate that the automation is allocated most of the control functions and that the human's function is to monitor the system (e.g., FM_a). The consequence of this issue is that the allocation of functions and responsibilities cannot remain static in an AdvSMR, due to the fact that different design basis accidents are already identified as requiring differing levels of human and/or automation involvement.

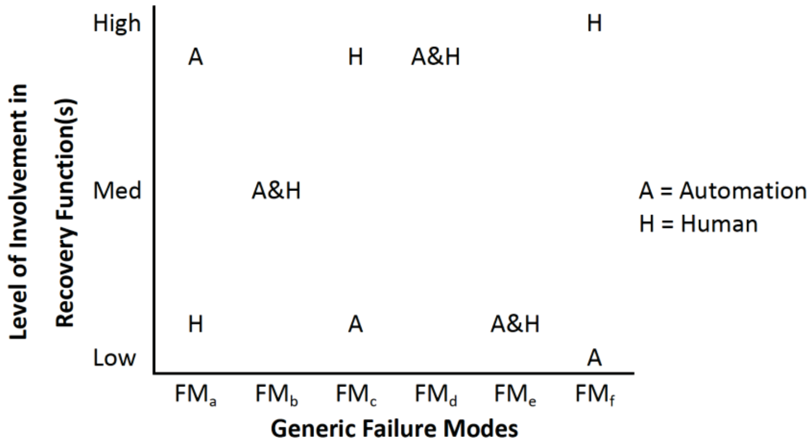


Figure 11: Hypothetical NPP Failure Modes

Given the effect these two issues (i.e. mode changes and accidents) have on static allocation of functions, it is clear that the AdvSMR FA framework will need to address or provide guidance on how to manage dynamic FA. Fortunately, the literature on automated support systems, which are also called *computerized operator support systems* (COSS) or *task support systems* (TSS), provides many important insights into how an AdvSMR FA framework could handle future working contexts within an AdvSMR's Concepts of Operations.

Rasmussen and Goodstein (1987 [49]) proposed how functions (and their associated responsibilities) in high-risk industrial systems could be dynamically allocated to different agents to facilitate the development of well-designed supervisory control systems, including automated decision support systems. Based upon previous field studies of power plant operators, Rasmussen developed a modeling tool known as the "decision ladder" that represents the standard information-processing logic (i.e., detection, identification, interpretation/sensemaking, decision-making, and action).[4]

One other important feature of the decision ladder is that it identifies the different "information-processing routes" that humans typically take, which correspond to the Skill-Rule-Knowledge (SRK) scheme. Rasmussen (1974 [48]) defined two types of information processing shortcuts, called associative leaps and shunting paths, which roughly correspond to the definitions of Skill-based and Rule-based thinking, respectively. These two kinds of 'opportunistic movement' are different from the 'normative' linear sequence, whereby information processing goes systematically up, and then down, the ladder through all of the stages. This systematic and effortful 'normative' linear processing corresponds to Knowledge-based thinking. Furthermore, it is important to note that Reason (1987 [50]) identified that certain kinds or types of human error, summarized in Table 6, are associated with different levels in the SRK scheme, and as a consequence, AdvSMR and HFE designers should keep in mind how their systems could be designed to mitigate these errors:

4 A detail discussion of this model falls within the cognitive psychology domain and is beyond the scope of this report. Interested readers may wish to consult Rasmussen, J., & Goodstein, L.P. (1987). "Decision support in supervisory control of high-risk industrial systems". *Automatica*, 23, 663–671

Table 6: Examples of Errors

Information Processing Mode	Examples of Resulting Errors
Skill-based (SB) thinking	1. SB error of commission due to how recently the SB thought/behavior occurred, and its frequency of previous use 2. SB error of commission, due to environmental cues signaling an incorrect SB thought/behavior (e.g., shared schema properties) 3. SB error of omission: Thought/behavior omitted following an interruption 4. Concurrent plans and/or conflicting goals causing incompatible SB thoughts/behaviors
Rule-based (RB) thinking	1. RB error of commission due to complacent mind set, over-confidence, etc. ("It's always worked before") 2. RB error of commission due to rule availability (e.g., the first rule that comes to mind that solves the problem is most preferred) 3. RB error of commission due to matching bias and/or over-simplification (e.g., stereotyping) 4. RB error of omission: feature or anomaly not checked because its presence did not fit the stereotype and its importance was discounted
Knowledge-based (KB) thinking	1. KB error of commission due to incomplete mental model. That is, bounded rationality caused by selectivity, the biased review of evidence, working memory overload, and/or illusory correlations 2. KB error of omission: fatigue, lack of motivation, and/or lack of time available to process thoroughly all salient and relevant information 3. Incomplete mental model due to problem complexity and ability to determine causal relationships among interacting variables

Rasmussen and Goodstein (1987 [49]) used the decision ladder to identify through functional control analyses how functions can be dynamically allocated to different agents according to the different information processing activities that are required to accomplish the function for a given operating context. More specifically, they identified three key agents: the human operator, the automation, and the designer, and demonstrated how the distribution of control functions could be dynamically allocated across these three agents depending on what the operating context for the high-risk industrial system (e.g., an AdvSMR) is. Given this FA by information processing stages approach, and the designer's desire to have AdvSMRs be highly automated, the results of the functional control analyses would be that under normal full power operations, the automation would be allocated virtually all of the control functions. The automation would be allocated the function responsibility to monitor the plant's state, and control the process of generating electricity in a manner consistent within the operating parameters that have been pre-defined by the designer (who has an understanding of the regulations and the fundamental principles of nuclear engineering). Furthermore, the human operator's primary functions would be to monitor and verify performance of safety systems, maintain communication with appropriate onsite and offsite personnel, and initiate recovery actions following an event[5]. Incidentally, this description of how functions would be allocated between humans and automation while the AdvSMR is operating normally at full power is consistent with the description provided in NUREG/CR-1368 [39] of the normal operating

[5] The operator would also have the capability to initiate reactor shutdown by manual scram or manual activation of the ultimate shutdown system.

conditions of Toshiba's 4S sodium-cooled reactor [57], and the Power Reactor Inherently Safe Module (PRISM) reactor (General Electric, 1987 [14]).

In his summary of Rasmussen and Goodstein's work, Vicente (1999 [58]) also described a number of generic failure modes, which further showed how this FA by information processing states approach would work in an NPP. The first failure mode example is when an automatic shutdown of the NPP is required. The automation would be assigned the function of monitoring and comparing the AdvSMR's operating state and relevant shutdown variables relative to criterion, or symptoms, that have been pre-defined by the designer. This failure mode would be triggered when the relevant shutdown variables exceeded the designer's pre-defined threshold values. Once the threshold values are exceeded, the automation would initiate the shutdown sequence for the reactor. By definition, because this is an automatic shutdown, the automation would be in control of the sequence of functions and actions, but it is important to note that it was also the designer's function or responsibility to 1) determine what the automation's functions should be in this context, before the reactor was even licensed and operational and 2) program the automation accordingly. The human operator would have almost no control functions assigned to him or her in this failure mode, but would have many supervisory functions to perform. That is, once the automation shutdown is initiated, the operator would be informed that the new desired end state is a safely shut down reactor. The operator's function would then be to monitor the relevant performance variables and to verify the performance of the automated safety systems.

The second generic failure mode Vicente described is one requiring human operator intervention. A more specific example of this type of failure more is a loss of coolant accident in a light water cooled NPP with a mostly analog instrumentation and control system. In a loss of coolant accident, the automation is allocated fewer control functions. Information on the NPP's operating status (i.e., relevant operating parameters) would be displayed to the human operator. The operators would be assigned the functional responsibilities of: 1) detecting the information presented, 2) making sense of what that information implies based on their training and procedures, 3) making decisions regarding what to do in response (e.g., shut down the reactor), and then 4) giving the orders to other humans and the automation to perform the response the operator in charge has decided to do. The automation's functional responsibility would be to execute the sequence of actions the designer has pre-programmed it to perform that shutdown the reactor. Clearly, the allocation of functions in this example is quite different from the automatic shutdown example. Overall, what functions the human operator or automation is assigned depends on the designer, and whether he or she (among other things) is confident or not that the automation's functional capabilities will work in the given operating context or not. Other factors, such as cost to implement automated solutions and regulatory constraints are also considerations, but have also been well documented by other previous work.

Combining the traditional abstraction-decomposition hierarchy approach with the work of Rasmussen and Goodstein (1987 [49]), and with the SRK information-processing routes provides additional insights into the nature of how an AdvSMR FA framework will need to address the dynamic allocation of functions across different agents. That is, the FA by information processing stages approach (e.g., Rasmussen and Goodstein) is an analysis that should be performed in conjunction with the traditional approach of using the results from the abstraction-decomposition hierarchy analysis to allocate functions to different agents. Taken together, they form the technical basis for some key requirements for how the AdvSMR FA framework should address the dynamic allocation of shared functions. Specifically, the abstraction-decomposition hierarchy and Rasmussen and Goodstein research approaches will show how functions and their associated responsibilities can be logically and coherently distributed among agents with respect to how functions are connected to their means (i.e., how's) and ends (i.e., mission goals), as well as information-processing requirements. The SRK information-processing routes further clarify the nature of the dynamic allocation of functions (and their associated roles and tasks) in that they show: 1) what kind of information the human should be requesting and automation should be providing, and 2) at what level that information should be to facilitate operator performance and human-automation coordination, and 3) what kinds of errors humans are more likely to commit (e.g., SB, RB, or KB errors) given the kind of thinking (i.e., information processing) they are doing. This interplay between humans and automation as a function of SRK thinking and behaviors is shown in more detail in Figure 12 (Hugo, 2006 [19]):

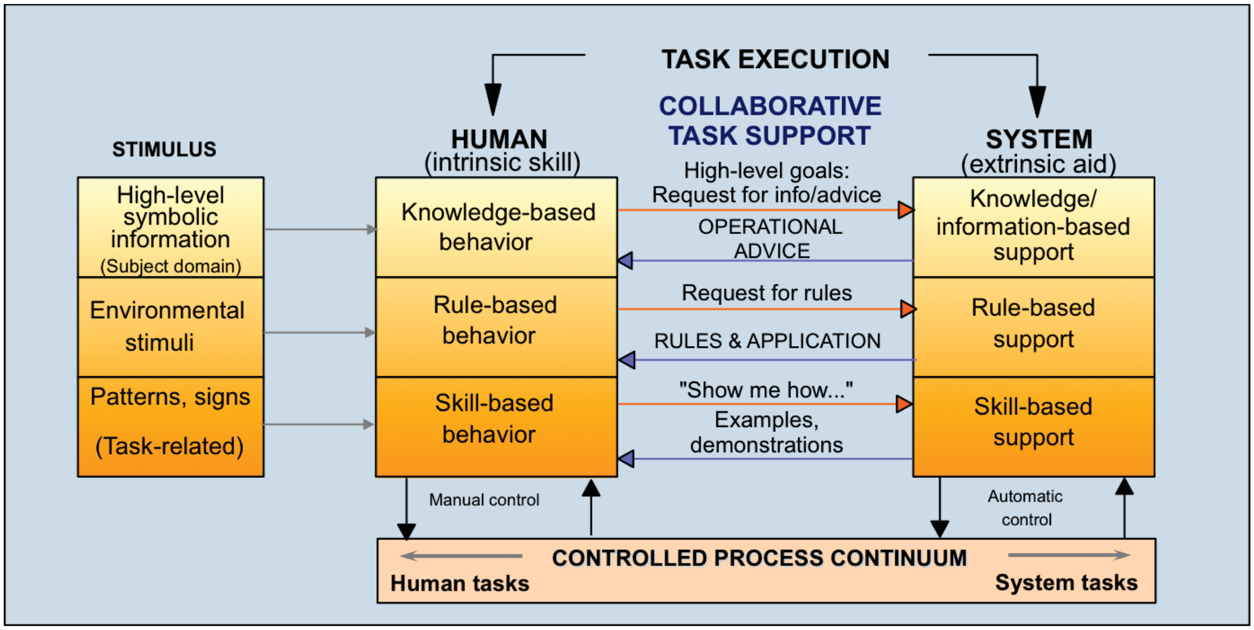


Figure 12: Interplay between humans and automation by SRK activities and needs

As Figure 12 shows, the kind of information processing that the human does (e.g., skill, rule, and/or knowledge-based) will depend on the demands of the task environment (e.g., different plant operating modes) and the stimuli (e.g., different system or plant failure modes) that are presented to the human and automation. It will be incumbent on the AdvSMR designer to know how to manage the allocation of functions in a manner that not only meets the mission goals of the system, but also effectively teams the agents together such that those mission goals can be accomplished reliably and efficiently.

