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Framework for Human-Automation Collaboration: Project Status Report

Johanna Oxstrand[a]
Jeffrey C. Joe[a]
Katya L. Le Blanc[a]
Heather Medema[a]
April M. Whaley[a]
John O'Hara[b]

June 2013

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[a] Idaho National Laboratory
[b] Brookhaven National Laboratory

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John O'Hara[b]

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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[a] Idaho National Laboratory

[b] Brookhaven National Laboratory

ABSTRACT

The Human-Automation Collaboration (HAC) research project within the Department of Energy's Advanced Small Modular Reactor (AdvSMR) program is investigating how advanced technologies that are planned for AdvSMRs might affect the performance and the reliability of the plant from a human factors and human performance perspective. The HAC research effort investigates the consequences of allocating functions between the operators and automated systems. More specifically, the research team is addressing how to best design the collaboration between the operators and the automated systems in a manner that has the greatest positive impact on overall plant performance and reliability.

As one step to accomplish this goal, the research team reviewed available information on AdvSMR designs and identified plant functions and operator tasks that might impact the design of the HAC. The identified functions and tasks will later be vetted against insights learned from the current fleet of Light Water Reactors (LWR), other industries where humans are collaborating with highly automated systems, and the results from the activities in the AdvSMR Concepts of Operations project to inform a high-level generic design model. This generic model will be used as a basis for experimental studies to study the effects of different HAC concepts as well as evaluating new human-system interface (HSI) solutions to support a well-functioning HAC.

Another important part needed to accomplish the research goal is a model of the collaboration between the human operator and the automated system. The team has developed a model of HAC that defines: (1) the important design dimensions of automation that impact automation's use by personnel and integrated human-automation performance, (2) what aspects of human cognition, behavior, and performance mediate automation's use by personnel, and (3) when and how the above factors affect the use of automation and the overall performance of the HAC system. The HAC model is utilized to identify areas in need of additional research, which forms the basis for planned HAC research activities. By detailing the relationships between characteristics of HAC, automation, and human cognition, the HAC model identifies what aspects of the human-automation interaction are important to consider in developing automation for AdvSMR systems.

Three analytical studies have been initiated to address questions related to the HAC model. These studies are 1) Models of Teamwork, 2) Standardized HAC Performance Measurement Battery, and 3) Initiators and Triggering Conditions for Adaptive Automation. Additionally, a number of field studies have been identified and are in progress, and a set of experimental studies that are on schedule to be conducted later in the project to address the main research question.

This report consists of three main parts: the preliminary identification of AdvSMR functions and tasks, a description of the updates and extensions to the HAC model, and a description of ongoing and planned analytical, field, and experimental research efforts that the research team has developed to accomplish the project's overall goal of establishing a technical basis for designing the collaboration of personnel and automation.

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ACRONYMS

AdvSMR	advanced small modular reactor
B&W	Babcox and Wilcox
CFR	Code of Federal Regulations
ECG	Electrocardiogram
EEG	electroencephalogram
GEH	General Electric-Hitachi
HA	human - automation
HAC	human-automation collaboration
HFE	human factors engineering
HSI	human-system interface
HTGR	high temperature gas-cooled reactor
I&C	instrument and control
lbm/sec	pounds mass per hour
LOA	level of automation
LWR	light water reactor
MPa	megapascal
MWe	megawatt of electricity
NGNP	Next Generation Nuclear Plant
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
O&M	operations and maintenance
PCS	plant control system
PRISM	Power Reactor Inherently Safe Module
psig	pound-force per square inch
PWR	pressurized water reactor
R/hr	Roentgens per hour
RVACS	reactor vessel auxiliary cooling system
SA	situational awareness
SAGAT	situation awareness global assessment technique
SART	situational awareness rating technique
SMR	small modular reactors
SSC	systems, structures, and components
4S	Toshiba Super-Safe, Small and Simple
WDA	work domain analysis

1. INTRODUCTION

The Human Automation Collaboration (HAC) research project within the Department of Energy's Advanced Small Modular Reactor (AdvSMR) program is investigating how advanced technologies that are planned for AdvSMRs, might affect the performance and the reliability of the plant from a human factors and human performance perspective. The HAC research effort investigates the consequences of allocating functions between the operators and automated systems. More specifically, the research team is addressing how to best design the collaboration between the operators and the automated systems in a manner that has the greatest positive impact on overall plant performance and reliability.

The ultimate goal of the AdvSMR HAC research effort is to develop design guidance that supports optimal interaction between humans and automated systems. The process by which the team plans to develop the guidance can be summarized as:

1. Identify HAC research needs
2. Identify functions and tasks for AdvSMR
3. Prioritize research needs based on functions and tasks identified
4. Conduct HAC research to fulfill the needs
5. Synthesize results from research to develop design guidance for HAC in AdvSMR

Oxstrand et al. (2013) describes the efforts to identify the research needs for HAC. The research team reviewed the literature on HAC, developed a model of HAC, and identified gaps in the existing knowledge of human-automation collaboration. These activities led to several insights regarding existing gaps that if addressed, could help improve the general understanding of HAC in the AdvSMR context. Namely, three high level research topics have already been identified based the literature review and the model development. These are:

- Impact of Highly Automated Advanced Small Modular Reactors on Operator Awareness
- Regaining/Reacquisition of Awareness
- Effect of HAC Characteristics on Operator's Use.

In addition to the high-level research needs, the model highlighted the important dimensions of a HAC design. It is critical to determine the optimal combinations of HAC dimensions to support operator performance in collaboration with automation. To address this, the research team aim to identify the set of HAC factors that support human-system performance and need further research. For example:

Reliability
Is there an ideal level of reliability to support properly calibrated trust and proper monitoring of automation?

Process
Is there a way to effectively communicate complex automation processes to human operators, or do all processes need to be simplified if an operator is intended to monitor the automation?

Level
Is there a LOA configuration that keeps operator workload at an acceptable level, but also keeps them in the loop?

Cognitive Function
Are there certain cognitive functions that should always be the operator's responsibility? What about automation?

Adaptability
Is adaptive allocation of tasks/functions better than static allocation? Under what conditions?

In addition to the automation design dimensions, the following factors contribute to the HAC:

- HSI Design
- Task Load
- Unanticipated conditions

All the topics and question listed above need to be investigated in order to achieve a thorough understanding of HAC; however, it is not feasible to address all of them in a single project. Thus, the team set out to prioritize these topics based on the specific needs in the context of AdvSMR. To accomplish this, the team conducted a preliminary identification of the functions and tasks for AdvSMR, which is described in section 2 of this report. Identifying the functions and tasks prior to conducting research ensures that the studies will be grounded in the context of AdvSMR, and that the conclusions regarding HAC will be valid for AdvSMRs. On a high level, all nuclear power plants have a mission to effectively produce energy (earn money) and to do so as safely as possible. Yet there are important differences between AdvSMRs and generic nuclear power plants with respect to their design and approaches to operation, and it is important to understand what those differences are and how they can potentially affect the nature of HAC. In order to prioritize research topics, the research team needed to consider the factors that set AdvSMRs apart from the generic nuclear reactor. These key factors include:

- Near-autonomous operation,
- Multi-modular operation, and
- Unique operational scenarios (e.g., production of process heat instead of /along with electricity and reduced staffing).

Based on the key features and the high level research topics and insights gained from previous activities in the research effort, the team defined a preliminary research question: How can automation for AdvSMRs be designed such that operator awareness and ability to regain manual control are maintained under conditions of near-autonomous operation? Additionally, the team will look for opportunities to develop research questions related to multi-modular operation and unique operational scenarios as the project progresses.

The version of the model of HAC described in Oxstrand et al. (2013) was a preliminary, high-level model. The team further developed the model with the intent to map out the paths to successful and failed HAC interactions, to identify the factors that influence those pathways, and to identify opportunities for recovery and resilience within the flow chart. The current model of HAC was an essential part in identifying the research needs to be addressed. The model is described in section 3.

Section 4 describes the identified near term research activities identified by synthesizing the insights from the identified research needs (based on the HAC model) and the preliminary functions and tasks for AdvSMRs.

2. PRELIMINARY IDENTIFICATION OF FUNCTIONS AND TASKS

The HAC research team was tasked to conduct a preliminary identification of AdvSMR plant functions and tasks to be performed by human operators or automation, based on available AdvSMR design and operations information, and other relevant sources, which could be used as a basis for experimental studies. It is important for the research team to gain more detailed information about AdvSMR functions and tasks in order to understand the AdvSMR performance requirements and demands that have to be addressed collaboratively by coordinated human-automation teams.

However, due to the current state of the different AdvSMR vendors' design progress, it proved difficult to gather information needed to identify and select a specific design that is developed and documented to the level of detail required for the HAC research effort. Therefore, the team decided to summarize the information regarding AdvSMR plant functions and tasks to be performed by human operators or automation gathered to date in this section. The summary is based on available AdvSMR design and operations information, and other relevant sources. Moving forward, the research team will expand their understanding of relevant functions and tasks based on experience form the existing LWR fleet as well as insights gained from other industries.

While conducting a preliminary analysis of functions and tasks is needed to help address the HAC near term research needs, it should also be noted that the activity of performing a Work Domain Analysis (WDA) for AdvSMR is largely covered by the AdvSMR Concept of Operations research project. However, the two research efforts are closely aligned, however, and share team members, which results in an active knowledge transfer between the projects. In order to reduce the overlap in reporting on the function and tasks activity, only a brief summary of the preliminary results will be presented in this report. The Concept of Operations project will provide more detailed information in their upcoming publications, and the HAC team will use the relevant aspects of the Concept of Operations assessment as it becomes available.

2.1 Selection of Reference AdvSMR Design

Functions and tasks need to be identified for AdvSMRs because, by definition, all AdvSMR designs differ from pressurized water reactors (PWR) with respect to the type of coolant used (gas or liquid metal versus water) and/or type of fuel it uses (metal or triso/prismatic/pebble versus oxide fuel). It is also anticipated that AdvSMRs will have multiple missions: along with generating electricity, they will produce another commodity, such as process heat and desalinized water (Ingersoll, 2009). Furthermore, in the production of electricity, some AdvSMR designers have proposed that their design would be suitable for load following in addition to providing base load. In order to accomplish these missions, designers of these reactors will need to define the plant's functions and tasks relative to its design constraints and its mission(s). More precisely, AdvSMR designers will need to determine the interactions among the plant's design, its mission, and its functions and tasks. The plant's design affects both how it will execute its mission and how functions and tasks are defined. The plant's mission can also inform the definition of functions and tasks. The means by which functions and tasks are defined clearly affect how the plant ultimately performs its mission.

Once the plant's functions are defined, the designers will need to decide how to allocate plant functions to the human operator(s), automation, or both. This will further clarify additional aspects of the plant's concept of operations, including but not limited to: defining operator tasks, and identifying the roles, responsibilities, accountabilities, and authorities of each agent or resource.

In order to adequately address and investigate the collaboration between the operators and the automated systems it is important that the research team understands the plant functions and operator tasks specific to an AdvSMR reference design plant. The functions and tasks will affect the nature of and serve as the basis for design requirements related to the collaboration between operators and automated systems. AdvSMR plant functions and tasks need to be identified to address the allocation between the operators and the automated systems, as well as the consequences of such allocation. The latter is the main focus of the HAC research effort.

A number of the AdvSMR and integrated PWR small modular reactor (SMR) vendors have published reports and journal articles that describe their designs, including:

- General Electric-Hitachi's (GEH) Power Reactor Inherently Safe Module reactor (PRISM; Triplett, Loewen, & Dooies, 2012),
- Toshiba's Super-Safe, Small, and Simple reactor (4S; Tsuboi et al., 2012),
- Next Generation Nuclear Plant's (NGNP) High-Temperature Gas-Cooled Reactor (HTGR; Shenoy et al., 2012).
- Babcox and Wilcox's (B&W) mPower integrated PWR (Halfinger & Haggerty, 2012)

In Joe et al. (2012), AdvSMR design selection criteria were established, and were used to evaluate which of the AdvSMR or integrated PWR SMR designs to use as a reference plant. The selection criteria included design characteristics such as extensive use of automation, multi-modular operations, representativeness of other AdvSMR designs, technical and economic feasibility of design, design maturity, simulation availability, and vendor cooperation.

To varying degrees, all of the designs in the bulleted list above met the design selection criteria. Multiple AdvSMR vendors have submitted design information to the United States Nuclear Regulatory Commission (NRC) for license review. With respect to other AdvSMR designs, the HAC team reviewed the Toshiba 4S and NGNP information submitted to the NRC, and even contacted vendors directly, but was unable to find or obtain specific information on the functions and tasks in either the 4S or NGNP designs. With respect to the mPower design, a considerable amount of information from the vendor on their human factors engineering conceptual design has been submitted to the NRC, but all of the design specific information has been redacted in the publicly available versions of these documents.

As of the writing of this report, GEH is the only AdvSMR vendor that has submitted information related to human factors engineering (HFE) for their PRISM design, including the instrumentation and control (I&C) systems, human system interface (HSI), main control room layout, and staffing levels (GEFR-00793, 1987). The NRC's pre-application safety evaluation report of the PRISM design (NUREG-1368, 1994) contains additional information about the PRISM's planned use of automation and its effect on staffing levels and the role of the operator. Furthermore, the PRISM design nominally meets many of the other selection criteria including extensive use of automation, multi-modularity, technical feasibility, and design maturity.

It should be noted, however, that none of the AdvSMR designs mentioned above have been built yet in the United States. Therefore, the publically available information about AdvSMR plant functions and the implication of those functions on operator tasks has not yet been validated in an operating or demonstration reactor.

Given that GEH's PRISM met more of the selection criteria than any of the other candidates, and in particular is the only AdvSMR design for which there is publically available documentation of the reactor design as well as the HFE designs for the control room, I&C, HSI, automation, and staffing, the HAC research team selected the PRISM design to conduct a preliminary identification of plant functions and operator tasks as a technical basis for subsequent HAC research activities.

2.1.1 High Level PRISM Design Information

The PRISM AdvSMR is a liquid metal (i.e., sodium) cooled, metallic fuel, pool-type, fast breeder reactor (Triplett et al., 2012). By way of comparison, pressurized water reactors (PWRs) in the United States are water-cooled, oxide fuel, loop-type, thermal reactors. While there are a number of similarities between

PWRs and PRISM with respect to major systems, structures, and components (SSCs), such as reactor vessel, containment structure, reactivity control, reactor cooling system, steam generators, and secondary systems that are central to both (1) the generation of electricity or other commodities, and (2) the protection of people, workers and the environment, there are a few key differences. For example, PWRs have a pressurizer and PRISM does not, due to the differences in coolant characteristics. PWRs have a chemical volume control system that introduces boron into the reactor coolant system. The chemical volume control system is also the main source of water for the reactor coolant system. Conversely, PRISM has a coolant purification chemistry system that removes impurities from the primary sodium coolant. PWRs also have emergency diesel generators to help remove decay heat from the reactor core when on-site or off-site power is lost, PRISM has a standby power supply system used to provide power to help with the orderly and controlled shutdown of systems in order to avoid equipment damage, and not for removal decay heat under abnormal conditions.

Additionally, there are a number of important differences with respect to PRISM's design and coolant type that differ from PWRs with significant implications on the nature of the plant's functions (e.g., how those functions accomplish the plant's mission), and operator tasks (e.g., what tasks operators perform to execute those plant functions). For example, there are a number of important technical differences, and associated advantages and disadvantages, in using sodium versus water as the primary coolant. Some of these differences are highlighted in Table 1, which was adapted from Bays et al. (2010).

Table 1. Differences between PRISM and PWR reactors.

		Reactor Type	
		PWR	PRISM
Coolant Characteristic	Coolant stability (Single-phase can be easier to control)	Two-phase fluid (coolant can be in liquid or gas state)	Single-phase fluid (coolant will only be in liquid state during normal operations)
	Coolant pressure (Lower pressure has safety benefits)	15 MPa	0.1 MPa
	Chemical inertness of coolant (Chemically inert is a safety benefit)	Moderately	Not inert (reacts with air and water)

Since the coolant in PRISM is chemically reactive, one key safety feature PRISM has that PWRs lack is the use of double-wall steam generator piping where sodium-potassium exchanges heat with water. Further, the PRISM's design and coolant type differ from PWRs in that the PRISM design manages the core's fissile inventory such that there is very little excess reactivity available for power excursions to occur. The sodium coolant has a high heat capacity that makes high-power-density cores feasible and facilitates a very slow thermal response (Tester et al., 2005; Bays et al., 2010). Figure 1 below provides high-level conceptualizations of PWRs and PRISM displaying the similarities and key differences between these two reactor types.