Hugo's (2006 [19], 2009 [20]) prior work on task support systems (TSS) is built on the preceding logic, and is instructive regarding how an AdvSMR FA framework could include dynamic allocation of functions to address future working contexts. TSS was originally part of the design concept of the HSI for the Pebble Bed Modular Reactor (PBMR – a high-temperature gas-cooled reactor design). It was that AdvSMR's proposed solution to addressing the greater use of automation, and the use of digital I&C systems that simplified the representation of complex plant processes by abstracting (i.e., synthesizing) lower levels of data (e.g., single sensor inputs) into higher levels of information that was useful to the operator. The TSS was designed to help operators and automation work effectively as a team to find and choose superior solutions to events that challenged nominal operational requirements. More specifically, recognizing that 1) the operator's role or level of involvement will be determined largely by the operational state of the plant, and 2) that different operational states of the plant require different levels of automation, the TSS was the manifestation of the thinking the PBMR designers engaged in to solve the problem of how to coordinate roles and responsibilities of the human and automation. This solution posits that for every automation level, ranging from highly automated to mostly manual, there is a corresponding specific plant operational state, which then also determines what the operator's corresponding role is, and accordingly what appropriate level of task support the operator needs from the HSI. The TSS concept is represented graphically as shown in Figure 13 (Hugo, 2009 [20]):

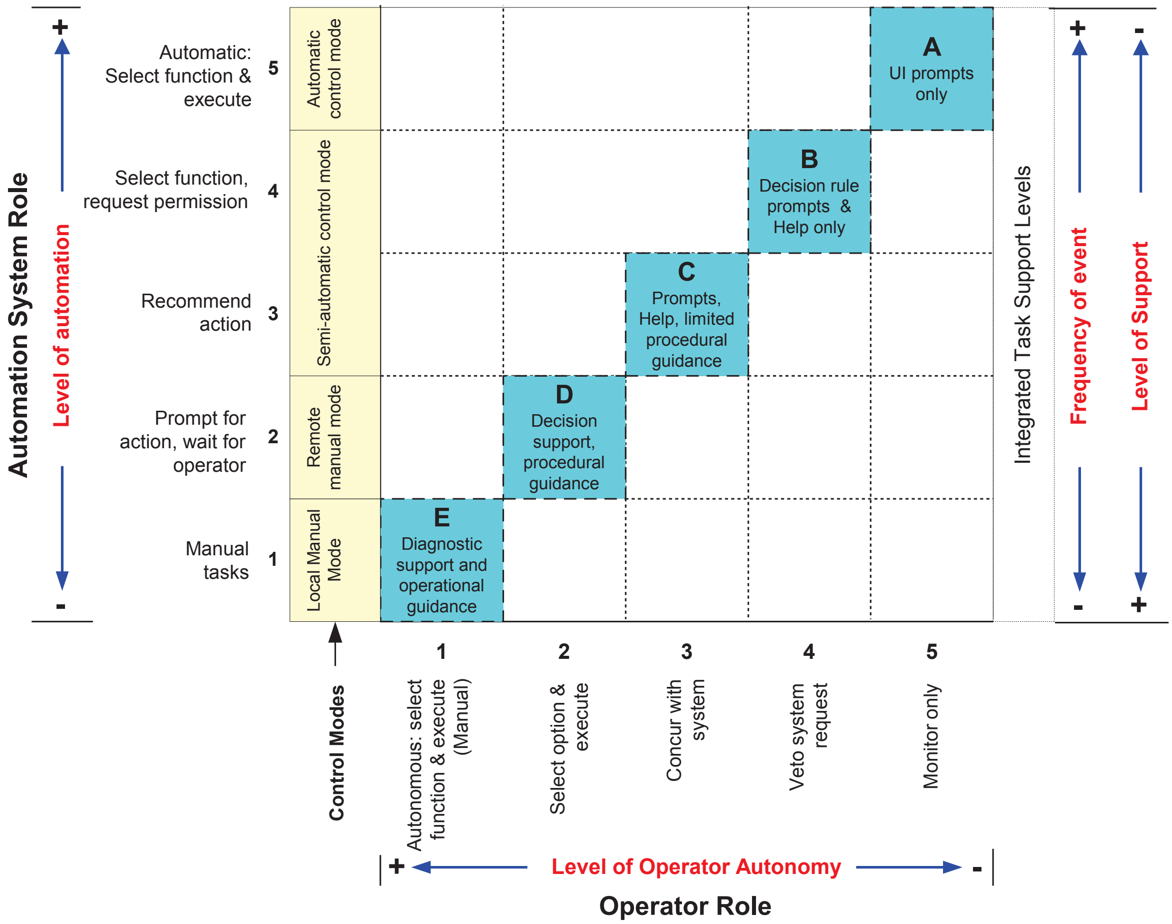


Figure 13: Relationship between automation role, operator role and task support

Figure 13 benefits from concepts established in the early work of Pulliam et al. (1983), Parasuraman and Mouloua (1996 [42]) and Sheridan (2002 [54]). It shows that the more autonomous the operator role, the more task support is required, especially for non-routine operations. In contrast, the more autonomous the automation system, the smaller the role of the operator, and therefore less task support is required. Table 7 below provides more detailed information on the nature of the support the TSS provides the operator.

Table 7: Task Support Components

Module Name	Description
1. User Interface Prompts	Automatic display (e.g. prompt line) of information about the current active object on the interface.
2. Context-sensitive HSI Help	Information on the structure and use of the HSI, linked to the active mode, process, system or object. This level can either be invoked by the operator, or automatically invoked by certain HSI operations (as determined by the configuration in the HSI Operator Profile).

Module Name	Description
3. Context-sensitive Process & Procedure Guidance	This comprises the core of the Computer-based Procedures. It provides structured, context-sensitive guidance on operational procedures. This includes display of process paths (e.g. plant modes and states or Piping and Instrumentation Diagrams [P&IDs]) and the corresponding procedure steps. The module provides a drill-down facility to display progressively more information, as well as a zoom-in and zoom-out facility, or expanding and collapsing levels of detail.
4. Operational Advisory System	This is a software agent-based module that provides knowledge-based advice as well as operational rules and policy. This module will enable the operator to engage in a human-like interaction with plant systems in order to elicit more complete information about the plant condition. Specific functions include signal validation and accident management guidance.
5. On-line Reference System	This is a database of hypertext (cross-referenced and cross-linked) on-line documentation (operating manuals, technical manuals, etc.) with a powerful search engine and query facility.
6. Task Performance Monitoring System	This optional subsystem monitors the operator's performance according to task performance criteria as set up by the Supervisor or Senior Reactor Operator. It also tracks HSI usage and provides reports as determined by the supervisor. Part of this facility also handles the operator's own performance and preference profiles, depending on permissions set up by the supervisor.

Interestingly, research by Flemisch et al. (2012 [11]) proposed ideas similar to Hugo (2009 [20]), when they investigated how the interaction and coordination of four concepts: ability, authority, control, and responsibility is integral to improving the dynamic balance between humans and automation in high-risk and complex systems that use assistant systems and adaptive automation. Whether the human or automated agents have the skills or means to accomplish an action appropriately or as expected by the designer is how Flemisch et al. (*ibid*.) defined ability. Authority is generally what the designer allows the agent to do or not do, and more specifically deals with what span of (functional) control the agent has, and who among the agents has the ability to change the span (or distribution) of control among the team of agents, there giving more or less control authority to a specific actor. Control is the force that an agent can exert to influence the system and its variables such that the process proceeds as designed or as preferred by the agents and designers. Responsibility is the anthropomorphic concept that defines the "rules of the game", and applies more to the designers and human operators in that it is the accountability that is placed on these agents or the automation to incentivize certain behaviors and actions and discourage others. If the desired outcome is not achieved, or an error occurs, the agent who is assigned responsibility for those actions and the outcome will be held responsible (i.e., blamed).

From these four concepts, Flemisch et al. (*ibid*.) developed a very elaborate model of how human and automated agents can collaborate dynamically. Their paper describes in detail the development of their model, starting with the operational relationships among ability, authority, control, and responsibility, and shows how the resulting final model, shown in the "FA graphical tool" in Figure 14, is methodically built upon these foundational concepts. Furthermore, in the methodical process of developing their model, they were able to identify a number of important implications for the dynamic allocation of functions between humans and automation. One of their main findings is the importance of maintaining internal consistency and balance between the ability, authority, control, and responsibility of all the agents involved in controlling a given function. To the extent there are inconsistencies, such as whether the human or automation has control of the function at a particular moment or for a given operating context, will lead to discrepancies in the human's and automation's "mental model," and will usually result in a kind of mode error.

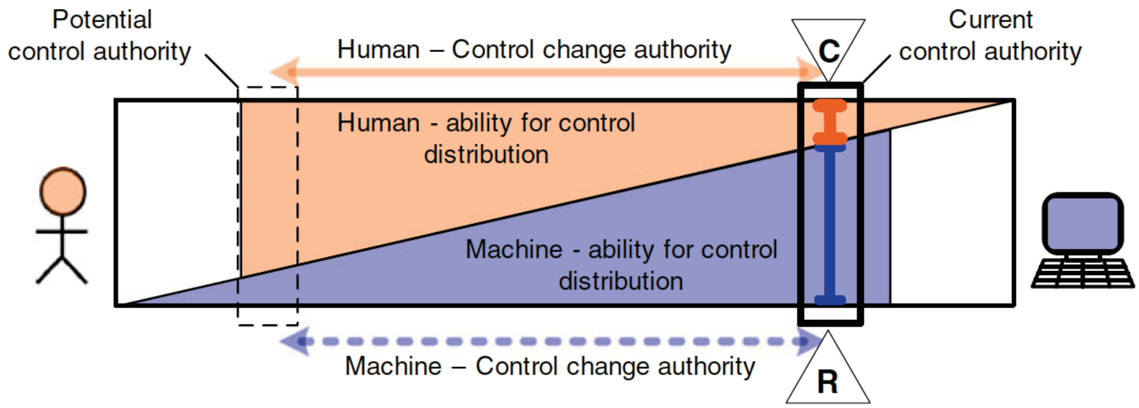


Figure 14: FA Graphical Tool (Flemisch et al. 2012)

4.4 Principles for the AdvSMR FA Framework

Based on prior FA research done in NUREG/CR-3331, Hugo and Engela, (2005 [21]), and Pritchett, Feigh, and Kim (2013a, b [45],[46]), as well as the automated assistant and TSS research by Rasmussen and Goodstein (1987 [49]), Vicente (1999 [58]), Hugo (2009 [20]), and Flemisch et al. (2012 [11]), a new FA framework for the AdvSMR context has been developed. This section describes the guiding principles for this AdvSMR FA framework and provides in more detail the procedure for implementing the FA process or method.

4.4.1 Principle 1: FA needs to capitalize on the fact that humans and automation have different, but complimentary, strengths and weaknesses.

Jordan (1963 [26]), and many others, have argued that humans and automation have different, but complimentary, strengths and weaknesses, and that overreliance on the comparative nature of Fitts' List can lead to the allocation of functions that is sub-optimal. Hoffman and Drury (2002 [17]) furthered this idea by re-casting Fitts' List to show their more complementary nature.

1. Machines are not "aware" of the fact that their model of the world is itself in the world. That is, a machine's understanding and sensitivity to context is ontologically limited. People are aware of the fact that their model of the world is itself in the world (i.e., their sensitivity to context is higher), but because their context is knowledge and attention driven, humans cannot develop complex and unbiased computational models of the world. Therefore, humans need machines to computationally instantiate their models of the world to give them a more complex representation of the context that helps keep them informed of context, but machines need people to keep these computational models aligned with the world (i.e., context).

2. Machines have an ontologically limited sensitivity to meaningful change. That is, their recognition of important anomalies is limited by their understanding of what reality is. People's sensitivity to change is higher, but is based on the cognitively mediated perception of stimuli and is biased heavily by the recognition of anomalies. Therefore, humans need machines to update

and correct their perceptions because they are based on a non-representative sampling scheme of anomalies, and, conversely, machines need people to keep them stable given the variability and change inherent in the world.

3. Machines are ontologically limited in their adaptability to change. People have better adaptability to change, but it is goal driven. Therefore, machines need people to help them adapt to change by defining, updating, and/or repairing (i.e., correcting) their ontologies, and humans need machines to help objectively evaluate different goals, and then affect positive change following situation change.

The important lesson from this principle is that many prior FA models and approaches viewed the decision making process as a competition between humans and machines, and that in a world of limited resources, there should only be one "winner." Implied in this approach is the idea that humans have little value beyond their abilities to execute a function (e.g., human creativity and problem solving abilities are undervalued). Dekker (2006 [5]) has argued that humans should not be labeled as just the least reliable and unsafe part of complex systems (and therefore are a primary focus of many engineered safety controls), but that they are also, paradoxically, often the safest part of complex systems. Dekker points out that humans are often making adjustments to the fielded system, based on their knowledge and experience of how the system works under various contexts, which improves the overall reliability of the system (i.e., humans are the 'glue' that keeps the complex system working, which would otherwise fall apart if left unattended). Yet, the actions that humans do that keep the system working are often overlooked and undervalued in safety analyses and engineering assessments. Said differently, this "winner-takes-all", "either/or" perspective in FA is reminiscent of the kind of thinking that drives a wedge between organized labor and management, and is not necessary when thinking about how to allocate functions between humans and automation. In fact, as Dekker (*ibid.*) and Hoffman et al. [17] show, there are likely many yet unrealized benefits to be gained by moving away from this implied paradigm.

A further implication is that if this kind of allocation indicates that human are "unnecessary", then major cost savings could be achieved by reducing the number of operators required. This is clearly a fallacy. Although it is potentially possible to simplify control room, local control station, HSI design and operations overall through automation and the use of advanced technology, it does not necessarily lead to staffing reduction. In spite of the urgent need to reduce O&M costs, designers should understand that automation is more likely to lead to role change rather than staffing reduction. The FA process should therefore always emphasize optimization of roles, which includes maintaining high safety and reliability standards.

4.4.2 Principle 2: FA needs to be based on the tenets for effective teamwork

As mentioned above in the evaluation of the FA framework developed by Pritchett, Kim, and Feigh (2013b), tenets for effective teamwork must be a guiding principle for the AdvSMR FA framework. This is the natural extension of Principle 1 in that if the FA framework is going to capitalize effectively on complementary strengths and weaknesses of humans and automation, the framework must be based on tenets or guidelines that effectively organize the work and functions to be performed by various members of the team. These tenets include:

- Commitment and Trust: Team members must be fully committed to achieving the mission and goals as required by the operational context. They must also understand their roles in this context.
- Communication: The members must have open lines of communication. Communication must be honest and flow between all team members equally.

- Diversity of Capabilities: Trust includes that members must have the assurance that each member possesses skills and strengths that complement the skills, strengths and weaknesses of other team members. This will ensure full understanding of what each one's contribution is expected to be.
- Adaptability: Team members must be flexible and adaptable to changing conditions. Team members should be able to meet new challenges head-on.
- Creative Freedom: Within the constraints imposed by the operational context, team members should be able to try innovative problem solving. They must trust that others will listen openly to their ideas, they must be able to confidently and openly communicate their new ideas, they must be trusted enough in their area of expertise to lead the way in new initiatives and they must be adaptable enough to accommodate the changes inherent in bringing new ideas to realization.

Translating these tenets into human-automation interaction guidelines produces the following requirements:

- The human agents must know and understand the system function and its purpose.
- The information required by the human agents is available, either provided by the system, or as an extrinsic task aid. This information is always available or revealed on demand and includes an indication of the reliability or accuracy of the indication.
- The actions of the human agents (or the results of human actions) can be sensed by the system and compared to the performance requirements.
- Deviations from the "plan" are indicated to the humans in a suitable perceptible form, with an indication of the severity and possible mitigation measures.
- The actions of the system are indicated to the humans in a suitable format.
- The human can intervene at steps in a process where such intervention will not compromise permissives.
- The system can offer suggestions to the human to automate predictable, fixed sequences that the operator frequently performance (e.g., Frequent actions in some computer applications can be turned into macros, requiring the user only to initiate the sequence).

4.4.3 Principle 3: FA guidance must be easy to understand and actionable

The FA guidance should not be too conceptual or abstract, nor too high level to provided the necessary detailed guidance the designer needs to implement the approach. The methodology must also be resistant to misuse and misapplication. Fuld (1993 [12], 2000 [13]) in particular has been critical of past FA methods for being abstract and based more on ‘art’ than ‘science’. Other methods were developed with more rigor and detail, but some designers have misappropriated the original method and oversimplified it to the point that they are essentially misusing the FA method (e.g., Fitts’ List).

4.4.4 Principle 4: FA needs to be able to address various anticipated future working contexts

The AdvSMR FA needs to address various anticipated future working contexts, and in particular standard NPP contexts (e.g., startup, full-power, shutdown, normal operations), as well as design basis and beyond design basis accidents (e.g., anticipated failure modes, severe accidents, etc.).

4.4.5 Principle 5: The FA framework needs to be a graded approach.

Not all HFE work, including FA, needs to be performed at the same level of detail. Obviously, resource constraints will dictate the level of effort, but one other key consideration is how risk-significant the function or functions being considered in the FA process. Functions that are more significant contributors to risk should be analyzed in greater detail. Additional guidance on how to take a graded approach to HFE can be found in EPRI Report #1010042 (2005 [6]).

4.4.6 Principle 6: The implementation of the results from the AdvSMR FA framework needs to avoid common issues in human-automation collaboration.

It is likely that the FA will need to adopt a technology-centered perspective, where the designer automates as many functions as possible. However, adoption of this perspective must not lead to a number of well-known human-automation collaboration issues including, but not limited to: 1) the human operator having a set of unrelated leftover functions that are difficult to manage collectively or coherently, or 2) giving the impression to the operator that they do not have an important role or function in the system. This is one of the focus areas for the AdvSMR Human Automation Collaboration project.

4.5 Towards a Foundational Framework for AdvSMR Function Allocation

4.5.1 Prior Technical Bases

The starting point for the technical basis for this AdvSMR FA framework is NUREG/CR-3331 (Pulliam et al., 1983 [47]). Updates to this method can also be found in Price (1985 [43]), and Price and Pulliam (1988 [44]). The high level steps for NUREG/CR-3331, and this method's allocation decision matrix are presented below for reference purposes, and to show that this AdvSMR FA framework uses this work as part of its technical basis.

1. Prepare for design, by organizing a multi-disciplinary team, identifying requirements and system constraints, and creating a records database.
2. Define functions as either necessary or accessory. Identify each function's inputs, outputs, and relationships to other functions (i.e., dependencies).
3. Hypothesize design solutions as a multi-disciplinary design team by proposing an engineering hypothesis, an allocation hypothesis, and a human factors solution.
4. Test and then evaluate the preliminary allocation solution.
5. Iterate the design cycle to correct errors, optimize the design, and complete the design to an acceptable level of detail.

Figure 15 is the allocation decision matrix that is central to this FA method, and is used as part of step 4 above.

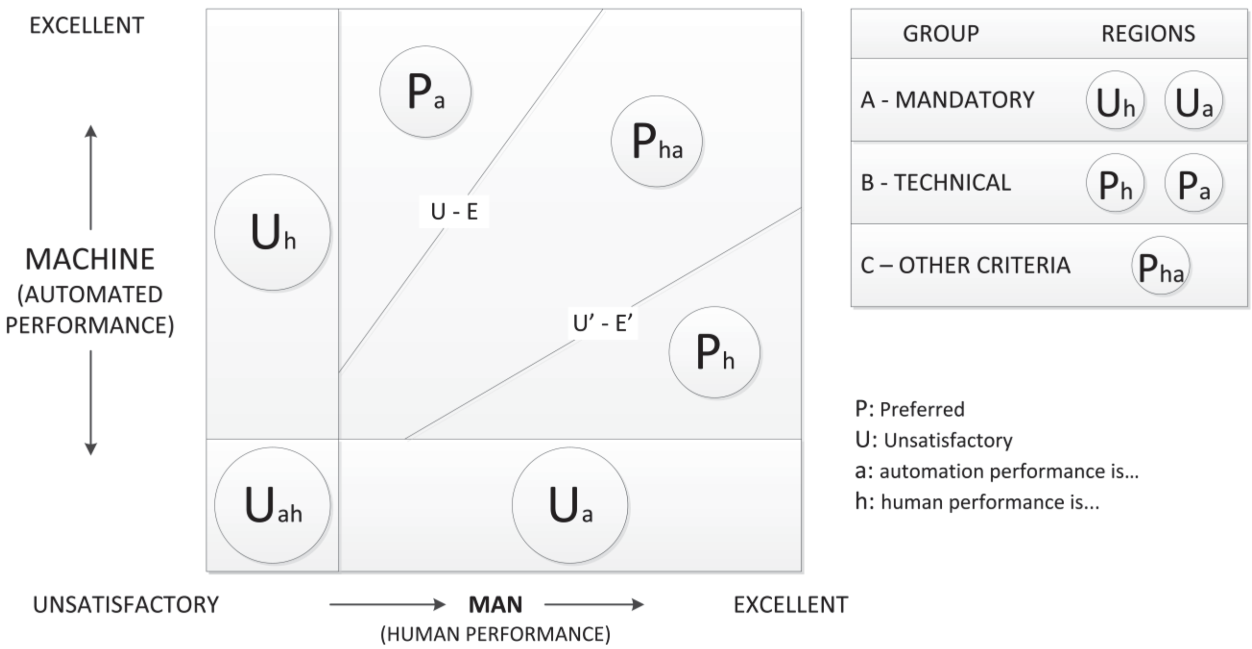


Figure 15: Allocation Decision Matrix (NUREG/CR-3331)

NUREG/CR-3331 explains this matrix by first describing the two regions: U_a (unacceptable: automation), and U_h (unacceptable: human). Functions falling in region U_a are too low on the "machine performance" scale to be considered for automation; they can presumably be allocated to human by default. Conversely, in region U_h, any allocation will presumably be to machine. However, at the intersection of U_a and U_h is the region U_{ah}, where both humans and machines perform unacceptably. Any function that falls in this region should be considered for redesign or included in a system only as a final resort.

The regions P_h and P_a represent functions that might be acceptably performed by either human or machine, with varying degrees of advantage. In the region P_h (preferred: human), the human is expected to be substantially superior as a control component. Functions in this region will be allocated to humans in the absence of other overriding considerations. Conversely, in the region P_a (preferred: automation), allocation will ordinarily be to machine.

Finally, there is the region P_{ha}, bounded by regions P_a, P_h, U_a, and U_h, and by the lines of constant proportional difference U-E and U'-E'. At all points in this region the difference between the expected performance of human and machine is not great. This is a region of less certain choice so far as the relative control performance of human and machine is concerned. In this region the allocation decision can be based on considerations other than the engineering performance of human and machine as control components. The considerations include costs, worker preferences, and the availability of proven design experience.

4.5.2 Overview of the AdvSMR Function Allocation Framework

As indicated above, the allocation of functions is determined by analysis of the functional control requirements and comparison of these requirements with the capabilities (mainly performance and feasibility) of the human and the machine. Additional information on the relationships between systems, processes, functions, measures and plant goals would be obtained from the WDA. Of particular importance for the FA process is the Contextual Activity analysis, which would provide high-level information on plant operating modes as well as the operating scenarios for those operating modes.

4.5.3 Allocation decisions

The functions that are shared between human and machine are functions that can be performed by both the automation system and the operator, given certain conditions, or one can perform parts of the function while the other should rather perform other parts. An example of such a function would be the adjustment of the output power of the plant. The operator will adjust the set-point while the system will adjust the individual component set-points according to a specific control function or technical specifications..

The allocation of some functions will be mandatory and predetermined by constraints established during earlier stages of design (for example, specifications or regulatory requirements).

Allocation decisions are made to maximize total system performance and effectiveness. FA will also be guided by information and decisions required to initiate, sustain, and otherwise support the functions.

Allocation is determined or influenced by:

- A comparison of performance between humans, hardware and software,
- Cost factors
- Cognitive support for the operators.
- The relative performance of humans, hardware and software
- The availability of support for the operators.

In some cases the allocation is not clear-cut and this can lead to functions that may be shared between human and machine. The process is based on the answers to the following four fundamental questions:

- Is automation essential or mandatory?
- Is human interaction essential or mandatory?
- Is it technically feasible to automate the function?
- Is it feasible for the human to perform the function?

4.5.4 Process Diagram

The Function Allocation Process Flow Chart below, based on NUREG/CR-3331, describes the logical decision process of the application of the high level stages:

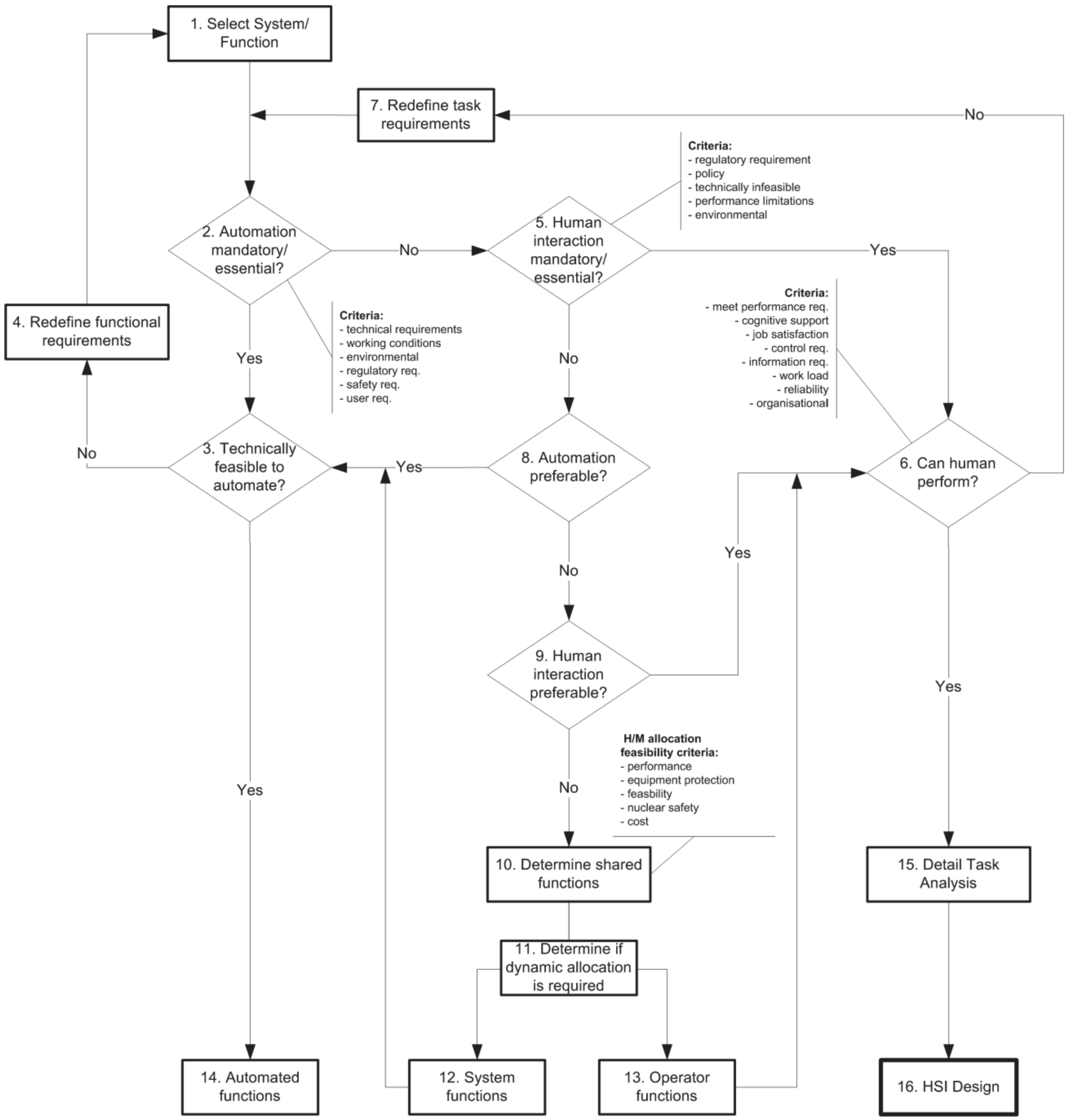


Figure 16: Function Allocation Decision Process

4.5.5 Procedural Stages

The first functions and decisions to be allocated are those having specific allocations mandated by system requirements, regulatory requirements, environmental conditions, organisational policy, the operator role, or other factors.

The assigned operator role will require that some functions or decisions be performed or made by humans within the system. Some functions or decisions must be performed or made by hardware or software components of the control system or by humans with the assistance of other system components in order to meet system requirements. The allocation of these functions and decisions may then logically require that other functions or decisions be allocated to a specific portion of the system.