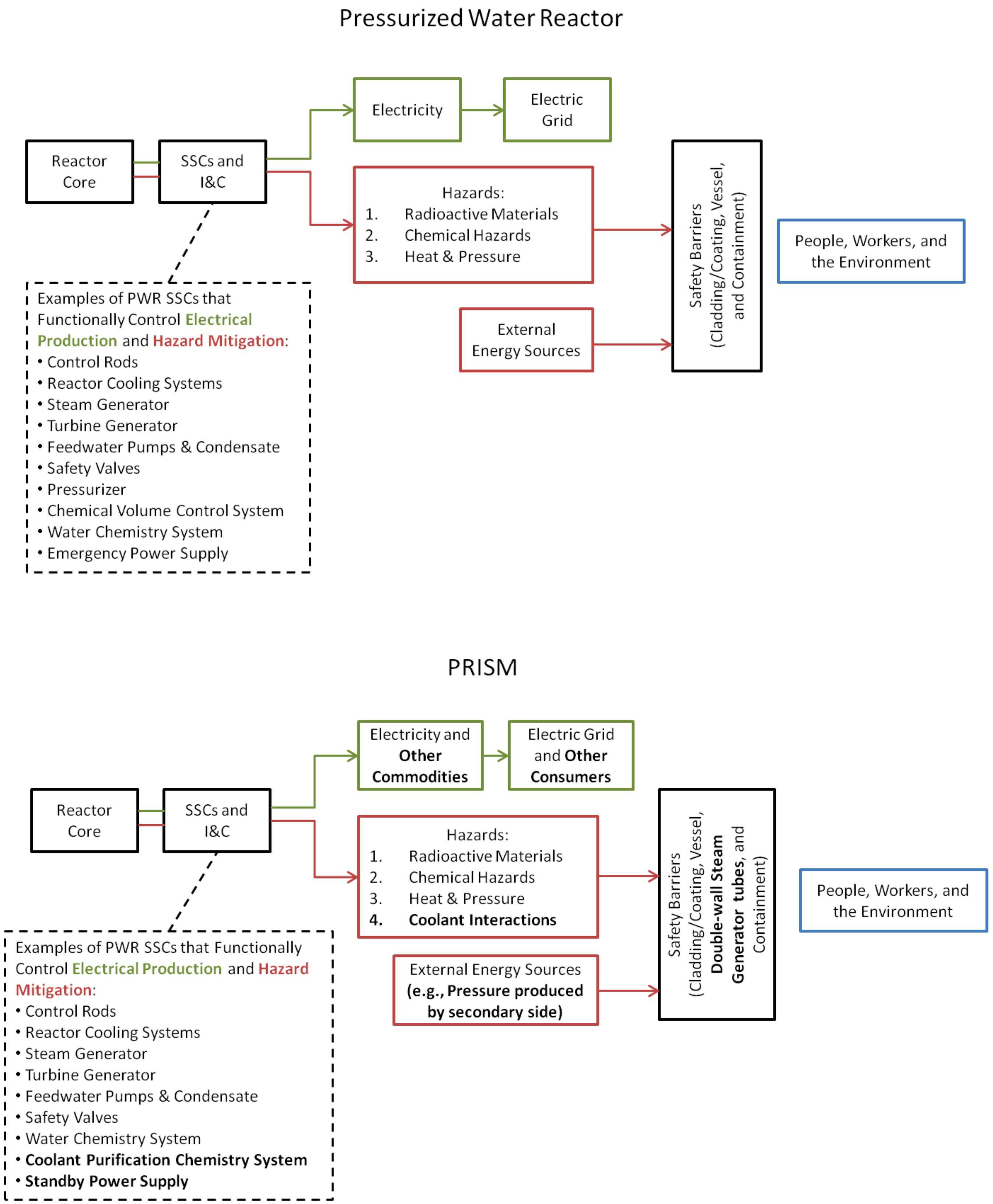

Figure 1. High-level conceptualizations of PWRs and PRISM.

2.2 Preliminary Identification of PRISM Plant Functions and Tasks

The information gathered by the team provided the basis for identifying AdvSMR plant functions and tasks via a simplified version of the Naikar et al., (2005) Abstraction Decomposition Space Approach. The Naikar et al. approach includes a set of generic questions that need to be answered in order to create the abstraction decomposition space, which for the purposes of the HAC research project also identifies the AdvSMR plant functions and tasks. A summary of the identified PRISM functions and tasks is provided below.

Functional Purposes and External Constraints

1. *For what reasons does the work system exist?*

The mission of the PRISM AdvSMR is to produce commodities safely, such as electricity and oxide fuels for PWRs from weapons grade nuclear materials (Hylko, 2011).

2. *What laws and regulations does the environment impose on the work system?*

If operated commercially in the United States, the NRC has the authority to regulate the operation of PRISM to ensure its use of radioactive materials is for beneficial civilian purposes while protecting people and the environment. That is, as PRISM uses radioactive materials to produce commodities, it must do so in a manner that does not pose unacceptable levels of risk to people, workers, or the environment.

3. *What functions are required to achieve the purposes of the work system, and what functions are required to satisfy the external constraints on the work system?*

To produce commodities while at the same time preventing the release of radioactive materials, there are a number of required functions in PRISM that control the various aspects of the production process.

To produce commodities, PRISM must be able to control the fission of radioactive materials which produces heat, and control the transfer of that heat via steam generators such that it is converted to a force that moves turbine blades connected by a shaft to an electric generator which coverts shaft movement or mechanical energy into electricity via induction (e.g., Rankine cycle).

To protect people, workers, and the environment, PRISM must be able to control/prevent the release of radioactive materials and toxic chemicals, control the production of heat (which can challenge the safety of SSCs that control radioactive materials), and prevent the interaction of the sodium coolant with air and water.

Systems, Structure, Components, and Processes/ Functions

4. *What are the SSCs in the work system? What processes/functions are the SSCs in the work system used for? What is the layout of the SSCs in the work system?*

Given the description above of the PRISM's purpose, external constraints, and primary functions, the main SSCs in the work system include the reactor core, control rods, reactor cooling system, steam generator, turbine generator, feedwater pumps and condensate system, safety valves, coolant purification chemistry system, water chemistry system, emergency power supply, and safety barriers (e.g., fuel cladding/coating, reactor vessel, double-walled steam generator tubes, and containment structure).

SSC Processes/Functions:

- The primary function of the reactor core is to facilitate fission and also helps prevent the release of radioactive materials.
- The main function of the control rods is to control fission and the heat produced.
- The reactor cooling system (called the primary reactor cooling system in PRISM) has a dual function. It provides cooling to the reactor core to mitigate the inadvertent release of radioactive materials and heat. Additionally, it facilitates the transfer of heat produced by the core to the secondary side of the plant.
- The function of the steam generator is to transfer heat from the reactor core to water, which becomes steam that is used as the force to move the blades of the turbine generator. In doing this, steam generators, like the reactor cooling system, also have a safety function by transferring heat from the reactor core to the secondary side of the plant.
- The function of the turbine generator is to convert the mechanical energy of the spinning turbine blades and shaft into electricity. As it does this, it also has a safety function by serving as a heat sink for the reactor core, thereby helping to mitigate the inadvertent release of radioactive materials and heat.
- The feedwater pumps and condensate system also have a dual function. They provide water to the steam generators to facilitate the production of commodities, and they act as a heat sink to the reactor core.
- Examples of safety valves in PRISM include the Intermediate Heat Transport System valves and power-operated relief valves for the steam generator. The Intermediate Heat Transport System isolation valves are designed to close to isolate the reactor from pressure surges from the high-pressure water-steam system that may occur during sodium-water reactions due to generator tube ruptures. The power-operated relief valves isolated the steam generator from overpressure events on the secondary side (NUREG-1368, 1994).
- The coolant purification chemistry system, or Primary Sodium Processing System in PRISM provides a means to purify the sodium coolant in the primary reactor cooling system by pumping the sodium through a nitrogen-cooled cold trap which facilitates the removal of impurities through distillation that cause the impurities to become precipitates that drop out of the sodium (GEFR-00793, 1987). The removal of impurities is important to allowing the sodium in the reactor coolant system to perform its functions of core cooling and heat transfer.
- The water chemistry system in PRISM is on the secondary side and is designed to, "Minimize the corrosion of the steam generator system, particularly the steam generator, and to minimize fouling of the steam generator heat transfer surfaces." (GEFR-00793, pg. 10.3-13). Minimizing corrosion and fouling is critical to the steam generator's ability to perform its safety and productions functions (i.e., act as a heat sink and facilitate the conversion of heat to electricity).
- Appendix B in GEFR-00793 states that PRISM has a standby power supply system in the event that onsite power is lost, but that it is not used for the removal of decay

heat. Rather, these diesel generators provide power to various SSCs to help, "Maintain an orderly shutdown and avoid equipment damage." Appendix B further clarifies, "PRISM does not use diesel generators for emergency power... No standby power is needed in PRISM to remove decay heat. The Reactor Vessel Auxiliary Cooling System (RVACS) uses naturally circulating outside air to dissipate all of the reactor's decay heat. RVACS performs its function without any human or mechanical action. Primary sodium flow through the reactor core is maintained by natural circulation." (pg. B-3).

- The fuel cladding/coating, reactor vessel, double-wall steam generator tubes, and containment structure all function as barriers to prevent the release of radioactive materials, and chemical hazards to the external environment, and/or protect the fuel and SSCs from external energy sources (e.g., earthquakes, tsunamis, and pressure produced by the secondary side).

Figure 2 is a high-level schematic of PRISM from Hylko (2011). Note that not all SSCs described above are depicted in the figure, but it is presented to show the basic layout of this work system.

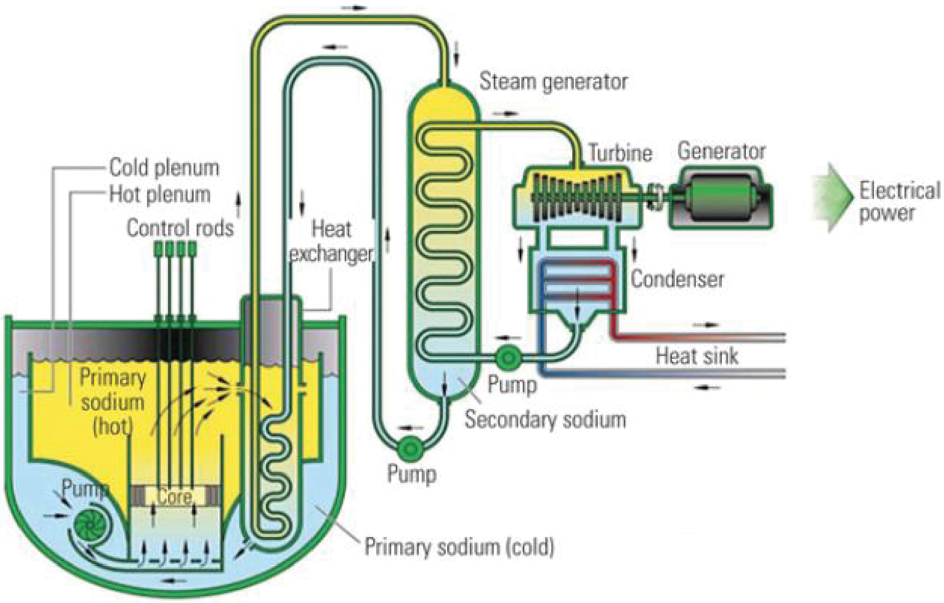

Figure 2. PRISM Schematic Illustrating Basic Layout of SSCs.

Values and Priority Measures

5. *What criteria can be used to judge whether the work system is achieving its purposes?*

While there are many potential criteria that can judge whether the work system is achieving its purpose, the primary measure is whether it is producing its commodities safely, and secondly, in an economically competitive manner.

6. *What criteria can be used to judge whether the work system is satisfying its external constraints?*

While there are again many potential criteria, the primary measure is whether there is any release of radioactive or other hazardous materials in sufficient quantity to harm people, workers, or the environment, or more precisely, in quantities that exceed the upper limits specified in the Code of Federal Regulations.

Task Implications

7. *How does the plant's mission affect the operator's and/or automation's tasks?*

From the perspective of PRISM's mission, the operator and/or automation will have tasks associated with ensuring the safe production of at least one commodity, and potentially multiple commodities, such as oxide fuels from the disposition of weapons grade nuclear materials (Hylko, 2011). Any tasks involved with production of multiple commodities would be different than what is expected of operators and automation in PWRs, and will have implications on HFE issues such as operator training and workload.

8. *How do the safety and production design features and functions of the reactor, coolant, and SSCs affect the operator's and/or automation's tasks?*

There are a myriad of ways in which the plants design features and functions and various SSCs affect operator and/or automation tasking. Given that this is a preliminary identification of functions and tasks, this report does not provide a comprehensive or exhaustive list of the ways in which design features and functions affect operator/automation tasking. Instead, this report highlights what the research team considered to be the most significant with respect to operator/automation tasking implications.

For example, the fact that PRISM is a pool type (vs. loop cooled) means, among other issues, that the operator and/or automation will not have tasks associated with monitoring for leaks in the reactor coolant system. Many loss-of-coolant accidents scenarios that can occur in loop type PWRS are no longer feasible given the pool type design. The fact that PRISM uses sodium as a coolant means, among other issues, that the operator and/or automation will not have tasks associated with monitoring the pressure of the reactor coolant system, but will have tasks associated with monitoring for sodium interactions with air and water. The fact that PRISM has a standby power supply system that is not needed to remove decay heat is an example of an SSC that has implications on the operator's/automation's task(s). In this case, the operator's/automation's tasks associated with a loss of onsite power event are postulated to be related to the orderly shutdown of powered systems and the protection of plant assets, not the removal of decay heat.

9. *How does the use of I&C automation, and the allocation of functions between operators and automation affect the operator's tasks?*

GEFR-00793 and NUREG-1368 both state that the PRISM designers/pre-applicants propose to automate as much of the control of operations as possible (i.e., automate operation to the maximum extent), and that the operator's role (i.e., tasks) will primarily be to monitor and verify the performance of safety systems. GEFR-00793 provides some information on how the PRISM designers propose to allocate functions between automation (i.e., computers) and the operator and how the allocation of functions changes under various plan control system (PCS) failure scenarios (see Table 3 in Section 2.4). Appendix F of GEFR-00793 also claims that the reactor protection system requires no operator intervention. This proposed approach to the conduct of operations (e.g., extensive use of automation and allocation of control functions to automation/computers) in PRISM is a significant departure from the conduct of operations in PWRs, and will likely have implications for HFE issues. The NRC noted in NUREG-1368 a number of concerns they have regarding the use of automation and its effect on staffing levels, the role of the operator, and operator workload.

These HFE issues and others, which are a result of these design decisions, are the main focus of the AdvSMR HAC project. The HAC project is investigating the consequences of using extensive automation, and the allocation of functions between the operators and automated systems on operator task performance and overall system performance, and has a specific activity within its scope of work to evaluate HAC performance through investigative studies. For example, one question HAC is investigating is the impact of highly automated AdvSMRs on operator awareness and system performance. The plans to address this issue and others are described in Section 4 of this report.

2.3 Comparison with NUREG/CR-7126

To assess the task of identifying the PRISM design's functions and tasks for this project, the team compared the results of this task to the results of an analysis that was published in NUREG/CR-7126 (O'Hara et al, 2012). They conducted an analysis showing the differences between current light water reactor (LWR) plants and SMRs with respect to their mission, function, design, and operational differences using an HFE-focused concept of operations model. An adaptation of the results of this analysis is reproduced in Table 2 below. From the results from NUREG/CR-7126, a number of different potential consequences on human performance (i.e., operator tasks) in LWRs and SMRs can be derived based on the different levels within this HFE-centric concept of operations model. The consequences on operator tasks are summarized in Section 2.4.

Table 2. Comparison Between Current Plants and SMRs on Conduct of Operations Dimensions That May Influence Operator Tasks.