An overview step-by-step procedure to perform the functions indicated in the process description is shown in Table 8:

Table 8: Function Allocation Procedure

Stage	Description
1. Decide on analysis formats	The practical application of the principles described in this document requires the analysis of information obtained from Functional Specifications developed by System Engineers. This analysis must be recorded accurately with all applicable references to ensure traceability. This guideline does not prescribe a specific format for the analyses - various formats are possible. However, in order to comply with the documentation requirements described in the Outputs section below, the following analysis should be recorded as comprehensively as possible: a. Function name b. System(s) c. Sub-system(s) d. Associated tasks e. Automation considerations: • Working conditions – hostile or benign • Feasibility for human – impossible or easy • Safety requirements – critical or not applicable • Technical feasibility – high or low f. Human interaction considerations: • Regulatory requirements • Policy requirements • Technical feasibility • Performance constraints • Environmental constraints g. Human performance considerations: • Compliance with requirements • Cognitive requirements • Adequacy of cognitive support • Adequacy of job satisfaction • Control requirements • Information requirements • Reasons for automation preference, or alternatives considered • Reasons for human control preference

Stage	Description
	h. Motivation for shared control strategy
2. Select systems and functions	Determine all candidate functions and systems
3. Identify requirements of operator role	Analyse the operator role to determine the impact on both function and decision allocation.
4. Select operator tasks	Determine all candidate operator functions
	NOTE: To compensate for the lack of operating experience and the lack of existing operating procedures, the following method may be used as an interim measure: a. An initial assessment of key operator roles during normal operational modes (including actions during and after state transitions), based on the known operational characteristics of systems. b. Extraction of generic operator tasks. These tasks must be reviewed and filtered for relevance and applicability to the . c. Compilation of a consolidated list of generic tasks d. Matching each task against scenarios and systems, as described below.
5. Develop operational scenarios	Describe all feasible operational conditions of the plant, system or sub-system that requires operator monitoring, diagnosis, interaction (control) or intervention of any kind.
6. Link operator tasks to scenarios	List all operator tasks that may be feasible during a given scenario.
7. Link systems to tasks	Determine all systems that may be involved during the performance of a particular task.
8. Perform a first-order allocation	Based on the operator role and other identified mandatory/essential allocation requirements, allocate functions and decisions to human, equipment, or combinations to account for mandatory function and decision allocations. A FA checklist can be used to allocate weights where possible to the following key criteria: **a. Compare Risk / Feasibility**: Compare allocation alternatives with respect to the technical feasibility and risk of allocating to human or machine. (Includes equipment protection). **b. Compare Time Required**: Compare allocation alternatives with respect to the time required to implement the design and for the system to perform. **c. Compare Performance**: Determine relative system performance benefits to be gained or performance deficiencies to be experienced by allocating the function to the human or machine.

<table>
<tr><th>Stage</th><th>Description</th></tr>
<tr><td></td><td>
<table>
<tr><td>d. Compare impact on nuclear safety</td><td>Determine safety benefits and deficiencies to be realized by allocating the function to human or machine.</td></tr>
<tr><td>e. Compare Workload</td><td>Compare allocation alternatives with respect to individual or group workload.</td></tr>
<tr><td>f. Compare Life-Cycle Cost</td><td>Compare allocation alternatives with respect to overall life-cycle cost.</td></tr>
<tr><td>g. Compare Availability</td><td>Compare allocation alternatives with respect to system or component availability to perform mission.</td></tr>
<tr><td>h. Compare Training</td><td>Compare allocation alternatives with respect to associated life-cycle training requirements.</td></tr>
</table>
</td></tr>
<tr><td>9. Evaluate against comparison system</td><td>Compare the current allocation of functions to the allocation within current similar systems (Operating Experience – see NUREG-0711). Use the comparison to estimate the performance and other characteristics of the current allocation.</td></tr>
<tr><td>10. Make trade-offs and Selecting Allocation</td><td>Determine which functions or decisions should now be allocated to a particular resource due to the previously allocated functions and decisions. Compare the system design for different allocations and for different mission phases and stages of the life cycle. The final result will indicate either a clear allocation to either operator or automation system, or a shared allocation to both.</td></tr>
<tr><td>11. Define required operator KSAs</td><td>Given the mandatory allocations, determine the KSAs (knowledge, skills, and abilities) that will be required of the humans that will be a part of the system. (Note that this step could be combined with the last phase of CWA where worker competencies are assessed).</td></tr>
</table>

4.5.6 Process description

As indicated before, the WDA is an essential input to the FA process. In addition to the information on functions, systems and operating scenarios obtained from the WDA, analysts will also require the following documents:

- Plant Concepts of Operations document that describes the operational characteristics of the plant overall. (This document was described in detail in the April 2013 milestone report). Note that typically the Plant Concepts of Operations would only be finalized towards the end of Basic Design, but it is essential to obtain high-level information as early as possible, especially policy and regulatory requirements regarding mandatory operator roles and safety qualifications of certain systems. Information from the WDA and FA should be fed back into the Concepts of Operations development thoughout the project life cycle.
- System Operating Descriptions (SODs) and System Design Descriptions (SDDs) that describe the operational and technical characteristics of the various systems identified in the WDA.
- Functional Requirements Analysis (FRA) report. This document will include a functional breakdown of the plant and its subsystems.

- Functional Control Specifications (FCS) for main and subsystems. This document will include the automation requirements for specific systems to achieve the plant's objectives. Note that for new plants these documents will go through several iterations as the design of the plant matures. It is vital that human factors principles, especially from the WDA and FA, be incorporated in automation system design as early as possible.
- Human capabilities and performance characteristics. The most recent human capability and performance characteristic research should be incorporated in the WDA and FA process. This will include international standards and guidance from major stakeholders in the nuclear industry like EPRI, NRC, and national laboratories.

The process steps are described in the following table:

Table 9: Detail Function Allocation Process Description

Process step	Description	Inputs to step	Outputs from step
1. Select system / function	Select the function that has to be allocated. The function is selected from the list of control functions determined with the function analysis.	WDA, FRA, SODs	Selected system functions
2. Automation mandatory or essential	Determine if automation is mandatory or essential? The criteria for mandatory automation requirements may be based on the following: • Technical requirements • Working conditions • Environmental constraints • Regulatory requirements • Safety requirements • User requirements The outputs from this step are mandatory automated functions that are fed to step 3 and non-mandatory automated functions fed to step 5.	SDD, FCS	Human considerations for automation (workload, reliability, performance shaping factors)
3. Technically feasible to automate?	The inputs to this step are the mandatory automated functions. The designer evaluates the feasibility of automation of these functions.	Automation SDD	List of mandatory functions
4. Redefine functional requirements.	If it is mandatory to automate a function, but automation is not feasible, the requirements for that specific function need to be redefined. This can be achieved by redefining the function or the applicable design requirements.	Automation SDD WDA	Redefined functional requirements
5. Human	Determine whether human interaction is	Automation SDD,	List of

Process step	Description	Inputs to step	Outputs from step
interaction mandatory?	mandatory or essential. The mandatory human interaction requirements are defined according to the following key criteria: a. Regulatory requirements b. Organisation policy c. Technical infeasibility d. Human performance limitations e. Environmental conditions Mandatory human functions are fed to step 6 and non-mandatory actions are fed to step 8.	WDA	mandatory/essential human interaction requirements
6. Can human perform?	Analyse the input function to see if the human can perform this function. The analysis is done in accordance with the widely documented performance characteristics and capabilities of humans, including the following: a. Performance requirements b. Cognitive support requirements c. Job satisfaction d. Control requirements e. Information requirements f. Work load g. Reliability h. Organisational requirements If this analysis indicates that the human can perform the function, it is passed to step 15, if not the function is moved to step 7.	Human capability and performance characteristic research documents (Use up to date recognised research documents)	Human performance capabilities
7. Redefine functional requirement.	If a non-feasible function is allocated to the operator, the function requirements should be redefined. Redefining the design requirements or re-evaluating the functional requirements or allocation criteria that led to the decision to allocate the function to the human may achieve this.	Automation SDD WDA	Updated functional requirements

Process step	Description	Inputs to step	Outputs from step
8. Automation preferable?	Neither automation nor human interaction is mandatory at this point in the process. The designer thus establishes if automation is preferred. The criteria for this preference may be based on: a. available technology capability b. consistency with design practice c. operator preference d. operating experience e. overall automation strategy If automation is preferred the function is passed to step 3, if not it goes to step 9.	WDA	Criteria for preferred automated functions
9. Human interaction preferable?	At this point, it is established that automation and human interaction is not mandatory and automation is not preferred. The designer now decides if human interaction is preferable. If human interaction is preferable the function is passed on to step 6, if not the implication is automatically that the function will be shared between human and machine and thus passed on to step 10.	WDA	Criteria for preferred human functions
10. Determine shared functions	In this step the shared functions are analysed to define in which way the function is shared between human and machine. The criteria for the assessment of the feasibility of the shared allocation are: a. Performance b. Equipment protection c. Technical feasibility d. Nuclear safety e. Cost The human part of the function is passed on to step 12 and the machine part of the function is passed on to step 11. An example of a shared function is where the automation system prompts the operator to perform an action, e.g.	WDA	Criteria for shared functions

Process step	Description	Inputs to step	Outputs from step
	initiate withdrawal of shutdown rods during start-up of the reactor, but the withdrawal action is performed by the automation system.		
11. Determine if dynamic allocation is required	For shared functions, the allocation can be static across all operating contexts, conditions, and failures, or it can dynamically change. If the allocation can remain static, use the criteria listed in step 10 to decide the allocation distribution. If the allocation is required to be dynamic, identify and model all of the anticipated operating contexts and/or credible failure modes that require functions to be dynamically allocated across agents. Then, determine how functions will be assigned: a. As a function of the requirements for well coordinated information-processing for each operating context and failure mode identified (Rasmussen & Goodstein, 1987) b. In a manner that connects the functions to their means (i.e., how's) and ends (i.e., mission goals) for each operating context and failure mode identified (e.g., abstraction-decomposition heirarchy) c. As a function of the requirements for effective human-automation coordination. For example, the Flemisch et al. (2012) concepts: ability, authority, control, and responsibility Then, model the human-automation interactions for each dynamic allocation using the SRK information-processing routes scheme to further refine: a. What kind of information the human should be requesting and automation should be providing b. What level that information should be at to facilitate operator performance and human-automation	WDA	FA report

Process step	Description	Inputs to step	Outputs from step
	coordination c. What kinds of information processing errors the human is likely to commit (e.g., skill-based, rule-based, or knowledge-based errors)		
12. System functions	In this step the part of the shared function that will be automated is documented.	None	FA report
13. Operator functions	In this step the human interactions of the shared function are documented.	None	FA report
14. Automated functions	This is the collection point for all the automation system functions (i.e. functions allocated to the machine).	None	Functional Control System Specification, OCS Specification
15. Detail Task Analysis	Perform and document detailed operator tasks. This is the collection point for all the operator functions, functions allocated to the human.	System Functional Analysis, Function Allocation	Task Analysis report
16. HSI Design	Design and develop all functions and components.	Task Analysis Report, FA Report, Automation System Specification	Complete, including control rooms, user interfaces and TSS.

4.5.7 Allocation Trade-offs

The allocation of functions to either machines or humans is further determined by a number of trade-off factors:

- Technology capability and limitations (i.e. technical feasibility)
- Human capability and limitations
- Operational requirements
- Nuclear safety requirements
- Equipment protection requirements
- Regulatory requirements
- Organisational requirements
- Cost, productivity and economic factors

The trade-off criteria for these factors are outlined below.

The following table presents a method to evaluate the factors listed above:

Table 10: Function Allocation Decision Criteria

Allocation Criteria	Description
1. Allocation to automation is a regulatory requirement	If automation is a regulatory requirement then the remainder of the evaluation is superfluous.
2. Allocation to humans is a regulatory or policy requirement	If regulations require the operator to perform the function, then the remainder of the evaluation is superfluous.
3. Decision-making is too complex for humans (e.g. based on complex calculations)	The operator should not be required to perform calculations in order to use a function. Where too many decisions need to be made and such decisions are also dependent on calculations, the function should be automated.
4. Environmental conditions prevent human operation	This applies to tasks outside the control room where working conditions are characterized by environmental hazards such as radiation, dust, heat, excessive vibration, noxious or asphyxiating atmosphere, air blasts, noise or other physical hazards.
5. The function is excessively difficult (physically or cognitively) for humans	This applies to tasks (inside or outside the control room) that are characterized by severe mental or physical workload, for example, excessive demands on working memory or cognitive processing, or an excessive need for physical strength, speed, dexterity, precision, endurance, agility, reach, flexibility, etc.
6. Function is too costly for human operation	While it may be feasible for the operator to perform the function, to do so would require extraordinary measures (for example special environments, protective clothing, costly hardware or software design, special tools, etc.) that would significantly exceed the cost of automation.
7. Extensive data analysis required	The function should be automated when the interpretation of inputs and intermediate results will increase the cognitive complexity of the task.
8. Proven automation technology is not readily available	Although it may be feasible to automate this function, the required technology is either not available or not practical
9. System needs auto-configuration	Auto-configuration means that the automation system is required to configure the system because requiring the operator to do so is either too difficult or prone to error.
10. Function is consistent with automated design practice	Considerable operating experience or installed base shows that the function/system is effectively automated.
11. Human operators have performance limitations for this function	**Cognitive constraints**: When the function requires rapid assimilation and interpretation of information, rapid response, keeping many variables in working memory, etc. **Physical constraints**: When the manipulation of tools or machines requires extraordinary physical ability or endurance. E.g. Automation is indicated where the system/function produces many variables in a short time or where the need for dynamic control of a process requires accuracy, precision and rapid response.

12. Automation is not feasible or too costly	While it may be feasible to automate the function, to do so would require extraordinary measures (for example special environments, costly hardware or software design, etc.) that would significantly exceed the cost of allocating the function to the operator.
13. Operators prefer automation	When the manipulation of tools or machines requires extraordinary physical ability or endurance.
14. Complex sequences must be controlled	A sequence is a series of actions taking place over time. Complexity of sequence is defined in terms of: - predictability of the sequence steps - number of systems involved - type of systems involved - number of I/Os - duration of the sequence - number of interlocks involved - amount of data produced - type of data manipulation required - criticality of the sequence (i.t.o. safety, equipment protection and process stability) - response time requirements for control - concurrency of actions - tempo/speed of execution - external factors that may affect the sequence Automate the function when these factors indicate excessive operator workload or cognitive complexity, Alternatively, provide cognitive support in the HSI.
15. The system can provide adequate cognitive support	Where a potentially complex function is allocated to the operator, cognitive support should be provided in the HSI through Task Support. If this is not feasible, the function should be automated.
16. Human operation will provide job satisfaction	This means that human abilities should be exploited to ensure job enrichment. Don't automate a function just because the technology is available - this could lead to dehumanization of the job.
17. Operators prefer to control the process and such control can be proven to be reliable.	This applies to functions where either the automation system or the operator could perform the function. Instead of making it a shareable function, rather allocate it to the operator operating experience has shown that operators generally prefer to control this function.
18. Technology costs could be reduced by allocation to the operator	This is the corollary of items 12, 14 and 18: Don't automate if the operator can perform the task effectively and cheaper. Specific cost criteria: ● Engineering trade-offs: Are there obvious improvements in engineering design that would reduce human factors cost? Are there technology costs that could be reduced by allocation to the operator? ● Technical feasibility: Can technology be developed in time? Are costs acceptable? ● Technical consistency: Check for gross imbalance of technology between human and machine. ● Balance of cost: Have designers increased system cost by overemphasising technology?

	● Have designers increased human cost by under-exploiting technology? ● Cost sustainability: Can costs for both system and humans be sustained over the lifecycle of the project?
19. Expected operator workload is…	If operator workload is expected to be high, the function may be automated. If low, it might be better to allocate to the operator.
20. Time available for operator response is …	If the time available to respond to an event is short and the response is critical, it might be better to automate the function. If there is ample time to respond and criticality is low, allocate to the operator.
21. Pace of work, rate of process or condition change	If a lot of things happen at once or if conditions change rapidly, it might be better to automate.

5 Human Performance Consideration for AdvSMR Concepts of Operations

5.1 Introduction

The WDA described in the preceding sections serves to identify the functions that must be accomplished in AdvSMR plants. This information then feeds into the function allocation analysis, which determines what functions and tasks are assigned to human operators and what functions and tasks are assigned to the automation. Once the operator functions and tasks are identified, the final step of the CWA and WDA is to determine the performance requirements associated with the operators' responsibilities.

It is critical to establish clear human performance requirements; this information is necessary for the design of the HSI and the automation. To design a control system, designers must know what the operators must monitor, what information they must have and how that information should be presented, and what actions they must take to operate the plant successfully and safely. In addition to informing the design of the HSI and automation, clear human performance requirements are necessary to design the procedures that operators must use when operating the plant, and to developing the probabilistic reliability analysis (PRA) and human reliability analysis (HRA) for the plant.

As stated in the April 2013 milestone report [23], the original plan was to risk-inform the identification of the human performance requirements. This would typically involve detailed review of the PRA and HRA for a plant and identifying and evaluating required human actions (NUREG-1792, Kolaczkowski et al., 2005 [30]). This classic approach is not feasible for the present project, for several reasons. First, while the PRA for the EBR-II reactor is available, there does not yet exist a PRA or an HRA for any AdvSMR designs. The EBR-II reactor may be informative, but it does not take into account the advanced automation and therefore does not directly translate to AdvSMR designs. Additionally, an HRA is not available for the EBR-II design.

However, it is possible to evaluate the scenarios and events for which the plant is designed to handle and to identify and characterize the role of the operator in those events. Once the role of the operators has been clarified it is possible to determine the associated performance requirements. This is the approach that the Concepts of Operations project is taking. The WDA and CWA analysis in progress include evaluation of normal and abnormal/emergency operating scenarios. The project team is identifying the difference between EBR-II and postulated AdvSMR designs in terms of the impact of automation, and based on this information, it is possible to analyze the postulated role and responsibilities of the operators. The goal of this analysis will be to characterize the required operator response for each normal and abnormal/emergency operating scenario that have been identified, and to characterize the challenges to those responsibilities and the consequences of failure. In this qualitative manner, the human performance requirements will be risk-informed.

The CWA/WDA is still in progress, but this section reports on the analysis done to date of two normal and one emergency operating scenario (see section 1.4.1). Additionally, we provide an overview of general, high-level performance requirements for operators at any NPP. These requirements are likely to be very similar to human performance requirements at AdvSMR plants.

5.2 Using the Work Domain Analysis to Inform Human Performance Requirements

As explained previously, WDA is a framework and process for determining the functional structure of the work domain, independent of the technology for achieving that work. It helps to identify the goals and functions of that domain and forms part of the overall CWA methodology, which includes contextual activity analysis, strategies analysis, organizational coordination analysis, and worker competencies analysis. The appropriate time in the product life cycle for determining operator performance requirements for advanced control rooms of any design including the multitude of AdvSMR designs under consideration, is during the conceptual design phase. The introduction of WDA and functional requirements analysis and FA is considered part of the Systems Engineering approach to Concepts of Operations promoted by INCOSE.

In terms of its relationship with system performance, human performance requirements are a product of, and are dependent upon the system performance requirements associated with a particular power plant design. As part of the WDA approach, general functions are identified and allocated between automation and personnel. Methods such as hierarchical task analysis and cognitive task analysis are worker or operator-centric and are oriented in terms of what is done by personnel, in what order, and to what tolerances. WDA is critical because it is the method of choice for specifying things at a much higher level and provides the basis for determining what must be done, whether by automation or by the human. Within the broader scope of CWA, the social structures of the workplace (crew size and complement, communication and reporting requirements) and technology that can be brought to bear are used to determine how the information would flow through the system.

When the WDA is completed in FY14, the high-level FAs determined from analyses would be key to identifying the knowledge, skills and abilities requirements for operators for AdvSMRs.

5.2.1 Human Performance Requirements at EBR-II

The EBR-II reactor design is the basis for many of the current AdvSMR sodium reactor designs, in spite of its 1970s-era technology, including analog I&C. In considering emerging sodium reactor designs, we have assumed that across all normal operating scenarios there will be a high degree of automation with considerations given to the likelihood that the capability exists for operators to take manual control of components, systems, and processes when necessary or appropriate. We also assume that the control rooms will employ advanced, digital instrumentation, controls, and HSI.

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

An abstraction hierarchy and a contextual activity template were developed for two normal operating scenarios and one abnormal/emergency operating scenario (see Section 3.4). Based on this information, the team identified the responsibilities of the operating crew, classified into six generic operator roles based on insights from NUREG 1122 [37], NUREG-1123 [38] and previous analyses performed for the PBMR design by one of the authors of this report as follows:

- Monitoring (of component(s), system(s), parameter(s), automation, or HSI)
- Control actions
- Diagnosis
- Recovery/mitigation actions
- Communication
- Configuration/setup

We evaluated the normal and abnormal/emergency operating scenarios based on these generic roles and specific functions that must be accomplished in normal and abnormal/emergency operations.

5.2.2 Normal Operating Scenarios

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

1. Drive the turbo generator (convert mechanical energy to electrical energy)
2. Maintain fast fission (convert potential energy to nuclear energy)
3. Maintain reactor cooling (utilize sodium coolant to remove reactor heat)
4. Manage and control plant operations

Two plant operating states, steady state operations and restricted fuel handling, identified during WDA analysis were selected and used in developing a framework for documenting operating crew responsibilities and performance requirements. Table 11 details the operator responsibilities for steady state and restricted fuel handling at EBR-II and the postulated operator responsibilities for the same operating modes in an AdvSMR sodium reactor plant. Steady state can be viewed as a base case for operator activity. Restricted fuel handling does not represent an abnormal state, however, restricted fuel handling is complex and operators have a large amount of activity and strong safety-related requirements that demand a high degree of situation awareness. During restricted fuel handling, workload is moderate to high and we envision that in an effort to reduce some of this workload that advanced designs will employ a great deal of automation.

Today's nuclear plants are considered as an electricity base load source; AdvSMRs breaks with that tradition by having the capability to load-follow more easily and economically. This load-following can take the form of response to grid demand, or pre-programmed variable load in agreement with the grid operator. In France and Germany there is already some degree of load-following in larger plants via primary frequency control. Load following with newer generation plants, also referred to as maneuverability, is expected to pass well-disciplined safety studies and be an expected, explicit characteristic. (in Lokhov 2011 [31]). As a result of the enhanced ability and corresponding expectation to load-follow, AdvSMR operators will likely have additional communication requirements and coordination with dispatch. If load-following is under automatic control, the operator workload may not increase appreciably. However, the human performance requirements during load-following will determine the level and type of workload to be experienced.

Another area where advanced reactors will differ from EBR-II is in the monitoring of sodium. The current design requires manual monitoring of sodium temperatures; in new designs this will be achieved by automation for steady state and restricted fuel handling operations. Performance requirements for operator manual use of the crane and control of fuel assembly movement in and out of the fuel basket during restricted fuel operations will be replaced by operator's initiating and monitoring robotic systems designed for that task. If there is a problem with the robotic movement, the operator will intervene and take manual control. Also, in the EBR-II design the operator depends on his/her haptic senses (that is, tactile feedback) to verify that there has been a positive capture of the subassembly. In the AdvSMR design, verification is expected to be an automatic process.

Table 11 describes the primary responsibilities of the EBR-II operator in the main control room (MCR) for normal operations and contrasts those functions with the expected equivalent for a modern FSR design:

Table 11: Operating crew responsibilities for selected normal operation scenarios in EBR-II and AdvSMR FSR designs

Scenarios	Steady State		Restricted Fuel Handling	
Functions	**EBR-II**	**AdvSMR**	**EBR-II**	**AdvSMR**
Drive turbo-generator	• Monitor turbo-generator • Communication with load dispatcher (LD)	• Monitor turbo-generator and automated control system • Communication with load dispatcher (decreased communication, LD→MCR in base load mode, increased communication LD↔MCR in load following mode)	• Monitor turbo-generator • Communication with load dispatcher	• Monitor turbo-generator and automated control system • Communication with load dispatcher (decreased communication, LD→MCR in base load mode, increased communication LD↔MCR in load following mode)
Maintain fast fission	• Monitor reactivity manually • Manual rod control (automatic control rod control available but not trusted or used)	• Automated system monitors reactivity • Operator monitors the automated system and reactivity • Automatic control rod control	• Monitor reactivity manually • Manual rod control (automatic control rod control available but not trusted or used)	• Automated system monitors reactivity • Operator monitors the automated system and reactivity • Automatic control rod control
Maintain reactor cooling	• Manually monitor ΔT (the difference between the intermediate heat exchanger (IHX) inlet and outlet temperature)	• Automated system monitors ΔT • Operator monitors the automated system and ΔT	• Manually monitor ΔT (the difference between the intermediate heat exchanger (IHX) inlet and outlet temperature)	• Automated system monitors ΔT • Operator monitors the automated system and ΔT
Manage and control operations	• Monitor manually all systems per a surveillance schedule (increased monitoring during online maintenance activities[1]) • Manual, expert-based diagnosis (mental, knowledge- based integration of data and diagnosis) • Manually control train-switching (often during	• Automation monitors the system, processes, and components, gathers data, and reports to the operators via the HSI • Automation (operational advisor system) conducts smart diagnostics, prognostics, trending, and data analysis	• Manual movement of fuel subassemblies, using crane and subassembly equipment • Manual grappling of subassembly in and out of the fuel basket and interbuilding coffin (IBC) • Manual/haptic verification of subassembly positive capture	• Automated fuel handling system, some robotics possibly involved • Operators monitor fuel handling system and robotics, manual intervention if necessary[2] • Automated movement of subassemblies in and out of the fuel basket • Automated

	online maintenance activities) ● Communication within MCR and between MCR and field/ maintenance operators	● Operator monitors the automation and shares responsibility for diagnosis of trends prior to thresholds ● Train-switching is automated	● Manual movement of subassemblies to fuel processing facility via IBC ● Communication between fuel handlers (two operators were required) ● Otherwise same as steady state	movement of subassemblies to and from the fuel processing facility ● Automated verification of positive subassembly capture ● Communication between fuel handler (one operator required to monitor the system) and I&C technician ● Otherwise same as steady state

1. Plants will often deal with planned or emergent maintenance activities while at power to save time during outages. This often involves switching active system trains to conduct maintenance on the train that is out of service. This is often the only activity that occurs during normal steady-state operations.
2. We expect that in AdvSMR designs, operators will not take manual control of the fuel handling system, but that they will call in an I&C technician in the case of a malfunction.

5.2.3 Abnormal/Emergency Operating Scenario

In support of documenting human performance requirements between the existing and advanced designs, the application of functional breakdown by human performance was extended to include abnormal/emergency plant operating conditions. A water-to-sodium leak scenario involving the secondary sodium system was identified for analysis through a combination of expert opinion, review of training materials, and procedures (see also Section 3.4.3). Although the event does not directly threaten the reactor as such, there is considerable financial loss associated with the event and it is expected to be challenging for the crew. A water-to-sodium interaction is particularly violent. When sodium and water interact, the oxygen atoms break from the hydrogen and bond with the sodium atoms to form sodium oxide. This releases hydrogen plus a large amount of energy in a strong exothermic reaction, which, if the interaction is of sufficient volume, will lead to fires and hydrogen explosions. These explosions can destroy equipment, cause fires in nearby combustible materials, and severely damage or destroy buildings.

This event. However, is not a concern for reactor safety since it does not involve the primary sodium system or the reactor, but requires investment protection of secondary systems. Once the event starts, the reactor is tripped, and the shutdown coolers, the reactor coolant pumps, auxiliary reactor coolant pump and/or natural circulation provide reactor cooling to remove decay heat. The secondary sodium system is separated from the primary system. In the EBR-II design the secondary system is isolated by stopping all secondary pumps and blocking flow through the intermediate heat exchanger (IHX). Operators will then drain the secondary sodium to the sodium drain tank. In AdvSMRs these actions will be performed automatically. Additionally, procedures require that the feedwater and steam systems are isolated and drained from secondary sodium heat exchangers, evaporators, superheaters, and the steam generator. The isolation and draining of these systems mitigate further potential damage that could be caused by additional water-to-sodium reactions. The plant will immediately lose the ability to generate power on the affected unit and if they do not quickly contain the damage, the event could severely limit future power generation capabilities.