ConOp Dimensions	Current Plants (LWRs)	SMRs
Plant Mission	Electrical production	Electrical production, and potentially, process-heat applications
	Current designs are incremental evolutions from previous designs with extensive operating experience	Many SMR designs are based on new technology with minimal predecessor plant experience
Role and Responsibilities	Crew responsible for electrical production	Crew may be responsible for electrical production and collateral mission, such as hydrogen production
	Crew responsible for a single unit	Crew or individual operator responsible for multiple units
	Automation, often simple, mainly applied to safety systems	Extensive use of automation, sometimes complex, for operations
Staffing	Staffing levels meet 10 CFR 50.54(m)	Staffing levels typically are below 10 CFR 50.54(m)
Normal Operations	Plants are based on LWR-technology with well-known operational requirements	Many SMR designs use non-light-water reactor technology that might pose new operational requirements

ConOp Dimensions	Current Plants (LWRs)	SMRs
	Large plants that typically can produce 1000+MWe	Smaller, simpler designs with electrical-generation capacity typically less than 400 MWe
	Plants are built on-site	Modular approach to constructing plants
	Limited use of shared systems	Some SMR designs use shared systems; some are shared across many units. An example is the NuScale reactor pool used by all 12 units
	Base-load operations	Load following as well as base-load operations
	A shift crew manages a single reactor unit from a control room	A single crew operator may manage multiple units, as well as additional missions from a single control room
	HSIs provided for plant evolutions	HSIs provided for plant evolutions of multiple units, and for monitoring and control of other missions
	A single reactor can be in a variety of states	Individual reactors may be in a variety of states (e.g., shutdown, startup, or refueling, and various types of maintenance and testing) and running at various power levels
	Additional reactors are introduced as separate plants	Additional units can be added when needed and while other units are operating
	Refueling is performed during outages	Novel approaches to refueling, such as on-line refueling, and relocating reactor modules to a dedicated servicing area for refueling
Off-normal Operations	Plants are based on LWR-technology with well-known hazards	Many SMR designs use non-light water reactor technology that might pose new hazards
	Currently operating plants use active safety systems; some new designs employ some passive systems	Safety systems mainly are passive
Maintenance	Major maintenance performed during outages	Novel approaches to maintenance, such as moving reactor module to a dedicated location in the plant or to the factory for servicing
	Maintenance practices and hazards are well-defined	There are many new maintenance practices and potential hazards

2.4 Discussion and Conclusions

In comparing results shown in Table 2 with the identification of plant functions and tasks for PRISM, there are some similarities (e.g., the idea that AdvSMRs using non-LWR technology imposing new operational requirements), but also a number of differences that compliment the analysis performed. For example, the fact that Table 2 shows that O'Hara et al. (2012) considered the implications of multi-unit operation and maintenance on operator tasks provides some new and important insights. By the same token, however, the analyses to identify functions and tasks performed for this research project also provide new and useful insights on this issue.

The research team has drawn a few initial conclusions about identification of AdvSMR plant functions and tasks. First, many AdvSMR designers have made information on their design publicly available, but this information is at a very high level. The majority of the available information is on the engineering features of the AdvSMR designs. Information on specific functions and tasks in AdvSMRs is limited. Information from PRISM is more detailed than other information that is publicly available on other AdvSMR designs, yet there are only a few descriptions of specific operator/automation tasking in the PRISM design (see below). Furthermore, the fact that this detailed information was published in the late 1980s and early 1990s raises the issue of whether it is current, or if it has been superseded by other design information that is not publicly available. However, given that no publicly available information could be found on other current AdvSMR designs the HAC research team concludes that this information is the best course of action until further information on AdvSMR functions and tasks can be obtained. Second, available HFE tools, such as the WDA, are formalized processes that can be used to identify plant functions and operator tasks. However, some tools (e.g., the Abstraction Decomposition Space Approach) are limited by the amount/level of detail and quality of information available, and involve some engineering assumptions and expert judgment.

Nevertheless, the research team is confident that the functions and tasks identified in PRISM are technically valid to the extent to which technical information could be obtained to establish their basis. The following summarizes tasks for operators in PRISM.

NUREG-1368 states that the primary role of the PRISM operator is to:

- Monitor and verify performance of safety systems, and have the capability to initiate reactor shutdown by manual scram or manual activation of the ultimate shutdown system
- Maintain communication with appropriate onsite and offsite personnel
- Initiate recovery actions following an event
- Serve as an important source of knowledge concerning plant status, design, and behavior, especially during the management of off-normal conditions.

Some specific examples of additional tasks for PRISM Operators, relative to PWR Operators, include: (1) supervising the safe production of both electricity and other commodities, such as oxide fuel for PWRs (Hylko, 2011), and (2) monitoring for sodium coolant interactions with air and water (Bayes et al., 2010). For example, monitoring for pressure incursions on the Intermediate Heat Transport System from the secondary side by ensuring isolation valve actuate and verifying the integrity of double-wall piping (NUREG-1368, 1994),

According to GEFR-00793 (1987, pg. 7.9-1), because the PRISM will be highly automated, the operator will have no tasks associated with the following plant functions:

1. Plant-wide energy management.
2. Plant operating configuration management.
3. On-line performance analysis.

4. Control strategy validation.
5. Sensor/command/actuator validation.
6. Plant-wide diagnostics and decision aids.
7. Maintenance planning and status.

Some specific examples of tasks PRISM Operators will not have to perform that PWR Operators do include: (1) monitoring for leaks in the reactor coolant system, (2) performing reactor shutdown actions (Triplett et al., 2012), (3) performing decay heat removal actions (Triplett et al., 2012; GEFR-00793, 1987), (4) performing post-accident containment cooling actions (Triplett et al., 2012), and (5) managing boron concentration levels in primary coolant system during normal operations.

According to GEFR-00793 (1987, pp. 7.9-5b and 7.9-5c), upon varying degrees of failure of the automated control system in PRISM (i.e., the PCS), the operator will have a number of different tasks, depending on the severity of the PCS failure. Table 3 summarizes the nature of the HAC in PRISM upon automation failure. Note that operator actions in Table 3 are bolded.

Table 3. Reproduction Of Table 7.9-1 From GEFR-00793, Which Lists Equipment Failures And The Resulting PCS/Operator Action.

Equipment Failure	PCS and Operator Action
1. Plant major component failure - (failure within scope of PCS automation)	• PCS reconfigures components whenever possible to maintain power generation of the power block or reduces load (rapid runback to match plant available capacity. • PCS apportions load among the remaining fully operational modules to maximize power generation capability of remaining equipment. • Operator alerted of failure. • **Operator alerts roving operator and maintenance superintendents**.
2. Plant major component failure - (failure outside scope of PCS)	• PCS senses inability to meet demanded load on affected module and reduces power to a safe level. • PCS apportions load among the remaining fully operational modules to maximize power generation capability of remaining equipment. • Operator alerted to failure. • **Operator takes manual control action to reconfigure failed components; and later increases power level if safe to do so.** • **Operator isolates failed components from the operating system.** • **Operator alerts roving operator and maintenance supervisors.**
3. PCS controller failure - (single channel)	• PCS is fault tolerant and redundant. Controller self-isolates failed component by self-reconfiguration. • PCS/controller remains operational. • Roving operator and maintenance supervisor alerted. • On-line repair initiated. • Controller fully operational (3 channels within 4 hours).
4. PCS controller total failure	Action is dependent on the level of control in the hierarchy. • If upper level controller (ULC) fails or all communications with ULC lost, then "hold" command initiated within the lower level controller (LLC). • **Roving operator and maintenance superintendent alerted to investigate.** • If LLC fails, or communications lost, roving operator and maintenance superintendent alerted. • **Local coordinated action may be taken with telephone CCR communication to shutdown affected module (or block if BOP**

	controllers failed), by coordinated action between the roving operator at the local station and CCR operator. - PCS remains operational for remaining module controllers. - If power block is running at reduced load, shutdown of a reactor or steam generator module due to local subsystem controller failure may be compensated for by PCS automated operation of remaining reactor/steam generator and BOP module controllers by automatic load reallocation.

In addition, according to GEFR-00793 (1987, pg. F7-3), the operator must monitor the following variables following an accident to ensure they stay within their specified range:

Variable	Range	Purpose
Reactivity Control		
Neutron Flux	10^{-6}% to 100% full power	Detection, Trip
Control Rod Position	Full in or not full in	Verification
Core Cooling		
Cold pool temp.	0 – 2000° F	Detection, Trip
Core outlet	0 – 2000° F	Detection, Trip
Coolant Level	0 – 20 ft	Detection, Trip
Core inlet pres.	0 – 200 psig	Detection, Trip
RVACS exit temp.	0 – 500° F	Monitoring
RVACS air mass flow	0 – 80 lbm/sec	Monitoring
Reactor Vessel Integrity		
Sodium Leakage	Yes/No (Spark Plug)	Monitoring
Cover Gas Pressure	10^{-5} – 20 psig	Monitoring
HAA Radiation	1 R/hr – 10^{7} R/hr	Surveillance
Environs Radiation	10^{-3} R/hr – 10^{4} R/hr	Surveillance
Head Penetration Valves	Open/Closed	Verification
Rotating Plug	Open/Seated	Verification

In conclusion, in order to understand the AdvSMR performance requirements and demands that must be addressed collaboratively by coordinated human-automation teams, the HAC research team had to obtain and study the more detailed information about AdvSMR functions and tasks. Based on the analysis of the PRISM design, the PRISM operator will have a few new tasks (relative to PWR operator tasks) associated with the plant's mission and monitoring the chemical reactivity of the sodium coolant. However, according to the published information from the PRISM designers, the operator will have virtually no tasks associated with control of normal operations. Their role will be primarily to monitor and verify the performance of safety systems. The PRISM operator will have some additional tasks upon failure of the PCS, and post-accident they will be responsible for monitoring variables associated with reactivity control, core cooling, and reactor vessel integrity. The extensive use of automation and allocation of control functions proposed by the PRISM designers is a significant departure from the conduct of operations in PWRs, and will likely have implications for HFE issues, including staffing levels, the role of the operator, and operator workload (NUREG-1368, 1994).

These HFE issues and others, which are a result of these design decisions, are the main focus of the AdvSMR HAC project. The remaining sections of this report describe the specific research activities the HAC team has been performing to investigate these HAC issues relevant to the AdvSMR operating context.

3. MODEL OF HUMAN-AUTOMATION COLLABORATION

3.1 Purpose of the Human-Automation Collaboration Model

As stated in Oxstrand et al. (2013), the objective of this project is to conduct research on optimizing HAC in order to maximize safe and productive AdvSMR operation. To facilitate this, the research team is developing a model of HAC as part of the project, based on the research literature summarized in Oxstrand et al. (2013). The HAC model defines:

- The important design dimensions of automation that impact automation's use by personnel and integrated human-automation performance,
- What aspects of human cognition, behavior, and performance mediate automation's use by personnel, and
- When and how the above factors affect the use of automation and the overall performance of the HAC system.

The research team is using the HAC model to aid in identifying what areas are in need of additional research, which forms the basis for planned HAC research studies. The model also helps specify in which circumstances particular factors are relevant to system performance. The HAC model does more than simply identify what the relevant issues are; it also identifies which factors are relevant for different types of interactions. Additionally, the researchers intend for this model to inform and guide HAC system designers. By detailing the relationships between characteristics of HAC, automation, and human cognition, the HAC model identifies what aspects of the human-automation interaction are important for a designer to consider in developing automation for AdvSMR systems.

3.2 Model Development Since March 2013 Milestone Report

The model depicted in Oxstrand et al. (2013) was a preliminary, high-level model. The preliminary model shown in that report highlighted several key issues: operator awareness, whether operator use of automation is well-calibrated to the automation's capabilities, and whether the balance of the system is resilient enough to recover automation failures and/or operator errors.

Since the March 2013 Milestone Report, the project team has developed the model a great deal. The intent is to map out the paths to successful and failed HAC interactions, to identify the factors that influence those pathways, and to identify opportunities for recovery and resilience within the flow chart. The team intends for the model to do more than just identify relevant characteristics of automation and HAC, so the first step in further developing the model was to expand the flow chart to include specific paths for different task allocations. The team is presently in the process of identifying the relevant factors at each branch point in the model, and will iterate the model (including adding or modifying branch points, relevant factors, recovery opportunities, and failure modes) as new insights are gained. The model presented in Section 3.3 is therefore an interim model that is still under development.

3.3 The Human-Automation Collaboration Model

The nature of HAC is dependent on many factors related to the characteristics of automation, aspects of the HAC, and other factors that act as mediators on the human-automation interaction. All of these factors interact with each other to produce either successful HAC or a variety of problematic or unsuccessful HAC outcomes, which may or may not impact overall system performance depending on the resilience of the system.

The HAC model identifies three groups of factors that impact HAC performance: (1) inherent characteristics of automation, (2) aspects of HAC, and (3) mediators of HAC. The HAC model currently identifies these factors separate from the flow chart, but in the future the factors will be integrated into the decision points in the model. Each of these factors is discussed in more detail in Oxstrand et al. (2013), and is summarized below.

3.3.1 Inherent Characteristics of Automation

There are several relevant factors that affect the HAC performance that are inherent within the design of the automation. These factors are a product of how the automation is designed and are invariant to an extent once the system is in place.

3.3.1.1 Reliability

Reliability refers to how well automation accomplishes its task, and is often expressed as a probability of the automation performing as it is designed to perform. This is typically presented as a percent reliability; a highly reliable system may be described as 99% reliable, for example. When the automation's tasks are complex, or when the automation must operate across different contexts or modes of operation, the system's reliability may vary. The effect of reliability and degradation of reliability on HAC, system, and operator performance is discussed in greater detail in Oxstrand et al. (2013). The HAC project is assuming that any automation for AdvSMR designs will be required by regulation to be as reliable as is technically possible.

3.3.1.2 Process

Process refers to the way an automatic system uses input from sensor feeds in the plant and from the human operator and assesses it relative to its programmed information processing routine (e.g., control algorithms and decision logic) to initiate its preprogrammed response. When well designed and operating correctly, the automation's preprogrammed responses are appropriate, or correct, for the input it receives and assesses. However, not all automatic processes are readily comprehensible by humans, and research summarized in Oxstrand et al. (2013) documents the consequences of opaqueness (e.g., Odour & Wiebe, 2008). Successful HAC performance frequently depends on the operator knowing what the automation processes are. The operator not knowing what the automation processes are contributes to the operator losing situation awareness (SA), which can have a detrimental effect on system performance.

3.3.1.3 Mode

Automation can be designed to have different modes and the behavior of and processes automation executes can be substantially different depending on which mode it is in. One example of the potential for mode error in a NPP is the automatic power control system. The automatic power control system can be set in (1) turbine following mode for load following or (2) reactor following mode for full power operations. If an operator takes a local controller out of automatic into manual, she/he will need to know in what mode the automatic power control system is functioning. If this is not communicated to the operator, their manual actions could result in degraded system performance. Another potential problem related to mode is the loss of operator SA on the mode in which the automation is operating, which can lead to human errors and diminished performance. See Oxstrand et al. (2013) for a more thorough review of this literature.

3.3.2 Aspects of HAC

There are other aspects of the human-automation interaction that are determined by the function allocation, but which are more easily modified after system installation, including level of automation, cognitive function, and adaptability. The characteristics of automation listed in Section 3.3.1 above are independent of HAC. These factors, on the other hand, are characteristics specific to the design of the HAC.

3.3.2.1 Level of Automation

Level of automation (LOA) describes the amount of automation used for a particular task. There are several different taxonomies of LOA, including Endsley and Kaber (1999), Parasuraman et al. (2000), and

Billings (1991, 1997), each of which is discussed in Oxstrand et al. (2013). While there are some differences between each of these three taxonomies, all of them vary from fully manual (the human operator does everything) to fully automatic (the automatic system does everything), with intermediate levels typically including some collaboration between automation and human. As discussed in Oxstrand et al. (2013), LOA has been shown to have an impact on human and system performance.

3.3.2.2 Cognitive Function

Cognitive functions, or the cognitive activities that operators normally perform, typically are described using human information processing analogies. With the introduction of automation, the automation can perform more of these cognitive functions, rather than the operator. In doing so, cognitive function is not separate from LOA: as LOA increases, the automation takes over more of the cognitive functions for which the operator was previously responsible. There are several different taxonomies of cognitive function, though there are more similarities than differences. See Oxstrand et al. (2013) for more discussion. This HAC model uses the breakdown described in O'Hara and Higgins (2010), which is monitoring and detection, situation assessment, response planning, and response implementation. As described in Oxstrand et al. (2013), research has shown a relationship between the cognitive functions that are automated and human performance. Thus, in order to provide guidance on HAC design, this characteristic is included in the HAC model in order to understand how it interacts with other factors and how it affects system performance.

3.3.2.3 Adaptability

The level and cognitive functions that are allocated to automation, the human, or both can be done statically (i.e., permanently) or dynamically (i.e., subject to change depending on the circumstances). In adaptive automation, the LOA or the cognitive functions that are automated can change depending on certain criteria, or triggering conditions, such as operator workload or complexity of the process or evolution. Initiators can be automation initiated, operator initiated, or a hybrid approach. Depending on how adaptive automation is implemented, there may be positive or negative impacts on the HAC and system performance, including effects on operator SA and trust in the automation. See Oxstrand et al. (2013) for a more detailed discussion of adaptive automation.

3.3.3 Mediators of HAC

There are a number of contextual factors that mediate the interaction between humans and automation. The HAC model calls out four factors presently; more may be added as the model is developed. Currently, the research team is focusing on identifying tangible and quantifiable factors that can be manipulated as independent variables. Other factors that are less observable may also be relevant, such as operator trust in the automation, and the team is still in the process of determining how to best include such factors in the model.

3.3.3.1 HSI

HAC is executed through the human-system interface (HSI) or graphical user interface. Therefore, design of the HSI and the effectiveness of the human-system interaction (also called the human-computer interaction) via the HSI will have important effects on the nature of the human-automation interaction. An HSI that has been modeled and designed through a well-established, human-system interaction methodology will make up for deficiencies created in the earlier stages of the HAC design that would have otherwise produced unacceptable HAC performance (e.g., an automated process previously obscured to the operator and thereby creating a human out-of-the-loop issue could be corrected with the proper indications presented in the HSI). Similarly, functions may be allocated to best take advantage of each agent's capabilities, but if the HSI design is poor, it will attenuate the positive effect the sound function allocation decision-making affect has on system performance. These two examples illustrate why HSI is treated as a mediating factor, because the extent to which the characteristics of automation design and HAC design characteristics affect HAC and system performance depends to a large degree on the design of the HSI. See Oxstrand et al. (2013) for more discussion of HSI and its impact on operator and system performance.

3.3.3.2 Task Load

The function allocation method will allocate functions to agents (i.e., automation, human, or both) in a way that should optimize performance. In many cases, the function allocation also will balance workloads and achieve cost efficiencies. However, unanticipated events or tasks may produce additional workload that was not considered in the original function allocation. This additional workload may change the way the human interacts with automation (e.g., it may reduce monitoring performance). For this reason, task load is included as a mediator in the HAC model.

3.3.3.3 Unexpected Conditions

When designing a system, it is impossible to predict all possible operating conditions a system will encounter; therefore, it is assumed that, at some point during the life of a plant, the system would be operating under conditions that were not considered in the original function allocation and HAC design. These changes may positively or negatively affect the ability of both the human and the automation to perform in the manner expected. For example, unexpected conditions may cause the automation to fail, and the operators must take manual control of the system. The unexpected conditions may also affect operator SA, which would impact their ability to take manual control should the automation fail.

3.3.3.4 Training

Training is a mediating factor that was not included in the preliminary HAC model presented in Oxstrand et al. (2013), but it became apparent to the project team that it is a mediator or influencing factor as they were expanding the HAC model. Training can influence the extent to which an operator trusts the automation, relies or over-relies on the automation, and how well the operator monitors the automation and the process. Training can have a significant impact on whether an operator is able to recognize that automation is not working properly, or take manual control when the system encounters conditions for which it was not designed to handle. More research is needed to determine whether training has a moderating or mediating effect on the HAC, but the project team recognizes that training is an important factor for producing successful HAC.

3.3.4 HAC Failure Modes

The HAC model has identified seven HAC failure modes to date. These failure modes are the product of the combination of unfavorable automation characteristics, HAC aspects, and/or mediating variables. In the flow diagrams shown in section 3.3.6 below, the failure modes are shown as red boxes in the model. The seven failure modes identified thus far are:

1. Automation fails and operator is unable to recover
2. Operator uses automation when s/he should not (i.e., misuse)
3. Operator does not use automation when s/he should (i.e., disuse)
4. Operator interferes with automation that is working properly (i.e., error of commission)
5. Operator fails to act on good information from properly working automation
6. Operator fails to provide correct input to the automation
7. Operator fails at manual task

Some of these failure modes were previously identified in the earlier version of the model (failure modes 1, through 5), and two were identified through the process of expanding the model (failure modes 6 and 7).

3.3.5 Resilience of the System

The first HAC model presented in the March 2013 Milestone report included a question toward the end of the flow diagram to assess the opportunity for recovery. With the modifications made to the model since then, the HAC team has endeavored to specify those recovery opportunities earlier in the flow diagrams. As such, there is not a “catch-all” recovery option in the current model. However, there is merit to the discussion of localized recovery (as is shown currently in the HAC model) and system-level recovery, if the system beyond the HAC is resilient enough to recover from failures in the HAC. The project team does not discount the possibility for this system-level recovery. The HAC model, in its current state of development, is a model of the human-automation interaction, and as such models success and failure of the HAC. The HAC model does not presently model larger system performance. As the model is further developed, the project team will continue the consideration and discussion of localized, within-HAC recovery versus system-level recovery and resilience, and will expand the model as can be supported by research findings and the literature.

3.3.6 Description of the Human-Automation Collaboration Model

The full model is too large to fit into one letter-size page, so it is appended in Appendix B. Rather than discuss each path branch-point by branch point, this section will describe the major sections of the model.

The first part of the HAC model, shown in Figure 3 3, starts with the assumption that some task needs to be accomplished, and then asks how the allocation of responsibilities for this task was carried out. This information requires knowledge of the function allocation conducted earlier in the HFE process.

The function allocation process can allocate a task to the automation, the operator, or shared responsibility between the operator and the allocation. For tasks assigned to the operator, the HAC model details the relevant issues and decision points down Path 1 (shown in Figure 4). Issues and decision points for tasks assigned to the automation are detailed down Path 2 of the model (shown in Figure 5). There are several types of shared allocations of tasking:

- The operator and the automation can each perform their portion of the task independently of each other, in which case success is required on both the Automation and Operator branches of the model;
- Collaborative shared allocation in which the operator and/or the automation require input from the other agent to complete the task (shown in Figure 6, Figure 7, and Figure 8); or
- Collaborative shared allocation in which the operator executes the task with discretionary use of automated aids (shown in Figure 9).

The two types of collaborative shared allocation have separate factors and paths to success or failure, so each is treated separately in the HAC model (Branches 3 and 4).

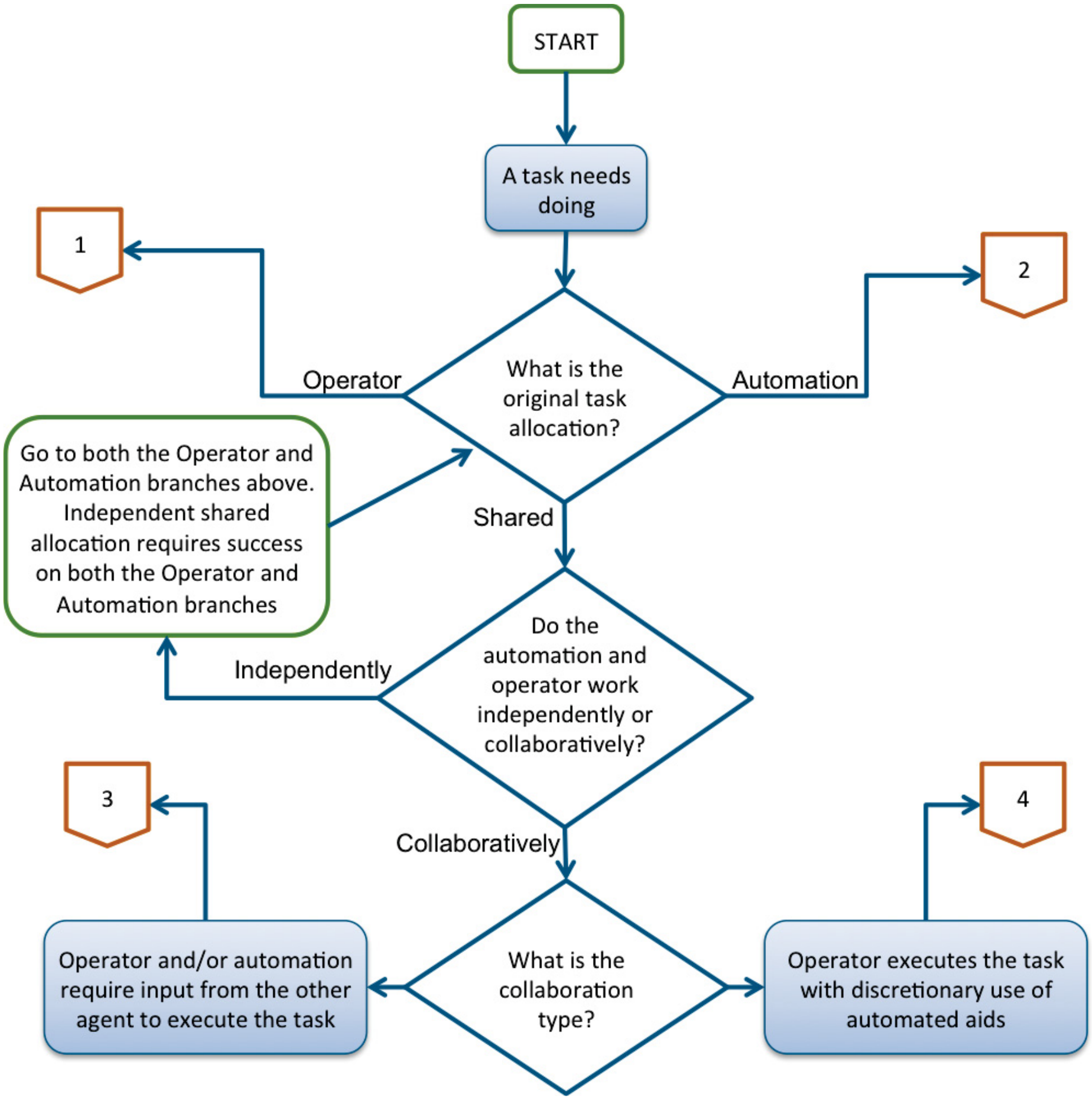

Figure 3. Start of the HAC Model: Identify allocation and collaboration type.

The first major branch, allocation to the operator, is identical to Endsley & Kaber's (1999) LOA 1, Manual Control, and Billings' (1991, 1997) "Direct Manual Control." Manual tasks, as shown in Figure 4, require that the operator be both aware of the task and have the skills necessary to complete the task. If those fail and the system (i.e., other crew members or the automation) cannot recover, then the task failed. The HAC failure mode associated with these errors is "Operator fails at manual task."

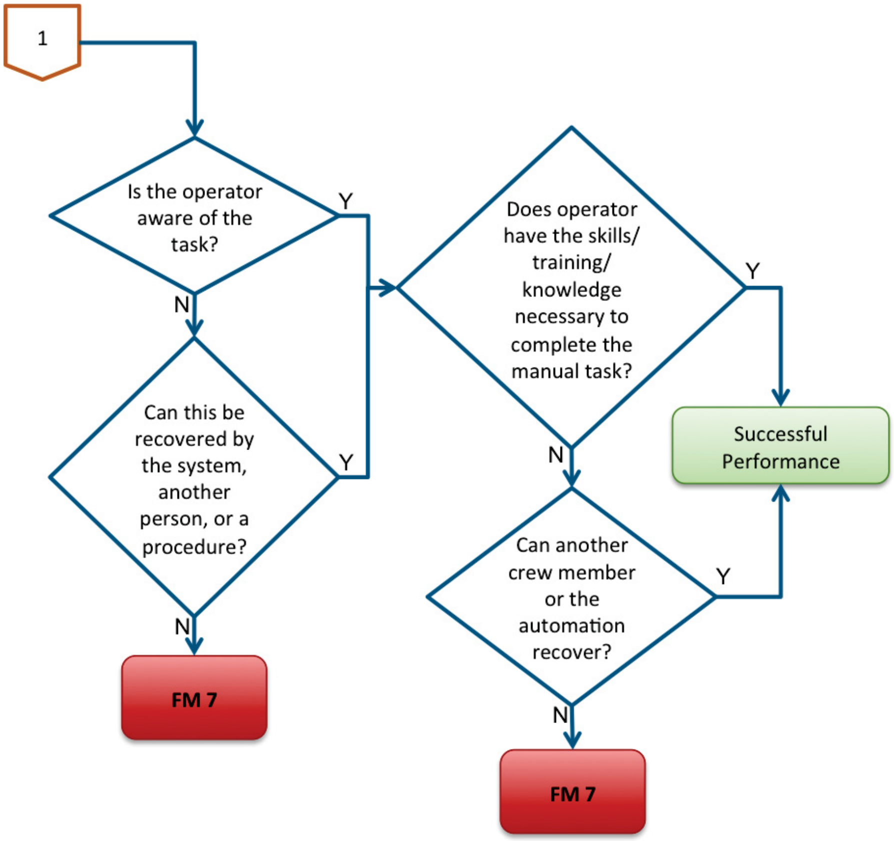

Figure 4. Performance path for manual tasks assigned solely to the operator.

The second major branch of the HAC model (depicted in Figure 5) details the paths to success and failure when the automation is responsible for the task. This would be comparable to Endsley & Kaber's LOA 9, Supervisory Control, and LOA 10, Fully Automatic. In both of these LOAs, the system is fully automated and the operator only has to intervene if there is a problem. As discussed in Oxstrand et al. (2013), a large body of research has demonstrated that a particular issue known as the out-of-the-loop performance problem is a concern in highly automated systems. When out of the loop, the operator is no longer directly involved in controlling the system, and the operator can lose SA—awareness regarding what the system is doing, what is going on with the process, and what needs to happen next. If the automation is working correctly, the out-of-the-loop performance problem does not lead to a larger system failure. However, the out-of-the-loop performance issue becomes a major issue if the automation is not working correctly, or if something occurs for which the automation is not designed to handle.

Accordingly, the automation branch of the HAC model details where loss of awareness can cause failure. The HAC model identifies two failure modes for this branch: "Automation fails and the operator is unable to recover," and, in the case where the operator loses SA and incorrectly believes that manual action is necessary, "Operator interferes with automation that is working properly."