As part of the ongoing WDA, a function-by-performance requirements matrix was developed and is presented in Table 12 below. In determining operator performance requirements for the water to sodium leak scenario, our abstraction-decomposition hierarchy identified the following functions:

- Maintain equipment integrity
- Maintain a habitable and safe environment
- Ensure containment of fission products
- Manage and control operations
- Provide electrical power
- Maintain reactivity control
- Maintain coolant circulation
- Maintain environmental control (HVAC)

Review of information in Table 12 suggests a number of performance requirement differences to be expected between EBR-II and advanced designs. The first major difference observed was associated with maintaining equipment integrity. In the case of AdvSMR, automation is expected to take over many of the monitoring duties performed by operators. The operator's situation awareness is likely to be improved by the addition of smart displays and trends including automatic diagnostic and prognostics that will be available (Endsley, Bolte, & Jones, 2011 [8]). In responding to this event, operators are required to communicate with the chemical operations technician. In future designs, communication is still needed between the SRO and the chemistry technician, but the system will have logged all recent chemical operations, thus helping to prevent errors in communication of status and ongoing activities. The operator's actions will be further reduced in that the current requirements for operator actuation of scram, building evacuation, sodium drain down and actuating the argon vent valve are all likely to be automatic actions.

In contrast with maintaining the equipment, operator requirements for maintaining a habitable environment are largely the same whether for advanced designs or the EBR-II design. This is because the water-sodium interaction event occurs outside of the main control room and the reactor building; the secondary sodium loop is housed onsite in another building located nearby. In our analysis, we assume a similar configuration for the AdvSMR.

With respect to containing fission products, all performance requirements are expected to be the same; this event does not pose a threat of radionuclide release. Protection of the intermediate heat exchangers (IHX) requires the same operator performance for both designs; the operators are to monitor shutdown cooling and the cooling louvers open automatically at preset temperatures.

As part of the scenario basis, offsite power is assumed to be available. Therefore, the operator's job for AdvSMR would be to monitor power conditions, but no actions are expected to be required. Although power monitoring capabilities may be more precise with the more advanced design, because no disruption to offsite power is anticipated, the actions required for monitoring are the same. Reactivity control performance requirements are also the same, the reactor has been successfully scrammed and operators will monitor reactivity via rod bottom light indication and verifying reactor power readings at zero power. Note that the researchers have analyzed the single module case. If the operator is to simultaneously monitor other modules during the event, the benefits of the automatic actions may be more pronounced.

In this particular event there are other functions where the human performance requirements are not expected to differ. Maintaining reactor coolant function is expected to have the same operator performance requirements for both designs. The reactor coolant pumps are operating properly and circulating the bulk sodium coolant. Shutdown coolers start automatically.

This sodium fire event does not involve the main reactor building and hence, the MCR for both the EBR-II and the AdvSMR are likely to be unaffected. Containing the fire will be the job of the emergency response team who are likely to coordinate with the control room crew and tech support center. Although automatic fire suppression may exist for the secondary sodium loop, it will be unable to contain the water-to-sodium reaction. However, the suppression system may extinguish secondary fires, thus reducing firefighter workload. Other than for purposes of communication and monitoring the global situation, the involvement of control room operators in support of maintaining environmental conditions is likely to remain low.

Table 12 describes the primary responsibilities of the EBR-II operator for abnormal operations and contrasts those functions with the expected equivalent for a modern FSR design:

Table 12: Operating crew responsibilities for a selected emergency operation scenario in EBR-II and AdvSMR FSR designs.

Scenario	**Secondary Sodium System: Water to Sodium Leak**	
Functions	**EBR-II**	**AdvSMR (FSR)**
Maintain equipment integrity	• The primary system and reactor integrity is not affected; primary and secondary systems are physically separated systems with heat transfer occurring in the IHX. • Monitor alarms (hydrogen monitoring system alarm, cover gas meter leak detector alarm, tube sheet leak detector alarm, secondary sodium relief header flow alarm, secondary sodium relief valve/flow detector alarm, and secondary sodium rupture disk alarm, secondary cover gas pressure alarm), trending data, verification of leak. • Diagnosis: crew must manually and mentally integrate the above information into a diagnosis of a sodium-water reaction. • Communication: SRO will verify with chemistry technician whether any cold trap operations that introduced air and/or moisture into the secondary sodium system have been underway. • Diagnosis: the SRO must watch the indications to verify if there is indeed a sodium-water reaction is occurring. • Control actions: SRO will scram the reactor when the sodium-water reaction is confirmed. • Recovery/mitigation actions: Secondary sodium operator (SSO) will manually actuate alarm to evacuate the sodium building.	• The primary system and reactor integrity is not affected; primary and secondary systems are physically separated systems. • Automation monitors the system parameters and alarms (likely to be the same or similar parameters and alarms as EBR-II) and provides integrated data, trends, and displays • Operators monitor the automation and data supplied by the HSI. • Diagnosis: the automation performs data analysis, diagnostics and prognostics, provides more integrated data and diagnosis information to the crew. • Indications will provide chemical system status (so SRO will know if there has been any chemistry operations (cold trap operations in the secondary sodium system). • Communication: SRO may verify status of the secondary sodium chemistry system with the chemistry technician. • Automatic reactor scram • Automatic sodium building evacuation alarm • Automatic actuation of sodium fire protocols, including stopping all secondary sodium pumps and isolation of the feedwater and main steam system (tripping the feedwater pumps and MISVs)

	• Recovery/mitigation actions: Crew will manually actuate sodium building fire push button, which will stop all secondary sodium pumps and flow in the secondary sodium system. • Recovery/mitigation actions: crew will manually secure feedwater and close the MISVs. • Recovery/mitigation actions: crew will manually drain the secondary sodium system into the sodium dump tank, and dump water from the steam system into an external tank. • Recovery/mitigation actions: crew will manually actuate sodium-argon vent valve to backfill secondary system with argon. • Recovery/mitigation actions: crew will manually backfill feedwater and main steam systems with argon.	• Automatic draining of the secondary sodium system and backfilling with argon. • Automatic isolation and draining of the feedwater and main steam systems and backfilling with argon. • Operator role is to anticipate required automatic actions, monitor automation, and verify necessary recovery actions occurred as expected and required.
Maintain habitable and safe operating environment	• The main control room is unaffected, no actions to maintain habitability are required. • Recovery/mitigation actions: evacuate the sodium boiler building (SBB) (manual alarm actuation).	• The main control room is unaffected, no actions to maintain habitability are required • Recovery/mitigation actions: evacuate the SBB (automatic alarm actuation)
Ensure containment of fission products	• Not applicable; primary system and reactor are safely shutdown and are not adversely affected by secondary sodium system events.	• Not applicable; primary system and reactor are safely shutdown and are not adversely affected by secondary sodium system events
Manage and control operations	• Intermediate heat exchanger (IHX) is inoperable; shutdown coolers louvers automatically open at preset primary sodium temperature providing for natural circulation cooling of the bulk sodium. • Operator role is to monitor shutdown cooling.	• Intermediate heat exchanger (IHX) is inoperable; shutdown coolers louvers automatically open at preset primary sodium temperature providing for natural circulation cooling of the bulk sodium • Operator role is to monitor shutdown cooling
Provide local electrical power	• Offsite power is available. • Operator role is to monitor.	• Offsite power is available • Operator role is to monitor
Maintain reactivity control	• Not applicable; reactor is scrammed. • Operator role is to monitor/verify rod bottoms lights and zero reactor power.	• Not applicable; reactor is scrammed • Operator role is to monitor/verify rod bottoms lights and zero reactor power
Maintain coolant circulation	• Reactor coolant pumps are operating and remove reactor decay heat to bulk sodium.	• Reactor coolant pumps are operating and remove reactor decay heat to bulk sodium

	• Shutdown coolers automatically start provide cooling of the bulk sodium. • Operator role is to monitor reactor decay removal.	• Shutdown coolers automatically start • Provide cooling of the bulk sodium • Operator role is to monitor reactor decay heat removal
Maintain environment condition control	• Reactor building and MCR are nominal, no recovery or mitigating actions are necessary. • SBB habitability based on the severity of the event and speed of mitigating actions. • Emergency response team(s) responsible for assessing severity of event and planning response. • HVAC for Reactor Building and MCR remains operable – providing habitability. • Fire crews take action on the sodium fire, if accessible (lay down silica sand), and combat any non-sodium fires that may have started as a result of the sodium fire. • No operating crew role unless designated as emergency response team members.	• Reactor building and control room are nominal, no recovery or mitigating actions are necessary • SBB habitability based on the severity of the event and speed of mitigating actions • Emergency response team(s) responsible for assessing severity of event and planning response • HVAC for Reactor Building and MCR remains operable – providing habitability • Fire crews take action on the sodium fire, if accessible (lay down silica), and combat any non-sodium fires that may have started as a result of the sodium fire • Possible automatic carbon dioxide fire suppression actuation (to fight/prevent other combustible fires; will not affect the sodium fire) • No operating crew role unless designated as emergency response team members

5.2.4 Functional Decomposition and Human Performance Requirements Findings

In comparing functions and performance requirements for EBR-II and AdvSMR, a number of high-level trends are notable. The first is that in EBR-II manual control of reactivity and monitoring of sodium temperature take up a large amount of operator time and focus. In AdvSMR, reactivity control and sodium monitoring are likely to be automated. However as shown in Table 12, AdvSMR operators are likely to have requirements for communication with dispatchers during load follow operations, the frequency of this communication and the potential for conflict with any other tasks has not been investigated. Restricted fuel handling activities at EBR-II involve the operator's use of the crane to grasp and manually positioning subassemblies is likely to be greatly benefited by the use of automation including robotic application. Although manual positioning of the fuel assemblies is to be discontinued for advanced designs, operator training is likely to continue as preparation for the event where the robotic system fails.

For secondary loop water-sodium interaction occurring outside of the reactor building, automation associated with advanced design offers considerable advantage for the operator and crew. Many of the operator's monitoring duties and integration of equipment and process status information will be performed by the automatic systems that perform diagnostics and prognostics. The mental calculations formerly performed by the operator will now be provided by automatic systems and the monitoring that is still performed will be aided by information trending. In the case of EBR-II, the feed water and steam systems are automatically drained and back-filled with argon. Shutdown coolers are also automatically started. This will be true for both plant designs. It is likely that operators will anticipate these automatic actions. For both designs, the failure of any of these systems to actuate automatically may result in operators taking manual control. It is important for advanced designs that the capability for operators to take manual control is preserved.

The analysis above is preliminary; it is expected that the set of distinguishing performance differences will become more apparent as more operating states and additional scenarios are analyzed. Because no WDA had been performed previously, the findings to date are solely those of the authors. A workshop covering expected changes to operator performance requirements would be a worthwhile addition to and validation of the findings in this report. US vendors involved in advance reactor design, such as that envisioned for the GE PRISM reactor, could form part of an external review or participate in a workshop.

5.2.5 Generic and Traditional NPP Human Performance Requirements

Human performance requirements are covered under personnel training, plant limiting conditions for operations (LCO) and the operating plant safety basis. The code of federal regulations (CFR) specifies training and qualification requirements for conventional power plants. Whether that will be modified as a function of advanced plant operating requirements and knowledge and skill on the part of operators has not yet been determined. For example, it is possible that the next generation of AdvSMR operators will in addition to reactor fundamentals be required to be well-schooled in aspects of computer science and information technology.

5.2.6 SMR Training requirements and implications.

CFR 50.120 calls out the training and qualification requirements for nuclear power plant personnel. Nine different job categories are listed. For each of these, the extent to which I&C and digital HSI for advanced design differs from conventional design must be reviewed for its training implications. The nine job categories from 50.120 include:

(i) Non-licensed operator.

(ii) Shift supervisor.

(iii) Shift technical advisor.

(iv) Instrument and control technician.

(v) Electrical maintenance personnel.

(vi) Mechanical maintenance personnel.

(vii) Radiological protection technician.

(viii) Chemistry technician, and

(ix) Engineering support personnel. (updated July 25 2013, from http://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part 050-0120.html)

5.2.7 Cognitive and performance requirements

In order to be successful, personnel operating advanced small modular reactors will benefit from having the following knowledge, skills and abilities beyond reactor fundamentals:

Plant knowledge

1. System dependencies and interactions including safety system interaction between safety and non-safety grade systems
2. Knowledge of dependencies between IT systems and varied plant automation – this is increasingly important for AdvSMR designs expected to have a high degree of automation
3. Knowledge of shared common systems and the safety and performance implications

Potential skill requirements

1. Respond to mixed allocation scenarios - operators manage one set of plant parameters while automation manages the other set (Pritchett & Feigh, 2013 [9])
2. Manage the addition of units as they are placed on line (Meshkati 2003 [33]), O'Hara, Higgins and D'Agostino 2012 [40])
3. Manage the same multiple parameters across reactors (O'Hara, Higgins and D'Agostino, 2012 [40])
4. Manage automatic power ascension by permissives (PRISM PSD 1987 [14])

Ability to understand and integrate process and plant status information

1. Awareness of collateral ongoing activities – operators at multi modular AdvSMRs must know the status of other AdvSMR or LWR units on the site, including ongoing maintenance activities, fuel reloading, operating modes (shut down or startup, emergency events), and status for common systems that might be called upon by one or more units
2. Context for multi-unit operations
3. Ability to discern when event or plant status conditions require taking manual control

5.2.8 Challenges to Human Supervisory Control in SMR: Human Reliability Perspective

Our review of the literature identified a number of potential challenges regarding the successful execution of operator performance in advanced control rooms such as those proposed for advanced SMRs. One potential issue is that lapses in attention can lead to error. Advanced control room operations will require operators to direct a lot of their time and much of their attention to the monitoring of displays, especially for multiple modules. Cheyne et al. (2011 [3]) have determined that lapse-induced errors from attentional demands can lead to additional lapses, resulting in a chaining effect. The links in the chain are alternating lapses and errors. Almost all supporting studies for this chaining effect have been conducted in the laboratory and with individual subjects; operator and crew response to errors in terms of errors inducing lapses has not been the subject of field studies. We will continue in our literature review to determine whether field studies have become available. If this phenomenon holds true for control room settings, it may be particularly meaningful in the advanced control room where: 1) the majority of operator time for many plant operating states may be spent in supervisory control activities involving scanning of displays, and 2) performance requirements for sustained attention may themselves be the source of random lapses in attention.

Note also that Grier et al. (2003 [15]) determined that there were limits in terms of effortful attention. They were also able to determine that vigilance tasks increase levels of mental workload as measured by the NASA-TLX and stress as measured by the Dundee Stress State Questionnaire. They maintain that prolonged effortful attention can result in reduced cognitive capacity. As Grier et al. state (*ibid*), increasing the use of auditory as opposed to solely using visual displays, and employing trending/ predictive displays may help in terms of reducing workload and lowering stress. Vigilance duration can also be changed by requiring operators to perform verifications and validations within the control room. Thus, for our purposes, the demand for long periods of vigilance and focused monitored of displays that may be included in AdvSMR detailed design, should be balanced or broken up with other control room activities to ensure that human alertness needed to meet the performance requirements assumed by designers can be met.

Another challenge for SMR designers regards the design of efficient highly automated environments where operators can execute multiple concurrent tasks. The question here is whether all the information needed by an AdvSMR is either simultaneously present or not. And if not, how many mouse clicks or screens away is that information. How do the operators now how to find this information? For example, at what point would the DCS or COSS begin to execute a concurrent procedure? How might the operator be informed regarding the procedural progress being made by the computer-based procedures system? How is the crew to be informed regarding its progress? Cullen et al. (2013 [4]) found that support by diagnostic automation for a multi task environment was more beneficial for some types of tasks than others.

5.2.9 Human Reliability considerations for multiple concurrent tasks

The scenario analysis and contextual activity analysis (CAA) portions of CWA analysis to be conducted in FY14-15 are well-suited to identify those instances where coordination and collaboration of multiple concurrent tasks will be required. The CWA work will identify which tasks are related, whether the automation of a particular task will help with its execution, and whether the automation of certain tasks over others can result in reduced workload and improved system performance. As part of FY14 activities the researchers will consider the balance between human and automation tasking, and develop a framework for guiding design also for multi-module designs.

5.2.10 Emerging Issues - Staffing

In the course of our research, a number of small modular reactor issues applicable to AdvSMR were identified. Smith (2011 [55]) and colleagues at the NRC Office of New Reactors (NRO) determined through expert sessions with representation from human factors, I&C, security and operations, a number of emerging issues related to control room staffing. Scaling, that is, the addition of reactor modules, was raised as the most important concern for staffing, in part because 10CFR 50.54(m) is prescriptive only up to 3 reactors. Although NUREG-1791 makes provision for exemption from the staffing requirements of 10 CFR- 50.54 (m)(i), the current rule does not consider any larger number of modules. Just as important, the addition of modules raises a number of human factors issues, not all of which are addressed in the open literature. For example, as a function of design and concept of operations, two different hypothetical designs from two different vendors, each with the same number of modules may require different staffing levels. How is this to be determined? Existing regulation made certain assumptions about the collateral duties of operators. What does that look like in terms of jobs, tasks, and workloads for the multi modular case? Another issue involves the growth from one reactor module to 12 (the maximum case considered). What is the growth in complexity from the operator's perspective as modules are brought in line? As they point out the complexity rise is not necessarily linear and could be complex with different inflection points for particular numbers of modules. Will these transitions require additional operators and will that number stay stable or be reduced? And on what basis?

Another staffing issue involves determining the number of operators required when existing modules are operating in mixed states and a new module is to be brought on line. Other uncertainties involve the issue of multi-modular accidents involving loss of I&C or loss of power, loss of control room indication and FSAR accidents. (*ibid.*)

> At a minimum future staffing analysis and decisions must be based upon observation and performance data from a simulated environment to identify any problem areas as well as a basis for approval.

5.2.11 Emerging Issues – Effect of Configuration Management on Operator Performance

Because EBR-II employed a lesser amount of automation than that expected for AdvSMRs, the effects of software configuration management associated with advanced HMI and I&C are likely to be more challenging than for a less advanced design. Simultaneous deployment of software upgrades supporting automation and digital HSI across multiple AdvSMR units could have challenging aspects for operations. A phased approach to software upgrades could cause displays from one module to respond differently than displays for a sister module, thus confusing the operator. Also, although the context for use of that display remains the same, the fact that the display functions differently or offers slightly different information is in itself important. For example, attention may be directed to that part of the display that was formerly more important, or the update rate that used to be 10 seconds is now 1 second. Even a well-thought out, configuration-controlled implementation schedule would have implications for training that needs to be captured in WDA.

If other aspects of the I&C are upgraded, then there is a need for close integration of I&C, operations, and human factors. As Smith (*ibid.*) points out, if sufficient time passes, then additional modules brought on-line will have different manufacturing dates and possibly different actuators and software upgrades. How will the operator be expected to deal with this situation? Finally, in terms of the state-of-the-art in risk assessment methods, dynamic HRA and PRA are not yet a reality. How is risk analysis in terms of characterizing automation and software implementation across multiple units to be performed? What credit should operator actions receive in a safety analysis of these potential situations? How does the risk envelop change as new units are brought on line?

6 Discussion

As previously discussed, the human performance requirements documented above are preliminary and therefore pre-decisional. The WDA must be completed before the human performance requirements can be finalized. However, at this point in time the researchers are convinced of its usefulness. This report describes work in progress and provides an example of the approach the team is utilizing to conduct this portion of the analysis. In the foregoing sections of this report, we documented our process for identifying the structural and functional characteristics and the human performance requirements in AdvSMR sodium reactor designs. We also described the in-progress results of the analysis. Using design basis events and procedures from EBR-II, we have documented the operator responsibilities at EBR-II for two normal and one abnormal/emergency operating scenario and demonstrated how this could be extrapolated to future AdvSMR designs with higher degrees of automation and advanced HSI. We have reviewed generic and domain-specific literature related to human performance with automation, advanced HSI and advanced design control rooms, and regulatory requirements for operator responsibilities to develop our preliminary list of human performance requirements. We also identified a high-level set of operator cognitive performance requirements, including basic skills, abilities, and knowledge that AdvSMR operators will need to possess, including knowledge of the plant physics and system interactions and dependencies, the ability to understand and integrate plant status information with plant processes, and manage multiple reactors. We continue these efforts by analyzing a complete set of normal and abnormal/emergency operating scenarios for EBR-II, expanding our literature review, and we will take the final output of the WDA to develop a competency matrix for operator roles and our final set of human performance requirements.

In reviewing the normal and abnormal/emergency operating scenarios, our interim findings for AdvSMR designs compared to EBR-II include a decreased operator role in taking control actions, but a large increase in system monitoring activities. Load following will involve increased communication with grid operators. Operators will have the capability to manually intervene in many cases, but this will be the exception to the rule of monitoring and supervising highly automated systems.

The expected dynamic nature of the interaction between humans and systems in future plants will be a direct result of the design and architecture of distributed control systems, but will also be influenced by advanced design concepts resulting from new materials, multiple product streams, modular plant layout, etc. A large part of automation system design will be beyond the influence of human factors considerations. The reasons for this will be found in the reliability, accuracy and controllability requirements of certain physical processes. It is the purpose of the WDA to also identify those functions that are clearly beyond human capability. This will result in a set of *de facto* or mandatory allocations to systems, in NUREG/CR-3331 terms. This raises the possibility of the so-called "left-over automation" issue, but this is why this project has developed the FA framework. This AdvSMR FA framework will consider the optimization of human and system role assignments in the different operational contexts. This is why our WDA includes the development of operating scenarios (derived from the Contextual Activity Analysis), and state matrices for the systems identified from the abstraction-decomposition for those scenarios. That is, the WDA (and the rest of CWA) produces input for the FA framework, which in turn produces input for task analysis and automation design, both of which have to be completed in as much detail as possible before detailed HSI design can begin. In practice, WDA and FA happen concurrently with automation system design, and in an ideal world there will be a lot of iteration, coordination and integration between the processes, but this is still a big challenge for HFE and it may or may not occur with the design and construction of commercial AdvSMRs in the U.S. In the meantime, the Concepts of Operations project is scheduled to perform its own validation of the AdvSMR FA framework. Once the WDA and the rest of the CWA based on EBR-II is complete, there will be sufficient information to test the FA framework's process steps and methods, which will allow the team to validate whether the FA framework and its underlying FA model work and produce the expected outputs.

7 Conclusion

This year's research did not consider instances where automation did not work as intended by designers. Data from other industries for operator response to failures in automation will be reviewed in future with the intent of being able to predict operator response to failed automation for sodium-cooled SMRs. We will also look at how different approaches to concept of operations; more specifically, philosophies regarding human-automation interaction, can lead to different expectancies regarding operator performance.

The preliminary WDA results achieved during this phase clearly demonstrated the power and utility of the method, especially as an organizing and analytical framework for describing existing sociotechnical systems. The CWA literature indicated that the method is particularly suited to the analysis of prospective and immature designs as well. The implication is that one would be tempted to generalize the findings from one analysis to a similar plant design. However, although there are clear similarities between EBR-II and prospective sodium-cooled reactor designs (for example, same basic reactor design, same coolant and therefore similar basic thermohydraulic processes), the differences between EBR-II and future AdvSMRs should not be underestimated. These differences would essentially be due to new materials and new components, but especially due to advanced automation systems, digital control rooms and human-system interfaces.

In addition, it must also be emphasized that FSR designs is just one of the emerging AdvSMR designs. Very little design information is available on, for example, lead-bismuth reactors, very high temperature gas-cooled reactors, and other even more esoteric designs that may become a commercial reality within fifteen to twenty years. However, the current R&D effort is challenging enough focusing on just sodium-cooled reactors, so extending the effort to include other technologies would be unrealistic in the near term. Nevertheless, the first phase of the EBR-II WDA has already provided ample indication that the methodology is scientifically sound and generalizable to any operating environment. We also documented preliminary findings from our literature review related to the challenges to human supervisory control in AdvSMR designs, including the challenges presented by monitoring automated systems, and challenges to measuring operator performance. In addition, the results from EBR-II provide strong evidence that the functional basis of this analysis would be transferrable to another FSR design, in spite of the expected differences in materials, components and automation. We will extend our review and discussion of these areas and test our assumptions in FY14.

Significant progress was also made in the development of a FA framework. It is especially significant because this is the first time in the history of the US nuclear industry since NUREG/CR-3331 that new research on FA concepts is being done. However, it is important to point out that this framework is also preliminary and is in need of verification and validation. The reason for this was explained in the WDA discussion: 1) FA is not a stand-alone process in the overall human factors engineering process, and 2) FA is dependent on high-level functional and organizational requirements that are ideally obtained from the CWA process, and more specifically, the WDA. The FA model documented in this report has a stable theoretical foundation, but since the WDA developed to date is incomplete, the FA model is also incomplete. However, the theoretical concepts established in the model do provide a testable foundation and for that reason the model will be revisited and evaluated towards the end of FY14 when the WDA and human performance criteria tasks have been completed.

Finally, the same principle applies to the work on human performance criteria for Concepts of Operations. This too is dependent upon a sound basis derived either from an existing design or from an appropriate reference or predecessor design. In this project the latter applied and therefore human performance consideration can also only be re-evaluated when the WDA has been completed. The results described in this report are of a more generic nature and based partly on assumptions about the characteristics of future plants. Future work will also test these assumptions.

8 Planned Work for FY 2014

Although significant progress has been made in the FY13 research, the results are still preliminary and cannot be applied directly in the industry without further refinement and expansion. In fact, the results achieved to date provide the basis for work being planned for the next phase. The continuing work for FY14 would therefore consist of the following three activities:

8.1 Human Performance Requirements for AdvSMR Designs

As described in this report, human performance requirements are complementary to the WDA process and reflect function allocations that were assigned by system designers and implementers. In our research and in this report in particular we have used the WDA method as an organizing framework. Currently, no multi-unit AdvSMR designs have been commissioned yet and hence are not available for review of their design features and operating experience. We have therefore relied on subject matter experts, including former EBR-II operators, open source literature, operating procedures from EBR-II, and plans for emerging advanced FSR designs such as Toshiba's 4S and GE-Hitachi's PRISM. No details were available for control room design or for FA for other emerging AdvSMR designs such as TerraPower or the Russian designs currently under construction in cooperation with the Chinese. It is expected that more information will become available in the near future and could then be included in the detail analyses.

The associated AdvSMR Human-Automation Collaboration project has conducted an extensive review of human performance in automated systems (Oxstrand et al., 2013 [41]). In FY 2014, this project plans to leverage and expand that review to develop further our recommended human performance requirements for AdvSMR designs, which will make extensive use of automation.

8.2 Refinement and Extension of Work Domain Analysis

During FY 2014 this research project will focus on the further development and completion of WDA and the rest of CWA across additional EBR-II design basis scenarios extrapolated to advanced designs. In particular, the role of the operator in relation to the operation of multiple modules will be a particular emphasis. The continuing research will also review more detailed information and literature specific to advanced FSR designs. From the WDA for EBR-II the project team will be able to produce a set of high-level functions (at least to the sub-system level). This set of functions will be mapped to the legacy FAs as they were applied in the actual plant. This information will be derived from the EBR-II operating procedures. The researchers will identify ways in which changes in control philosophy will lead to differences in AdvSMR operator performance requirements. Furthermore, the team will expand the review of human performance requirements in highly automated systems and with advanced HSIs and we will combine this information with the CWA, our matrix of operator responsibilities for EBR-II and AdvSMR designs, and our skills-abilities-knowledge analysis to develop a detailed list of human performance requirements for AdvSMR designs.

The continuing work planned for FY14 will consist of the following three activities:

Task 1 - March 2014: Complete a detailed WDA for EBR-II

This will include development of the following:

a) A set of state matrices for key primary and secondary systems for the major plant modes.
b) A Contextual Activity Analysis, consisting of set of operating scenarios for normal operations, anticipated operating occurrences, and design basis events.
c) A set of abstraction hierarchies and abstraction-decomposition frameworks for the operating conditions mentioned above.
d) A framework and procedure for extrapolating the EBR-II analysis to a modern, highly automated design

Task 2 – September 2014: Develop a complete WDA for a selected or generic FSR design.