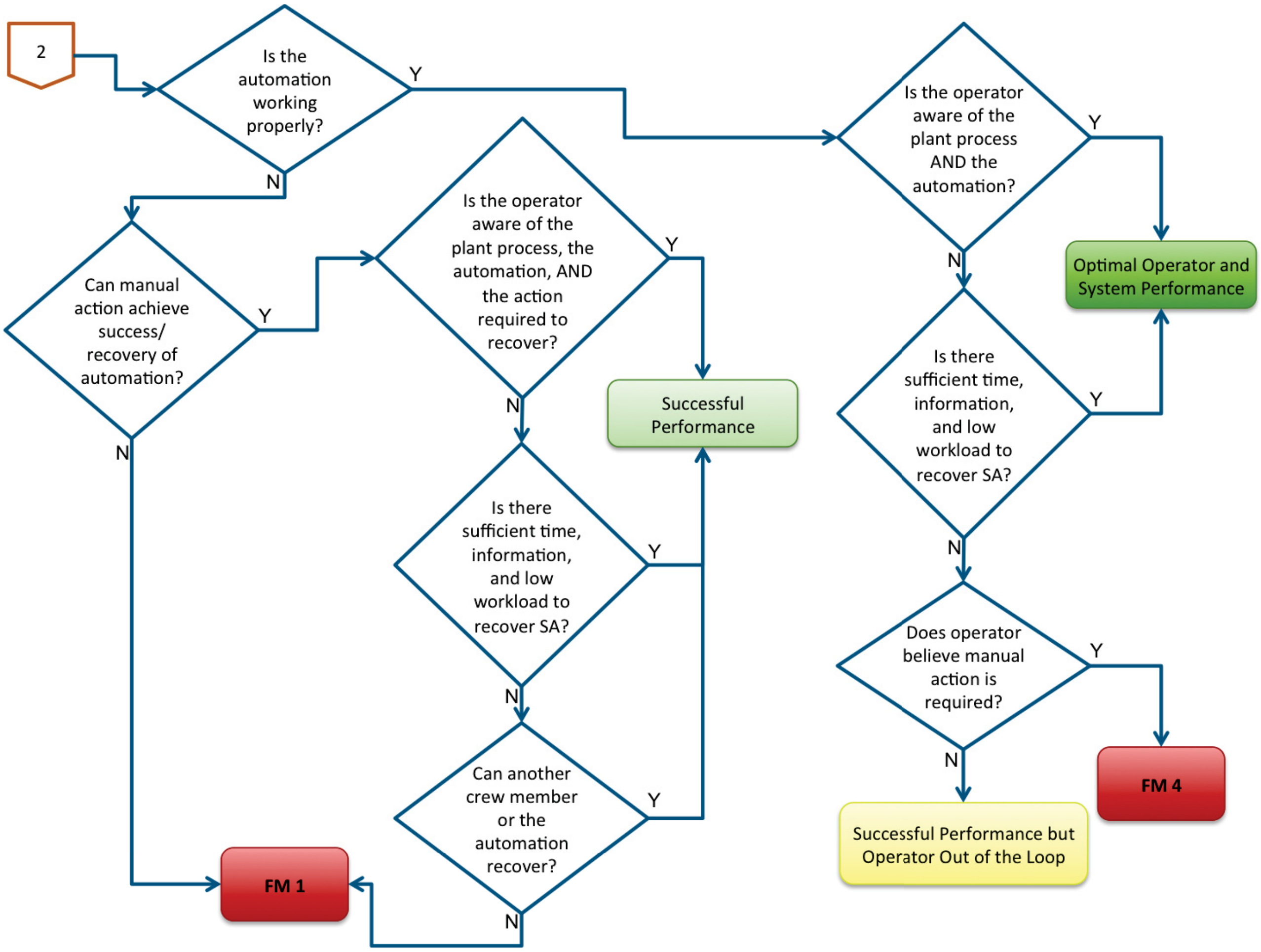

Figure 5. Performance path for tasks allocated to the automation.

The third major branch of the HAC model is dedicated to shared allocation tasks in which the operator and/or the automation require input from the other agent to complete the task. This type of collaborative allocation applies to situations where the operator has to act on information from the system, or where the operator must provide input to the automation for the task to be accomplished. These shared allocations are comparable to more intermediate levels of automation. With this greater degree of interaction between the operator and the automation, there are more pathways to both success and failure.

Figure 6 below shows the first path in this branch: “The operator is the primary agent and must use input from the system to conduct the task.” This is comparable to intermediate LOAs in several taxonomies. In this case, the key issue is whether the system provides correct information. Relevant to this branch are factors such as reliability, trust, and operator SA. As with the branch in Figure 3, operator awareness is most critical in the case that the automation is not working correctly; if the operator is out of the loop and is not aware that the system-provided information is incorrect, this can lead to system failure if the error is not recovered.

This branch of the HAC model describes the paths to reach three separate failure modes:

- Operator fails to act on good information from properly working automation
- Automation fails and operator is unable to recover
- Operator uses automation when she/he should not (i.e., misuse).

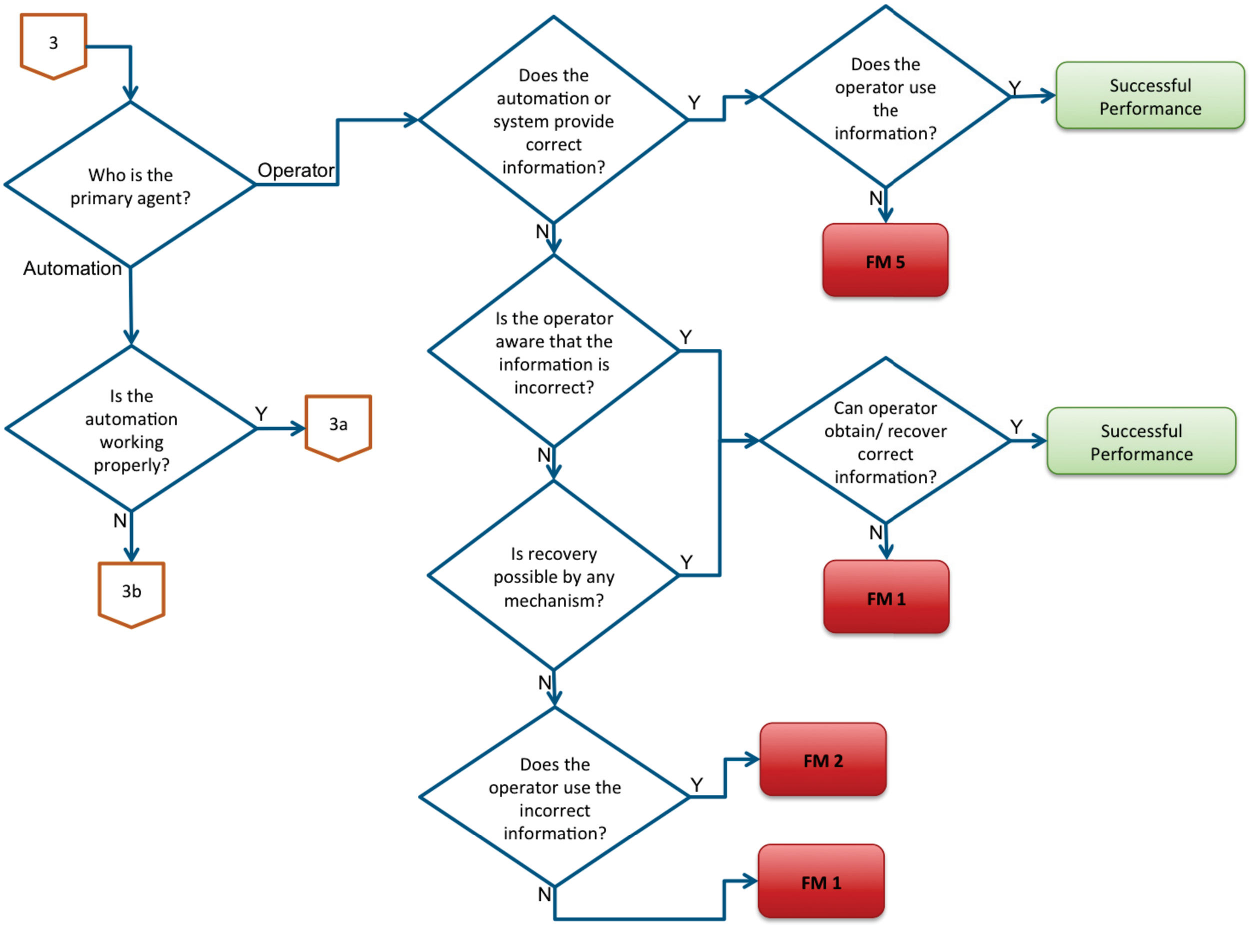

Figure 6. Performance path for collaborative allocation where the operator and/or the automation require input from the other agent to execute the task.

In the case where the automation is the primary agent to which the operator must provide input (such as a decision or approval to start a process), there are two additional branches, shown in Figure 7 and Figure 8. Figure 7 shows the path for the case where the automation is properly working. In this path, the key issues are whether the operator is aware of the need to provide input to the automation, and whether the operator has the knowledge necessary to provide the input to the automation. Should failure occur on those branch points, this section of the HAC model shows how three failure modes can be reached:

- Automation fails and operator is unable to recover
- Operator interferes with automation that is working correctly
- Operator fails to provide correct input to the automation.

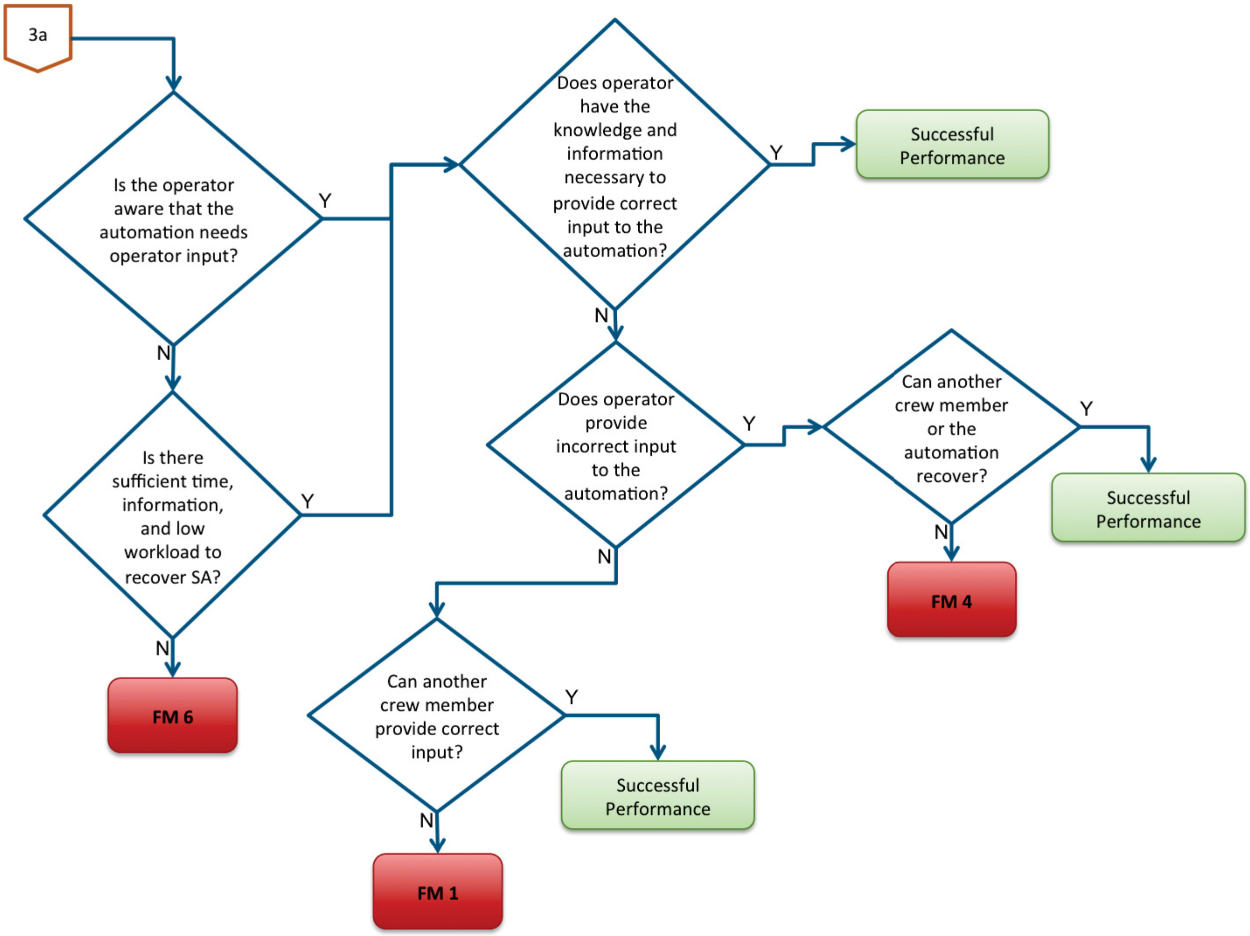

Figure 7. Performance path for collaborative allocation where properly working automation requires input from the operator to execute the task.

Figure 8 displays the paths to success and failure in cases where the automation is primarily responsible for the task and requires operator input, but the automation is not working properly. This path is similar to the automation allocation branch in Figure 5. Key to this path is whether the operator is aware that the automation is not working properly; if not, and if there is no opportunity for recovery, then the failure mode is “Automation fails and operator is unable to recover.”

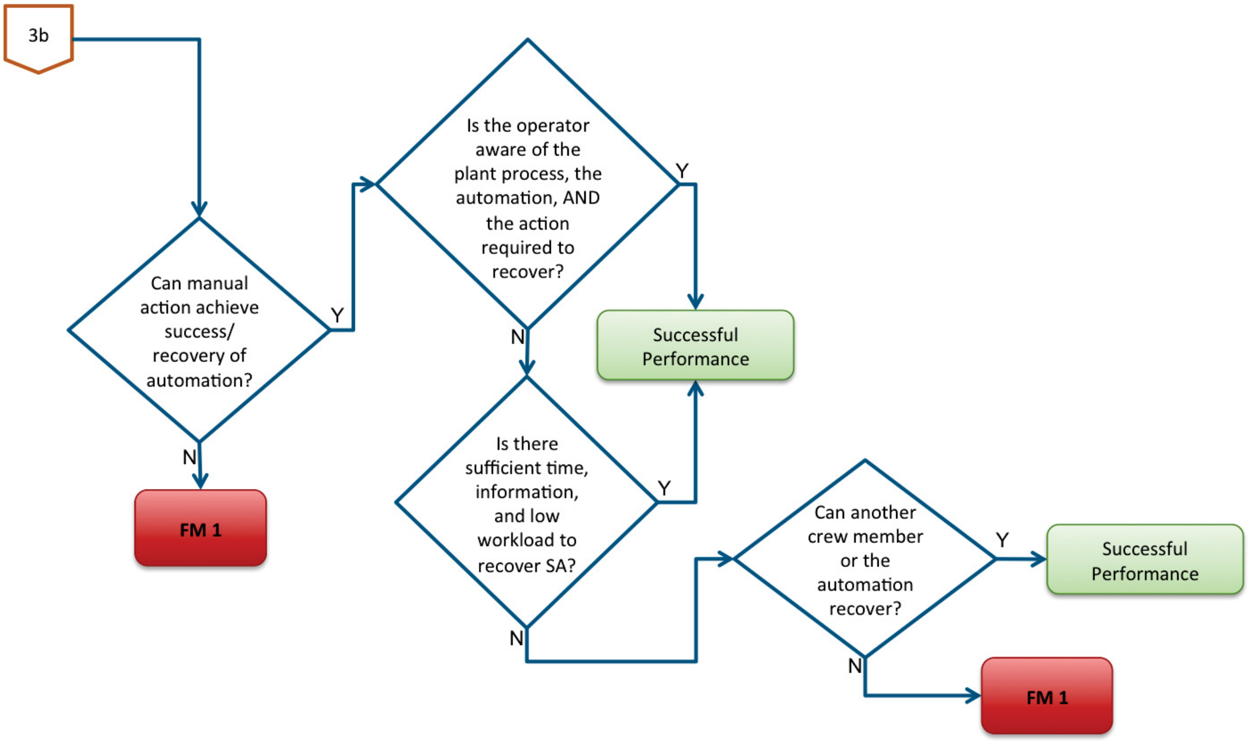

Figure 8. Performance path where automation requires input from the operator but the automation is not working properly.

The fourth major branch of the HAC model, shown in Figure 9, details the paths to success and failure in situations where the operator is assigned to complete the task but has the discretion to utilize automated aids to assist with the task (comparable to Endsley & Kaber's LOA 5). An example of this would be cases where operators can use automated decision support systems. In this branch, the key factors are whether the operator chooses to use the automated aids (and the factors that influence that choice, such as trust and reliability), and whether the aids are working properly. Additionally, a key issue is whether the operator has the skills to complete the task manually, without the aids. Paths on this branch lead to three separate failure modes:

- Operator uses automation when she/he should not (i.e., misuse)
- Operator does not use automation when she/he should (i.e., disuse)
- Operator fails at manual task.

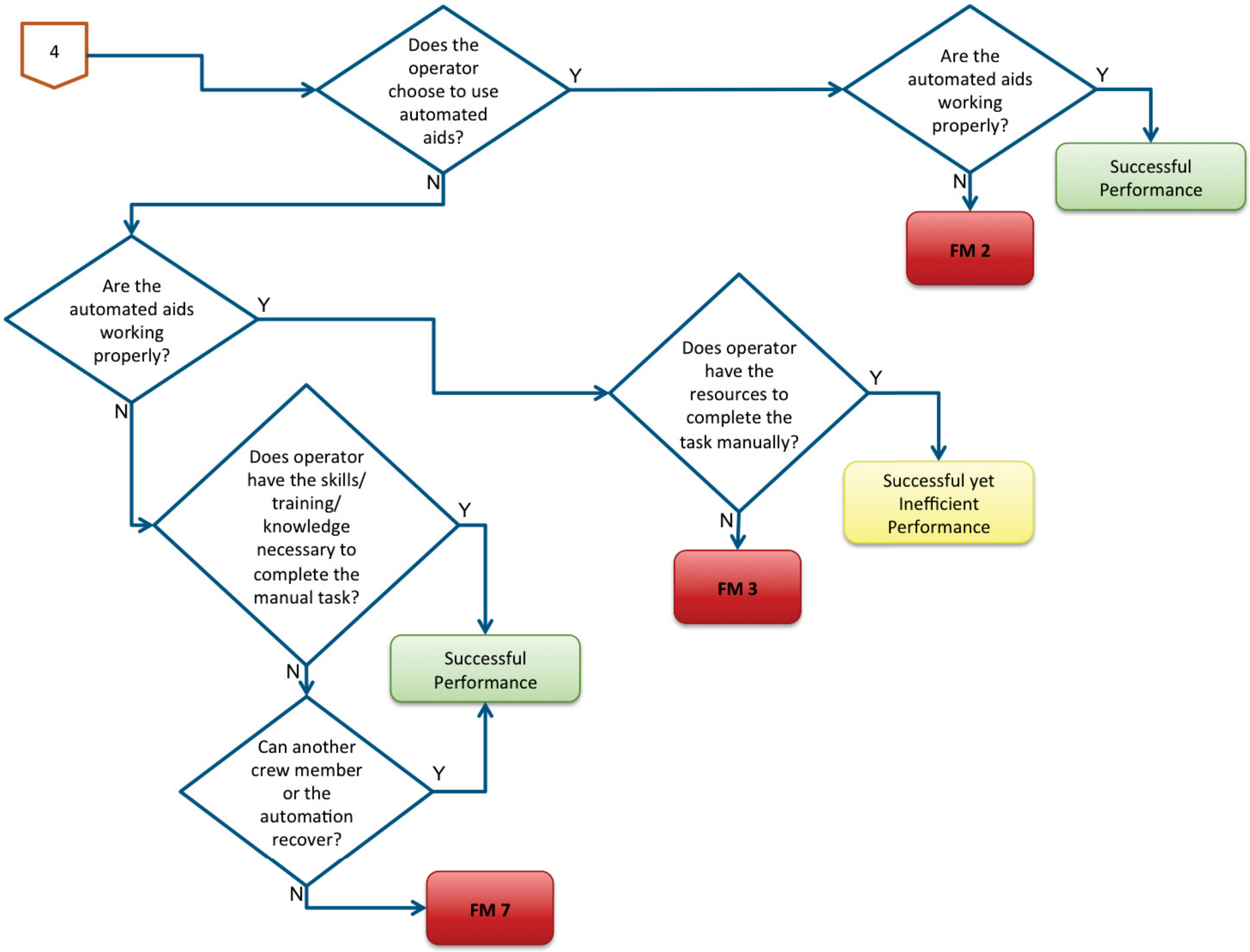

Figure 9. Performance path for collaborative allocation where the operator executes the task with discretionary use of automated aids.

3.4 Future Model Development

The HAC model as presented in this report is still considered to be in progress. The project team has additional development planned for the model. Specifically, development is planned for the following areas:

- Identification and discussion of relevant issues, mediators, and HAC characteristics at each branching point in the model.
- Using the field and empirical studies to determine if there are any pathways or failure modes that have not yet been included in the model, and to determine whether the current pathways and decision points are properly characterized.
- Discussion of the binary nature of the model, and developing guidance for non-binary situations, as well as developing the model to accommodate adaptive automation.
- Clarifying the distinctions between the failure modes and reducing or eliminating any overlap in the failure modes.
- Integrating the possibility for system resilience and recovery subsequent to HAC failure modes.

4. DESCRIPTION OF HAC RESEARCH ACTIVITIES

The research team prioritized the research topics identified in the introduction (Section 1) based on the specific needs in the context of AdvSMR. The prioritization was based on two sources of input: 1) The preliminary functions and tasks, and 2) The model of HAC.

This section describes the identified near term research activities identified by the team, which includes three analytical studies, a number of field studies, and one experimental study the HAC team is actively pursuing.

4.1 Proposed Analytical Studies

Three analytical studies have been initiated to address questions related to the HAC model. These studies are 1) Models of Teamwork, 2) Standardized HAC Performance Measurement Battery, and 3) Initiators and Triggering Conditions for Adaptive Automation. This section describes the reason why the three topics were selected, the objectives, technical approaches, and the use of the results for each of the studies.

4.1.1 Models of Teamwork

4.1.1.1 Background

Considerable research has been conducted to address how to make automation "team players" (e.g., Christoffersen & Woods, 2002; Land, et al., 1995; Lenox, et al., 1998); Steinberg, 2012). This is a logical result of the findings that poorly designed HAC, such as poor communication between automation and it human supervisor, often leads to problems for operators, including:

- Undesirable changes in the overall role of personnel
- Difficulty understanding automation
- Poor monitoring, lack of vigilance, and complacency
- Out-of-the-loop unfamiliarity and situation awareness
- Workload to interact with automation and when transitioning to greater manual control
- Loss of skills for performing tasks automation typically performs
- New types of human error

For multi-agent systems, designing automation to be a good "team players" has typically based on an implicit notion of what it means to be a team player and how members of a team should perform to function successfully. General concepts of team characteristics and behavior are employed, such as trust, goal and intention sharing, cooperation, and redundant responsibilities (especially in the case of adaptive automation where shifting of responsibility is a hallmark of the approach). These concepts are based loosely on a sense of how teams of humans perform.

Thus, the concept of multi-agent teamwork is ill-defined at best and relies considerably on simplifications and popular notions about what is needed to foster teamwork. That is, the work to define how automation should behave (be designed) to be a team player has not been based on a comprehensive model of teamwork or the recognition that there are different models of human teamwork, each with its own set of member responsibilities and behaviors (Salas et al., 2008). As a result, prior work on identifying how automation can be a team player is fragmented and incomplete at best.

Further, even if a belief regarding human teams behavior is at the core of this research, it does not sufficiently address the fact that automation agents are not humans. These agents can neither completely fulfill the role of a crewmember nor can they fully behave as a human member of a team would. For example, automation agents cannot assume responsibility; automation can be given the authority to act, but responsibility will always be relegated to the human (Pritchett, 2001; Sarter & Woods, 1992). As another example, automation is not "concerned" about the consequences of its actions nor is it as able to innovate in the manner that human crews will do in response to unanticipated events.

To ensure that guidance on the design of successful HAC is developed the research team needs a model or models of human-automation (HA) teamwork. Such a model(s) will help us to fully understand the relative roles, characteristics, and expected behaviors of automation and establish a basis for the development of comprehensive guidance for HAC. Further the model(s) must reflect the types of differences between human member of a team and automation discussed above.

4.1.1.2 Objective

The objective of this research is to identify model(s) of HA teamwork that are appropriate in a commercial nuclear power environment. Once identified, the researchers can elaborate the requirements of team members and use these requirements to develop guidance for what automation characteristics and attributes are needed to be good "team players."

4.1.1.3 Technical Approach

We will examine different models of teamwork, including HA teams and human-automation teams to identify lessons learned regarding what makes for effective teams. As part of this evaluation the researchers will:

- Review recent research on models of human teamwork
- Review the literature on models of HA teams
- Place emphasis on complex systems – as close to NPPs as possible
- Place emphasis on highly automated systems
- Identify lessons learned regarding what makes for effective teams and the characteristics needed.

Once the characteristics of effective human-human teams are identified, a characterization of human-automation teams will be developed to:

- Emphasize the differences between human and automatic agents
- Assess the implication of agent roles within a team (e.g., in higher LOA systems, autonomous agents may act independently from their human teammates; while in lower LOAs automation may play only a supporting role)
- Identify how HA teams are different from human-human teams.

When the HA teams are characterized, the researchers will select (or develop) an appropriate model of teamwork for HA teams:

- Teamwork models identify team characteristics critical for team success. We will identify these characteristics and translate them into terms that are adapted to our operational environment
- Identify performance measures suitable for determining whether the requirements are achieved.

The key output of this study is a model or models of HA teamwork. For each model, the requirements for the expected roles, characteristics, and behaviors for both human and automation agents will be identified.

4.1.1.4 Use of Results

The products of this research will be used as a technical basis upon which to establish guidance on designing effective HA teamwork.

Aspects of the models may be used to design subsequent experimental studies.

In addition, the products of this research will provide input to the "Development of a Standardized HAC Performance Measurement Battery" study concurrently being conducted. It will provide measures for the desired teamwork characteristic and behaviors for the both the human and automation agents.

4.1.2 Standardized HAC Performance Measurement Battery

4.1.2.1 Background

Oxstrand et al. (2013) captured the need for a more complete set of performance measures focusing on the relationship between humans and automation, including trust and neglect, as well as those measures needed to depict multi-agent teamwork. Existing measures may not adequately assess individual and team performance in highly automated systems as are expected in AdvSMR designs.

The selection of appropriate performance measures is vital to establishing a technical basis upon which findings can be generalized to form guidance for designers. Selection of poor or insensitive measures can result in misleading findings and the possibility of missing important HAC relationships altogether.

The availability of a standardized HAC performance measurement battery helps to ensure our studies evaluate all of the important aspects of performance, using the best measures available. The use of a standard battery also supports the comparison of results across studies and, therefore, generalization of findings. Additionally, a standardized battery can help ensure that performance measures used are appropriate for high-automated systems being operated in a commercial nuclear power and AdvSMR domain.

4.1.2.2 Objective

The objective of this study is to develop a standardize HAC performance measurement battery that:

- Can be used in experiments conducted as part of the AdvSMR HAC project, and
- Can serve as input to the later project Activity titled "Develop a Human-Automation Collaboration Evaluation Methodology" which will provide guidance to vendors for validation of a design-specific HAC.

4.1.2.3 Technical Approach

The first step in developing the standardized HAC performance measurement battery is to identify what dependent variables should be measured in HAC research. Accordingly, the team will conduct the following activities:

- Identify what aspects of human, system, and HAC performance should be assessed in human-in-the-loop studies. This will be conducted based on a review of human-in-the-loop studies.
- Consider important characteristics of HAC, e.g., trust in automation. The research team developed a model of human automation interaction that defines the factors that influence the success or failure of HAC. This model, along with the existing literature on human automation interaction will be used to define the important characteristics of HAC.
- Evaluate whether existing measures adequately asses known HAC performance issues
- Identify unique human performance challenges of AdvSMR operational environment, e.g., multiunit monitoring and control.

The second step in developing a standardized HAC performance measurement battery is to determine what specific measures should be used for each aspect of performance (i.e., identify how the performance characteristics identified should be measured) per the following:

- Identify what has been measured in other HAC studies (what were the specific measures, e.g., SAGAT or SART for SA)
- Evaluate characteristics of each measure, e.g., validity, reliability, sensitivity, etc.
- Define which measures are scenario specific and which are standard measures that can be used across research scenarios.
- Provide recommendations for the development of new measures for important HAC performance characteristics for which there are no existing measures (or the existing measures are inadequate).
- Define our HAC performance measurement battery (i.e., HOW should it be implemented).

These activities will be conducted in FY13. Based on the results, subsequent research activities will be defined in more detail and will be performed in FY14.

If the team determines that new existing measures do not capture all of the important aspects of HAC performance adequately, the researchers will develop new measures to fill in the gaps. This will include such activities as:

- Identify aspects of performance to be measured
- Develop measurement approach (e.g., questionnaire, objective performance, indirect methods)

Once the standardized HAC performance measurement battery has been defined, the research team will specify how data will be analyzed, pilot test the measures, and use it in planned HAC experiments.

4.1.2.4 Use of Results

As noted above, the standardized HAC performance measurement battery will be used in our HAC experiments and will ensure that all appropriate dimensions of performance are comprehensively assessed using the most appropriate measures for a highly automated commercial nuclear power context.

Experience gained through use of the battery in our experiments will provide a solid technical basis to serve as input to our efforts to develop guidance for vendors on validating design-specific HACs.

4.1.3 Initiators and Triggering Conditions for Adaptive Automation

4.1.3.1 Background

The concept of adaptive automation, defined as a dynamic task allocation to either a human operator or automation, has received considerable attention recently. Adaptive automation may be an effective way to enhance human automation collaboration (HAC) performance because the operator's task load can be shifted to match the current situation. An important aspect of adaptive automation is how that shift is triggered or initiated. The triggering mechanism chosen for adaptive automation can have important consequences for both system performance and operator workload.

The following triggering mechanism have been proposed or investigated to initiate adaptive automation:

- Operator initiated
- Critical events (that will change demands on ops – like an emergency operating procedure initiator)
- Operator performance measurement
    - Errors
    - Performance Time
- Operator physiological assessment
    - Eye tracking

    - ECG
    - EEG
- Modeling
- Hybrid methods combining one or more of the above

Additional research is required to identify the appropriate triggering mechanisms for automation changes, and how they should be implemented to minimize any disruptions to the operator's performance when the change occurs.

4.1.3.2 Objective

The purpose of this research is to identify the triggering mechanisms that:

1. Provide the best support for operator and system performance
2. Are likely to be achievable in the AdvSMR control room context

4.1.3.3 Technical Approach

For each of these possible initiators listed above, the research team will evaluate:

- The feasibility of using the method in the context of an AdvSMR control room
- The influence each method has on HAC performance. Are there any tradeoffs associated with using the method (e.g.., reduced workload under some conditions but increased workload under others)?

This evaluation will be based on both a review and synthesis of the existing literature on adaptive automation as well as critical evaluation of the contextual factors that may reduce the feasibility of some of the methods in the AdvSMR control room.

4.1.3.4 Use of Results

The results of this research will be used to inform the HAC guidance developed by the research team. Additionally, the results could be used to inform requirements for AdvSMR control room design.

4.2 Proposed Field Studies

4.2.1 Background

AdvSMRs are anticipated to use higher degrees of automation than the existing fleet of light water reactors in the US. The main goal for the HAC research effort is to develop design guidance for HAC in AdvSMR. Before the research team develops guidance regarding how to effectively design a HAC for AdvSMR, it is necessary to understand operating experience regarding HAC in highly automated systems. Because there is little to no operating experience with highly automated systems for day-to-day operations in the nuclear field (let alone the AdvSMR field), the research team will seek input from other process control facilities that use high degrees of automation.

4.2.2 Objective

To determine how process control and power generation industries handle HAC in highly automated systems. Specifically, the researchers will seek the answers to the following questions:

- What is/are the plant mission(s)? How does the plant mission relate to that of a traditional LWR? How does it relate to AdvSMR?

- What functions and tasks are assigned to automation, human operators, or both? How 'automated' is the system?
- What are some of the difficulties that operators encounter when interacting with these highly automated systems? Are there negative impacts on human-system performance?
- How does the HSI support HAC? What problems do operators encounter when interacting with automation via the HSI?

4.2.3 Technical Approach

4.2.3.1 Site Visits

The site visits will be carried out in 2 phases. The first phase will involve sending out a questionnaire to the point of contact at each site the team plan to visit.

- **Questionnaire**. The majority of the questions on the questionnaire will be related to the plant mission, the approach to function allocation, and information about operators (e.g., number and qualifications) and operator training (see Appendix A for the questionnaire).

The second phase will involve a site visit. The site visit will include a review of the plant HSI and structured interviews with as many operators as the researchers can access.

- **Review of plant HSI**. Researchers will be provided with a list of features to review (e.g., alarm system, operating procedures, controls,). They will conduct the review by touring the control room with an operator. Researchers will inspect the HSI elements, and ask the operator for additional information where appropriate (See Appendix A for the HSI checklist).
- **Operator Interviews**. The researchers will be provided with a list of interview questions to ask the operators. These questions will focus on what tasks the operator carries out on a typical day, how the operator interacts with the automation and what challenges he/she perceives associated with the HAC design (e.g., it is too automated, or the HSI doesn't provide enough information). In addition the operators will be asked about any accident scenarios they have encountered, and how the HAC design supported (or hindered) the process (See Appendix A for the operator interview questions).