This task will include updated versions of items a, b and c above for a modern FSR design. It will also include a plan for FY15-16 for simulator-based experiments and field studies to evaluate end verify all findings to date.

Task 3 – September 2014: *Develop application guidance for Function Allocation and Human Performance considerations for AdvSMRs.*

This task will include, where necessary, an update of the September 2013 information on FA and Human Performance and will focus on the application of the concepts to advanced designs.

8.3 Future Refinement of the Function Allocation Framework

As indicated previously, the theoretical basis of the present FA framework is regarded as stable, but it needs to be evaluated against the extended WDA and also correlated with the previously defined human performance criteria. The next step for this project is therefore for the team to postulate a level-of-automation scheme for future AdvSMRs, based on the expectation that automation (which includes a reduced need for operator involvement in certain functions) will be key contributors to reducing O&M and staffing costs. Automation of functions and processes that previously required manual operator action naturally implies not only defining different Concepts of Operations, but also (re)defining how and why humans interact with specific systems in specific contexts. The key objective of this part of the project is thus to show how non-conventional operating concepts are necessary to ensure that both human and technical resources are employed effectively and efficiently to reduce O&M costs. This activity will form part of work planned for the end of FY14 and start of FY15.

9 References

[1] Bailey, R. W. (1982). *Human performance engineering*. Englewood Cliffs, NJ: Prentice Hall.

[2] Bisantz, A. M., and Vicente, K. J. (1994). Making the abstraction hierarchy concrete. *International Journal of Human-Computer Studies*, *40*, 83-117.

[3] Cheyne, J.A. , Carriere, J.S.A., Solman, G.J.F., Smilek, D (2003) Challenge and error: Critical events and attention-related errors, *Cognition,* Volume 121, Issue 3, December 2011, Pages 437-446.

[4] Cullen, R.H., Rogers, W.A., and Fisk, A.D. (2013) Human performance in a multiple-task environment: Effects of automation reliability on visual attention allocation, *Ergonomics*, 44 (2013)

[5] Dekker, S. (2006). Resilience engineering: chronicling the emergence of confused consensus. *Resilience Engineering: Concepts and Precepts*. Aldershot, United Kingdom: Ashgate Publishing.

[6] Electrical Power Research Institute (2005*). Human factors guidance for control room and digital human-system interface design and modification: Guidelines for planning, specification, design, licensing, implementation, training, operation, and maintenance* (Report #1010042). Palo Alto, CA: EPRI.

[7] Endsley, M. R. (2000). Theoretical underpinnings of situation awareness: A critical review. In Endsley, M. R. and Garland, D. J. (Eds), *Situation Awareness Analysis and Measurement*. Mahwah, NJ: Lawrence Erlbaum Associates.

[8] Endsley, M. R., Bolte, B., and Jones, D. G. (2011). *Designing for Situation Awareness: An Approach to User-Centered Design*, 2nd Ed. CRC Press.

[9] Feigh, K. M. and Pritchett, A.R. (2013). Requirements for Effective Function Allocation: A Critical Review, *Journal of Cognitive Engineering and Decision Making*, Santa Monica CA.

[10] Fitts, P. M. (1951*). Human engineering for an effective air navigation and traffic control system* . Columbus, OH: Ohio State University Foundation Report.

[11] Flemisch, F., Heesen, M., Hesse, T., Kelsch, J. and Schieben, A. (2012). Towards a dynamic balance between humans and automation: authority, ability, responsibility and control in shared and cooperative control situations. *Cognition, Technology and Work,* 14:3-18.

[12] Fuld, R. B. (1993). The fiction of function allocation. *Ergonomics in Design: The Quarterly of Human Factors Applications*, 1(1), 20-24.

[13] Fuld, R. B. (2000). The fiction of function allocation, revisited. *International Journal of Human-Computer Studies*, 52(2), 217-233.

[14] General Electric, Advanced Nuclear Technology (1987). *PRISM Preliminary Safety Information Document* (GEFR- 00793 UC-87Ta, Vols. I-VI). San Jose, CA: General Electric. Retrieved from http://pbadupws.nrc.gov/docs/ML0828/ML082880422.html.

[15] Grier, R. A., Warm, J. S., Dember, W. N., Matthews, G., and Galinsky, T. L. (2003). The vigilance decrement reflects limitations in effortful attention, not mindlessness. *Human Factors*, 45(3), 349–359.

[16] Hassall, M. and Sanderson, P. (2012). A formative approach to the Strategies Analysis phase of Cognitive Work Analysis. *Theoretical Issues in Ergonomics Science*. Boca Raton, FL: Taylor & Francis.

[17] Hoffmann, E.R, and Drury, C.G. (2012). Comment on "Visual layout modulates Fitts's law: the importance of first and last positions". *Psychon. Bull. Rev*. 2012 Feb;19(1):146-50. doi: 10.3758/s13423-011-0183-9.

[18] Hoffman, R. R., Feltovich, P. J., Ford, K. M., and Woods, D. D. (2002). A rose by any other name... would probably be given an acronym [cognitive systems engineering]. *Intelligent Systems*, IEEE, 17(4), 72-80.

[19] Hugo, J. (2006). A model-based approach to the integration of Human Factors in Systems Engineering. *Proceedings of the 2006 Conference of the Ergonomics Society of South Africa*. Pretoria, South Africa.

[20] Hugo, J. (2009). Design requirements for an Integrated Task Support System for Advanced HSIs. *Proceedings of the 2009 Conference of the Ergonomics Society of South Africa*. Port Elizabeth, South Africa.

[21] Hugo, J., and Engela, H., (2005). Function allocation for industrial human-system interfaces. *Proceedings of CybErg 2005, the Fourth International Cyberspace Conference on Ergonomics*. September 15-October 15, 2005.

[22] Hugo, J., Boring, R., Forester, J., Gertman, D., Joe, J, Medema, H., Persensky, J., and Whaley, A. (2012). *Draft Framework for Advanced SMR Concepts of Operations Research*. (INL/EXT-12-27299/SMR/ICHMI/INL/TR-12/01). Idaho Falls, ID: Idaho National Laboratory.

[23] Hugo, J., Forester, J., Gertman, D., Joe, J, Medema, H., Persensky, J., and Whaley, A. (2013). *Draft Function Allocation Framework and Preliminary Technical Basis for Advanced SMR Concept of Operations*. (INL/EXT-13-28601/SMR/ICHMI/INL/TR-2013/02). Idaho Falls, ID: Idaho National Laboratory.

[24] Hugo. J. (2012). Towards ad Unified HFE Process for the Nuclear Industry. *8th International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies, NPIC&HMIT 2012* , San Diego, CA, July 22- 26

[25] Jenkins D.P., Stanton N.A, Salmon, P.M., Walker, G.H., and Young, M.S. (2008) Using Cognitive Work Analysis to explore system flexibility. *Theoretical Issues in Ergonomics Science*. Volume 11Volume 11, Issue 3, 2010. Issue 3, 2010. Boca Raton, FL: Taylor & Francis.

[26] Jordan, N. (1963). Allocation of functions between man and machines in automated systems. *Journal of Applied Psychology*, *47*(3), 161–165.

[27] Katopol, P. (2006). We don't do that here: Using cognitive work analysis to learn about organizational culture, *Bulletin of the American Society for Information Science and Technology*, 33,11, 9-11.

[28] Katopol, P. (2007). “Just enough” information: Information behaviour, organizational culture, and decision making in municipal government, *Canadian Journal Of Information And Library Science-Revue Canadienne Des Sciences De L’Information Et De Bibliotheconomie*, 31,3-4, 233-247.

[29] Kim, S. Y. (2011). *Model-based metrics of human-automation function allocation in complex work environments*. PhD Dissertation, Georgia Institute of Technology, ProQuest.

[30] Kolaczkowski, A., Forester. J., Lois, E., and Cooper, S. (2005). *Good Practices for Implementing Human Reliability Analysis* (NUREG-1792). Washington DC: U.S. Nuclear Regulatory Commission.

[31] Lokhov, A. (2011) Load following with nuclear plants, *NEA News 2011* – No. 29.2, France

[32] Malone, T. B. and Heasly, C. C. (2003), Function Allocation: Policy, Practice, Procedures, & Process. *Naval Engineers Journal*, 115: 49–62.

[33] Meshkati, N. (2003). Control rooms' design in industrial facilities. *Human Factors and Ergonomics in Manufacturing*, 13(4), 269–277. doi:10.1002/hfm.10043

[34] Naikar, N., Hopcroft, R. and Moylan, A. (2005). *Work Domain Analysis: Theoretical Concepts and Methdology*. Air Operations Division. Defence Science and Technology Organisation, Australia.

[35] Naikar. N. (2013) *Work Domain Analysis: Concepts, Guidelines and Cases*. Boca Raton:CRC Press.

[36] NUREG-0711, Revision 3 (2012). O'Hara, J., Higgins, J.C., Fleger, S.A and Pieringer, P.A. *Human Factors Engineering Program Review Model*, US Nuclear Regulatory Commission, Washington, DC, USA (2012).

[37] NUREG-1122 Rev 2 (1998). *Knowledge and Abilities Catalog for Nuclear Power Plant Operators: Pressurized Water Reactors*. U.S. Nuclear Regulatory Commission, Washington, DC.

[38] NUREG-1123 Rev 2 (1998). *Knowledge and Abilities Catalog for Nuclear Power Plant Operators: Boiling Water Reactors*. U.S. Nuclear Regulatory Commission, Washington, DC.

[39] NUREG-1368 (1994). *Preapplication Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor: Final Report*. U.S. Nuclear Regulatory Commission, Washington, DC.

[40] O'Hara, J., Higgins, J, and D'Agostino, A. (2012). Multi-unit Operations in Non-nuclear Systems: Lessons Learned for Small Modular Reactors. *Proceedings of the Eighth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT 2012*, San Diego, CA, July 22–26, 2012.

[41] Oxstrand, J., O'Hara, J., LeBlanc, K. L., Whaley, A. M., Joe, J. C., and Medema, H. (2013). *Development of an Initial Model of Human-Automation Collaboration--Results from a Needs Analysis* (SMR/ICHMI/INL/TR-2013/01, INL/EXT-13-28682). Idaho Falls, ID: Idaho National Laboratory.

[42] Parasuraman, R. and Mouloua, M. (1996). *Automation and Human Performance: Theory and Applications*. Mahwah, NJ: Lawrence Erlbaum.

[43] Price, H. E. (1985). The allocation of functions in systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *27*(1), 33-45.

[44] Price, H.E., and Pulliam, R. (1988). Functional analysis and allocation of functions. In: Gael, S. (Ed.)*, The job analysis handbook for business, industry, and government,* Volume 1 (pp. 639- 650). New York: John Wiley & Sons.

[45] Pritchett, A. R. and Feigh, K. M. (2013a) Modeling Human-Automation Function Allocation, *Journal of Cognitive Engineering and Decision Making*, pp. 1 – 19, DOI: DOI: 10.1177/1555343413490944. Santa Monica CA.

[46] Pritchett, A. R. and Feigh, K. M. (2013b) Measuring Human-Automation Function Allocation, *Journal of Cognitive Engineering and Decision Making*, pp. 1-26, DOI: 10.1177/1555343413490166. Santa Monica CA.

[47] Pulliam, R., Price, H. E., Bongarra, J., Sawyer, C. R., and Kisner, R. A. (1983). *A methodology for allocating nuclear power plant control functions to human or automatic control* (NUREG/CR-3331). Washington DC: U.S. Nuclear Regulatory Commission.

[48] Rasmussen, J. (1974). The human data processor as a system component: Bits and pieces of a model (Report No. Risø-M-1722). Roskilde, Denmark: Danish Atomic Energy Commission.

[49] Rasmussen, J., and Goodstein, L. P. (1987). Decision support in supervisory control of high-risk industrial systems. Automatica, 23(5), 663-671.

[50] Reason, J. (1987). Cognitive aids in process environments: prostheses or tools? *International Journal of Man-Machine Studies, 27*(5), 463-470.

[51] Roth, E. M., Patterson, E.S. and Mumaw, R. J. (2002). Cognitive Engineering: Issues in User-Centered System Design. *In J. J. Marciniak (Ed.), Encyclopedia of Software Engineering, 2nd Edition,* 163-179. New York: Wiley-Interscience, John Wiley and Sons.

[52] Sanderson, P., Naikar, N., Lintern, G. and Goss, S. (2012). Use of Cognitive Work Analysis Across the System Life Cycle: From Requirements to Decommissioning. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. September 2012, 56(1).

[53] Seong, P.H., Kang, H.G., Na, M.G., Kim, J.H., Heo, G. and Jung, Y. (2013). Advanced MMIS toward substantial reduction in human errors in NPPs. *Nuclear Engineering and Technology*. Vol 45:2. April 2013. Korean Nuclear Society.

[54] Sheridan, T.B. (2002). *Human and Automation: System Design and Research Issues*. Santa Monica, CA: Wiley.

[55] Smith, J. (2011) *Small modular reactor issue identification and ranking program*, US Nuclear Regulatory Commission, Final Report, Washington DC, May."

[56] Strain, J. and Eason, K. (2000): Exploring the Implications of Allocation of Function for Human Resource Management in the Royal Navy. In *International Journal of Human-Computer Studies*, 52 (2) pp. 319-334.

[57] Toshiba Corporation (2013). *Design Description of the 4S Instrumentation and Control Systems*. AFT-2012-000241 Rev. 2.

[58] Vicente, K. J. (1999). *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

[59] Wood, R. T. (2012). U.S. Department of Energy instrumentation and controls technology research for advanced small modular reactors. *Nuclear Safety and Simulation, 3*(4), 292-299.

[60] Woods, D. D., and Hollnagel, E. (2006). *Joint cognitive systems: Patterns in cognitive systems engineering*. Boca Raton, FL: CRC Press.