The following sites have been identified as potential candidates for the field study:

- Idaho Falls Power
- Coal fired plants in Idaho
- Monsanto phosphate facility (Soda Springs, ID)
- Simplot fertilizer facility (Boise, ID)
- Other fossil fuel plants

4.2.4 Use of Results

The results of this study will be compiled in a report which describes the:

- Approach to HAC in each of the process control facilities visited
- A summary of how the HSI supports effective HAC, and a summary of ways in which the HSI is inadequate for supporting HAC

- These results will be framed in the context of how they apply to anticipated AdvSMR operations.

The results will be used to inform HAC guidance for AdvSMR by identifying successful (and perhaps unsuccessful) features of HAC design in other process control facilities.

4.3 Proposed Experimental Studies

The purpose of the AdvSMR HAC project is to carry out the foundational research needed to enable AdvSMRs to achieve operations and management (O&M) costs comparable (within an order of magnitude) to the existing fleet of power reactors. In order to be economically viable, it is unlikely AdvSMRs be able to maintain the same per unit staffing as the current fleet because the per-kilowatt O&M costs will be much higher. It is anticipated that the necessary reduction in staffing will likely be achieved through a greater use of automation. A large body of research suggests that higher levels of automation can lead to desirable performance outcomes, but often at the cost of reduced operator monitoring (often referred to the human-out-of the-loop phenomenon). This reduced monitoring can have negative consequences in the event of an automation failure, leading to the operator having difficulty in regaining manual control. Therefore, one of the key research questions for HAC in ADVSMR is: how can HAC be designed such that operator awareness and the ability to regain manual control are maintained under conditions of near-autonomous operation?[1]

In addition, how can automation be designed so that:

- Operators are aware of automations activities and the degree to which its goals are accomplished?
- Operator workload to monitor and manage automation is acceptable?
- Operator can promptly detect automation degradations and failures and the workload associated with the transition to backup operations is acceptable?
- Operators have the skills necessary to assume automation's responsibilities when they need to do so?

The research team has developed several experimental studies, however, only the most detailed plan is presented here. The other studies will be further developed and carried out at a later date.

4.3.1 Levels of Automation

Many researchers have acknowledged the importance of LOA in maintaining SA during human-automation collaboration. Several taxonomies have been proposed to describe the way that different roles can be delegated to either humans or automation. Endsley & Kaber's (1999) model is the most detailed and specific of the various LOA models; in terms of which agent performs which cognitive function. Their taxonomy describes the following ten LOAs, see Table 4 below.

Table 4. Endsley & Kaber's (1999) Taxomomy for LOA.

Levels of Automation		Roles Monitoring	Generating	Selecting	Implementing
(1)	Manual control	Human	Human	Human	Human
(2)	Action support	Human/ computer	Human	Human	Human/ computer
(3)	Batch processing	Human/ computer	Human	Human	Computer

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[1] It is recognized that some additional aspects of some AdvSMR operations are likely to include lots of automated assistance for monitoring, maintaining situation awareness, and response planning, etc. that may not be fully autonomous, but according the GEFR-00793 the operators of PRISM have no functions related to normal operations to perform.

		Roles			
Levels of Automation		Monitoring	Generating	Selecting	Implementing
(4)	Shared control	Human/ computer	Human/ computer	Human	Human/ computer
(5)	Decision support	Human/ computer	Human/ computer	Human	Computer
(6)	Blended decision making	Human/ computer	Human/ computer	Human/ computer	Computer
(7)	Rigid system	Human/ computer	Computer	Human	Computer
(8)	Automated decision making	Human/ computer	Human/ computer	Computer	Computer
(9)	Supervisory control	Human/ computer	Computer	Computer	Computer
(10)	Full automation	Computer	Computer	Computer	Computer

Research conducted with Endsley & Kaber's taxonomy shows SA is best at intermediate levels of automation (LOA6 = Blended decision making); however, optimal system performance is achieved at higher levels of automation (LOA9 = Supervisory control), which has the cost of human out-of-the-loop problems. Endsley & Kaber define LOA 9 as nearly full automation, with the human in the role of monitoring the automation and intervening only when necessary. The HAC research team considers LOA9 to be near-autonomous operation.

Other researchers have emphasized that, to minimize the out-of-the-loop phenomenon, automation should be engaged at lower levels in making decisions, particularly for high-risk functions (Parasuraman et al., 2000), see Figure 10 below. Endsley & Kaber's taxonomy above does not include an LOA higher than blended decision making that includes the operator in the decision making process.

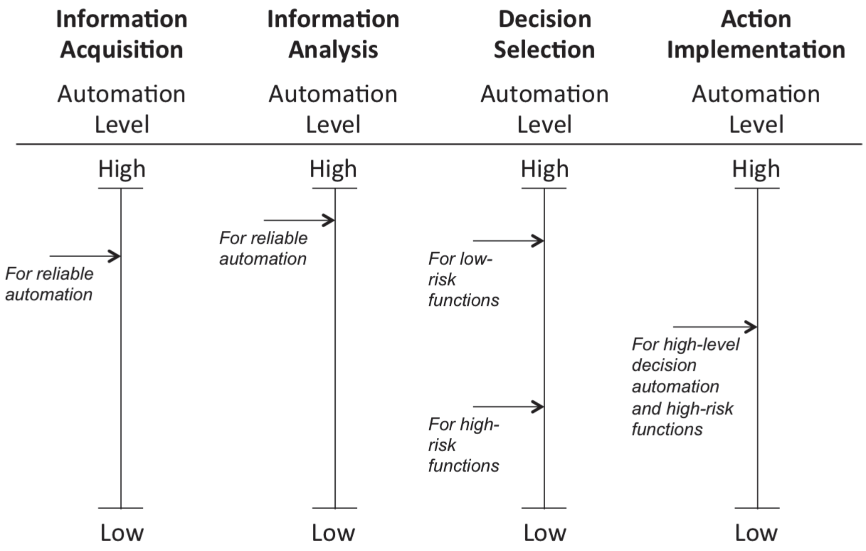

Figure 10. Model of LOA (Parasuraman et al., 2000).

There is uncertainty as to whether there are additional LOAs, not represented in existing taxonomies, that could yield the system performance benefits of higher levels (i.e., supervisory control) while also mitigating human-out-of-the-loop problems?

It is recognized that some of the automation literature is moving in the direction of adaptive automation, and that it is possible that adaptive automation will be the approach AdvSMR designer take to address the three high level HAC research topics the team has identified (Oxstrand et al., 2013). However, since adaptive automation is an issue that is not entirely separate from LOA or cognitive functions, it can be argued that LOA issues need to be addressed first in order for adaptive automation to work effectively. That is, one way of conceptualizing adaptive automation is that it involves changing the LOA (and/or the cognitive functions allocated to the automation) depending on the specific circumstances of the situation. Given this conceptualization, it is important to know what LOAs are best for overall system performance, operator workload, SA, etc. such that a shift in LOAs (as a function of some triggering condition) changes to a LOA that is in some way optimal for system performance and/or operator considerations.

Using Endsley & Kaber's taxonomy as an example, level X in Table 5 below is one proposed change to the roles and responsibilities assigned to the human and/or computer (though Endsley's taxonomy has been used in this example, the proposed modifications to the LOAs could easily be characterized in other LOA taxonomies). This new proposed level allocates the monitoring/vigilance role to the computer because it is well established that computers are better able to perform monitoring tasks than humans over long periods of time. The implementing role is also allocated to the computer because it improves overall system performance (as computers are more precise in their implementation actions than humans). However, in level X, the cognitive function of selecting is executed in a shared manner. The operator is involved in the generation and selection of action plans, but at a high level. The automated system handles the low-level detail. Thus, the operator's role is shifted from monitoring (which requires vigilance) to one of being involved in the decision making, but at a level that may not increase workload drastically compared to lower levels of automation. The hypothesis is that these added intermediate levels will enable the operators to maintain awareness because the tasks shift from a pure vigilance task to being actively engaged in the process.

Table 5. Proposed New Level of Automation.

Levels of Automation		Roles Monitoring	Generating	Selecting	Implementing
(6)	Blended decision making	Human/ computer	Human/ computer	Human/ computer	Computer
(9)	Supervisory control	Human/ computer	Computer	Computer	Computer
X	TBD	Computer	Computer	Human/ computer	Computer

4.3.1.1 *Situation Awareness Study*

The purposes of the proposed SA Study are to test LOAs 6, 9, and X to determine how LOA X affect SA and overall system performance, as well as to compare LOA X to LOA 6 and 9. More specifically, the team aims to address the following questions:

- What effect does Levels X have on SA? Does Level X produce SA equivalent to LOA6? Or, does Levels X produce SA that is only better than LOA9?
- What effect does Levels X on operator workload? Does Level X produce higher or lower workload than LOA 6?
- What effect does Level X have on system performance? Does Level X produce system performance equivalent to LOA9? Or, does Levels X produce performance that is only better than LOA6?

The research team recognizes the answers to these questions will be dependent on a number of factors including:

- The task or tasks to be performed by the Human Automation team
- The context provided by the other tasks human may have to do (e.g., a secondary monitoring task as a gauge of operator workload).
- The design of the HSI used to monitor and interact with the automation.

The research team is working on developing and defining these, and other, aspects of the study. The following text describes what work and decisions the team has made as of the writing of this report. Further refinements will continue until all necessary details of the experiment are specified.

The experimental design would focus on participants performing a single or set of tasks (described below) with an automated agent on a computerized simulation. The roles and responsibilities would be allocated as prescribed by the LOA being tested (e.g., LOAs 6, 9, X).

The task or tasks to be performed are framed in the context of the Failure Modes (FMs) and other consequences identified in the HAC model (Oxstrand et al., 2013). In particular, FM1 (i.e., Automation fails and the operator is unable to recover), FM4 (Operator interferes with automation that is working properly), and Operator-out-of-the-loop (OOTL) unfamiliarity that does not lead to a failure mode, but contributes to 'operator unavailability upon demand' are important in the context of supervisory control of a highly automated system situation, see Figure 11.

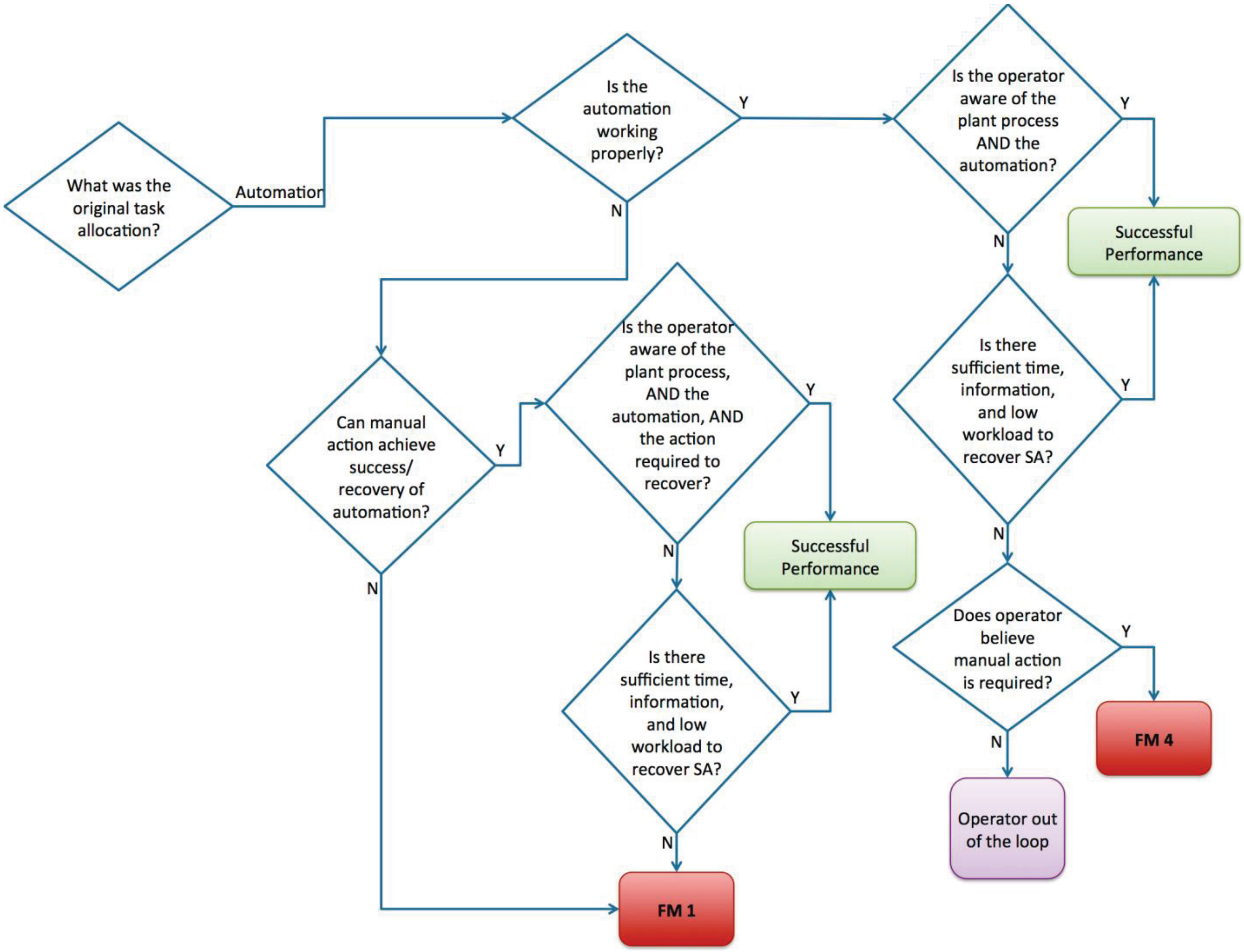

Figure 11. Excerpt from the HAC Model (Oxstrand et al., 2013).

Figure 11 is the part of the HAC model related to the situations where the I&C is highly automated, in that virtually all of the tasks are allocated to the automation (at least during normal operations, and perhaps even under other plant states). The research team is working on how to easily derive and design the task(s) performed and the simulated scenario created for these experiments such that they test how new LOA configuration affects the likelihood of these FMs or OOTL occurring, and then gain further insights into what can be done to create successful performance. Information gained from identifying plant functions and operator tasks in the PRISM design will also be used to inform the development of the experimental tasking.

Furthermore, though they are not depicted in the model, the team has also discussed the idea that there are specific characteristics of HAC and mediators of HAC that act as "performance shaping factors" (PSFs) at certain 'steps' in the model. For example, HSI is an important mediator of HAC that should affect SA. The extent to which PSFs will have an influence on a particular 'step' is another element of the research that the team is addressing.

The team is striving for this to be a one-factor study, assuming there is only one task for the subject. The research team is working on defining this part of the study further. Additionally, the team is proposing to use a within-subjects study and run all participants through all conditions, order counterbalanced. A within-subjects design would require fewer people and less training, but it also means the person is in the experiment for a longer period of time. The team plans to collect subjective measures of which LOA participants prefer better, as well as comparisons for how the participants perform in each condition. Most studies of this type reviewed by the team use the within-subjects design.

Many studies focusing on the effects of automation on performance employ a secondary monitoring task as a gauge of operator workload, which is a major concern with operator interactions in AdvSMRs. The research team is evaluating the pros and cons of adding a similar task, as the inclusion of a secondary monitoring task depends greatly on the overall task context.

Research has also shown that operator SA is improved when the HSI is designed according to ecological interface factors design principles. Depending on resources and schedule constraints, an additional HSI factor may be included whereby all of the LOAs are tested across different HSIs. One experimental condition will use a "traditional" nuclear power plant HSI layout and functionality, in that its design would follow the single sensor, single indicator design philosophy that has been used in virtually all U.S. LWRs in the United States. The second condition will use an "advanced" HSI based on ecological interface approaches (Vicente & Rasmussen, 1992), or use information-rich displays that present aggregated or grouped information. This design reduces the inherent information complexity, and reliance on representational aiding principles (Woods, 1991) to effectively map lower-level data to higher-order functional information that gives the lower-level data meaning.

Additionally, if the human operator can perform the task that automation is performing, there is a need for an experimental condition where their performance is manually "calibrated" in order to gauge the overall effects of the automation. This also helps maximize the "primary variance" (effect size of the main variable of interest) so that an effect can be found.

The dependent measures will be Situation awareness, System Performance (% correct, errors, time to complete, etc.), Workload, Trust in Automation, and Usability Survey of the Traditional HSI.

5. PATH FORWARD

The activity of identifying AdvSMR functions and tasks initially aimed to gain better understanding of a specific plant design to facilitate subsequent HAC research. However, such an activity requires detailed documentation from the vendor regarding the specific design. Most vendors have made information on their design publicly available, but this information is at a very high level and the identification of specific functions and task allocations requires making a number of inferences. Hence, the publically available vendor documentation does not currently meet the requirements for identifying the function and tasks for AdvSMR. The researchers redefined their activity to study a plant design from the 1980s (i.e., PRISM) for which the documentation is more detailed than the majority of the other designs. Though, it should be noted that in a recent publication on PRISM (e.g., Triplett et al., 2012), GEH states that the PRISM design was resurrected in 2006 as a part of DOE's Global Nuclear Energy Partnership, and so many parts of its design have been updated from its original 1980s conceptualization.

Moving forward, the researchers will develop a generic AdvSMR design model based on insights gained from the different AdvSMR vendors as well as both the current LWR fleet and planned new LWR designs. Additionally, to gain more insights regarding operating multi modular units and the collaboration between operators and highly automated systems the team will study other industries, such as hydro and coal power generating stations. The generic plant design model will be developed in collaboration with the AdvSMR Concept of Operations research project and will be utilized as a basis for future experimental studies focused to study specific aspects of HAC.

Additionally, the research team has identified activities that will address known knowledge gaps related to HAC. An extended version of the model of HAC was developed by the team, as described in section 3. This more detailed version of the HAC model was the basis for identifying important research activities. The result for each activity will become a piece in the puzzle the team needs to build to understand the intricate details influencing the collaboration between automated systems and human operators. The activities that will be initiated during FY13 are the three analytical studies described in section 4, at least one field study, and the planning and preparations of an experimental study. The experimental study will be conducted in FY14 due to the amount of preparations needed for this type of study. The activities initiated in FY13 will be conducted in parallel and the result for these efforts will be presented in a report scheduled to be published in November, 2013.

Table 6 below provides a high-level schedule summary for the research activities described in section 4. The team recognizes that revisions of schedules and plans are inevitable based on insight gained along the way. Therefore, the table below should only be viewed as preliminary. However, the table do illustrates how different activities will be conducted in parallel. Figure 12 illustrates the planned activities in the HAC research effort between FY13 and FY15 and how they relates to the overall goal of developing guidance for HAC design and evaluation.

Table 6. Preliminary Schedule for FY13 -FY14.

FY13	FY14
Models of teamwork	
Standardized HAC performance measurement battery	
Initiators and triggering conditions for adaptive automation	
Field Study – Idaho Falls Power	Field Studies – To be determined
	Situational awareness experimental study
	Other studies (to be defined)

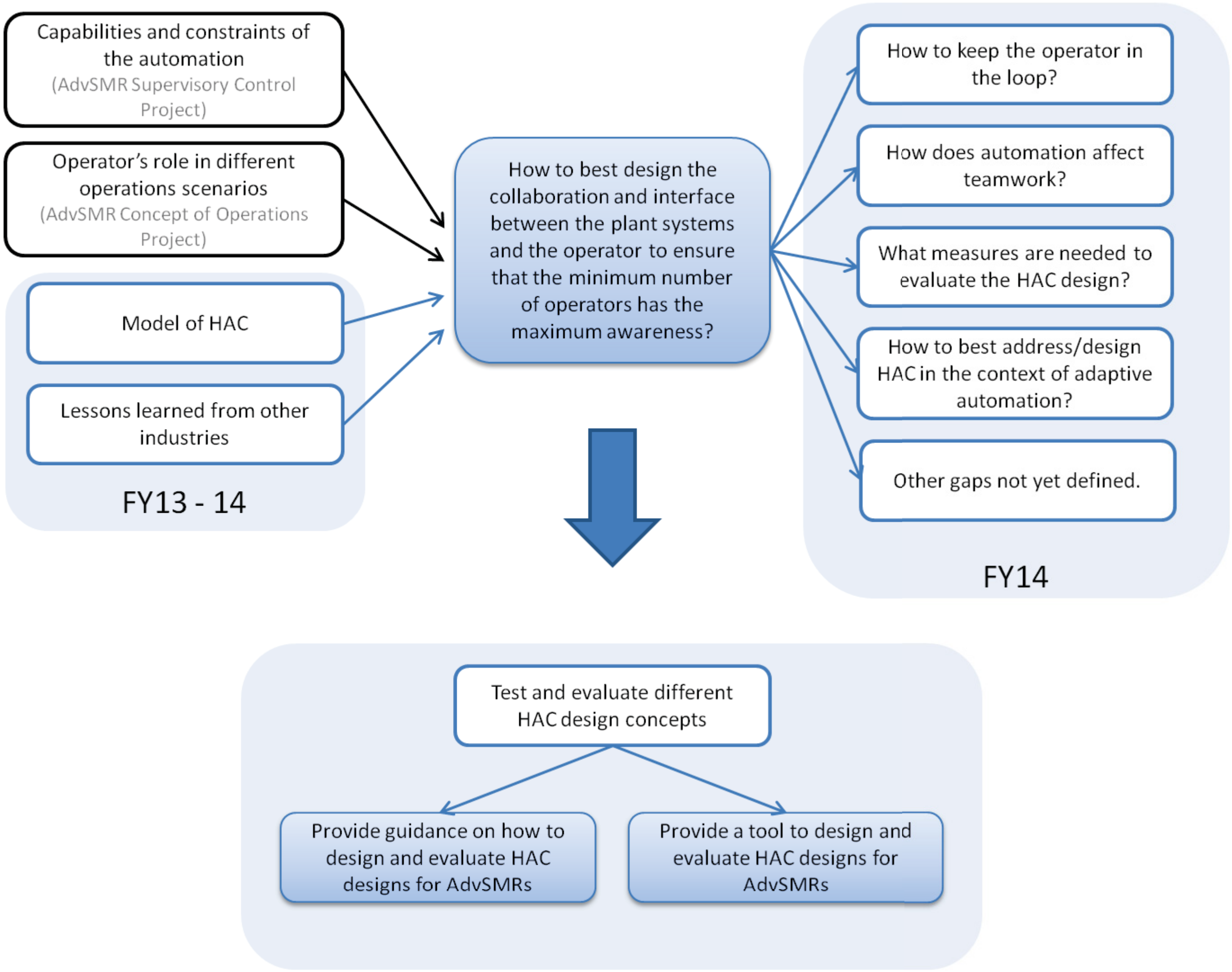

Figure 12. HAC Project Overview.

6. REFERENCES

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APPENDIX A – FIELD STUDY MATERIALS

Pre-Visit Questionnaire

1. Describe the overall mission or purpose of the facility?
2. Which high level functions must be performed to accomplish the mission of the facility?
3. Describe the overall approach taken to carry out the mission of the facility?
4. Describe any secondary purposes of the facility?
5. Is this a multiple unit facility?
6. What systems, if any, do the multiple units share?
7. The operating framework for this research identifies this plant as a process control system, described as an engineered system with a set of activities carried out to ensure processes are predictable, stable, and consistently operating at a proposed level of performance with normal variation. Do you feel that this is an accurate generic description of this plant?
8. If you do not agree with the description above, how would you characterize the plant operating system?
9. Are there aspects of this plants design that make it significantly different from the process by which standard hydroelectric plants function?
10. What features of the design are especially relevant for the AdvSMR research work?

Facility Staffing:

1. How is the facility staffed?
2. What are the specific staff positions?
3. How many of each position are on staff at any one time?
4. What are the relative roles and responsibilities of each staff position?
5. How were staffing needs determined?
6. Are there defined qualifications for each position?
7. What type of training is provided for each staff position?
8. What tools are available for training, e.g. simulators?
9. How many shifts are used?
10. How is shift turnover managed?
11. What are the major tasks of personnel?
12. How has the current concept of operations been determined (use of engineering analyses, human factors engineering, past operating experience, etc.)?

13. If multiple units are monitored and controlled by the same crew, do single operators monitor multiple reactors and their BOP systems, or are monitoring responsibilities split between the reactor and BOP?
14. How do unit differences impact multi-unit monitoring and control?
15. Describe the normal operations carried out by plant personnel including:
    - Startup
    - Low Power
    - Full Power
    - Shutdown
    - Refueling
16. Describe additional tasks required of personnel for normal operations:

HSI Checklist

What human-system interfaces (HSIs) are used, e.g., alarms, displays, controls, decision/job aids, communications, procedures? Consider the following for each:

  - What is the purpose for each?
  - When is it being used, for what, and how frequently?
  - How is the need to take action identified?
  - When functions are degraded or lost, how do personnel recognize that such a condition exists?
  - How much time (on average) does the operator spend on using the HSI?

- Displays
  - Are displays mainly digital or analog?
  - Are the displays spatially dedicated or configurable?
  - List any observations regarding displays. Are there any human factors issues that stand out?
  - Is there a large screen overview?
- Controls
  - Are controls soft controls or hard controls?
  - Are controls spatially dedicated?
- Alarms
  - Are alarms presented in a list or on alarm panels?
  - Are alarms filtered or prioritized?
  - Approximate number/rate of alarms on a typical day

- Decisions Job Aids
    - What decision or job aids are available?
    - What procedures are available to guide personnel actions?
    - How are the procedures used? (i.e., what is the purpose of the procedure? To guide every single step or to provide high-level guidance?)
    - To what degree do operators have to comply with procedures?
    - What procedures are available to support off-normal conditions and emergencies?
    - Do the procedures reflect multi-unit operations?
    - Are the procedures computerized or paper-based?
        - If CBP, what advanced features are available?
- Are there tasks that are fully controlled/executed by automation?
    - What are the reasons for making this task fully automated?
    - How is the HSI used to inform the operator regarding the task status?
- Are there tasks that are fully manual?
    - What are the reasons for keeping this task fully manual?
- Are there dedicated HSIs for handling off-normal conditions and emergencies?
- What aspects of normal operations may be challenging to personnel, e.g., require knowledge-based behavior or associated with high workload?
- What aspects of emergency operations may be challenging to personnel, e.g., require knowledge-based behavior or associated with high workload?
- Are there any operating modes or transitions that we should consider (e.g., load following)?
    - How does the HSI support these?
    - Did designers seek guidance on how to design the HSI and the human-automation interaction? If so, what (e.g., specific standards)?

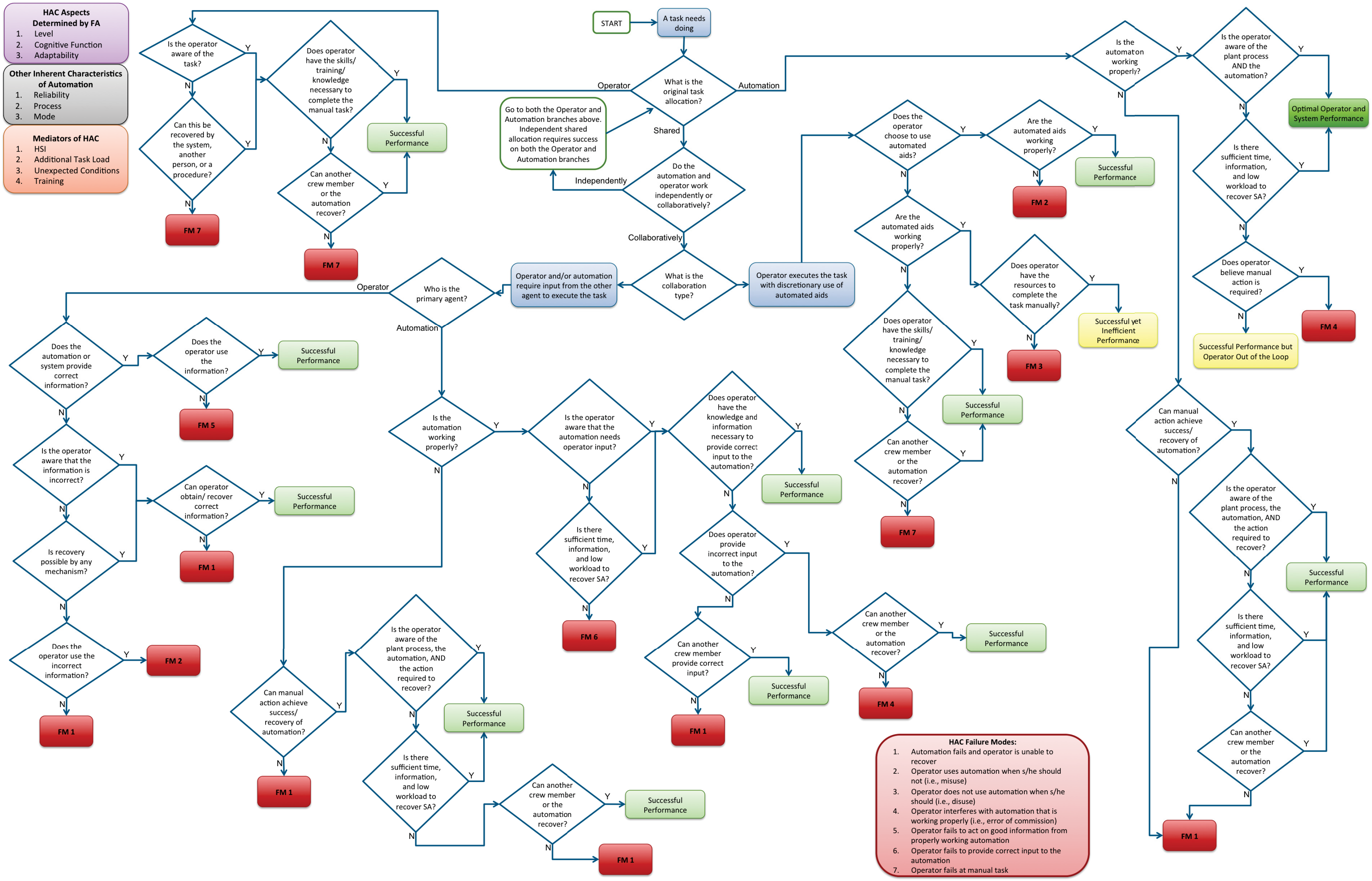
Operator Interview Questions

- Please describe your primary task(s) on a typical day?
- On a typical day, how often does the system require planned manual intervention?
- On a typical day, how often does the system require unplanned manual intervention?
- Do you have any difficulties with the HSI in the control room? e.g., there is information missing, information is in the wrong place, or there is too little or too much information.
    - Please describe
- How would you characterize your trust in the automatic system?

    - Please assign a number between 100%-0%
- Are there any situations/circumstances in which your trust would be higher or lower? Please describe.
- How reliable is the automatic system overall?
    - Please assign a number between 100%-0%
- Do you feel you have an accurate understanding of the process?
- Do you feel you have an accurate understanding of what the automation is doing?
- Are there any situations/circumstances that would cause you to rate the reliability as higher or lower? Please describe.
- Have you experienced conditions of mistrust (i.e., situations where you are unsure the HSI is giving them accurate information)?
- How do you handle these situations of uncertainty and/ or mistrust?
- How do you stay engaged in the process?
- Are there particular parts of the process which create situations of boredom more than others?
- What do you do to combat boredom?

APPENDIX B – MODEL OF HUMAN-AUTOMATION COLLABORATION

This appendix contains the revised model of HAC, which is described in section 3.


HAC Aspects Determined by FA
1. Level
2. Cognitive Function
3. Adaptability
Other Inherent Characteristics of Automation
1. Reliability
2. Process
3. Mode
Mediators of HAC
1. HSI
2. Additional Task Load
3. Unexpected Conditions
4. Training
START
A task needs doing
What is the original task allocation?
Operator
Automation
Shared
Go to both the Operator and Automation branches above. Independent shared allocation requires success on both the Operator and Automation branches
Independently
Do the automation and operator work independently or collaboratively?
Collaboratively
What is the collaboration type?
Operator executes the task with discretionary use of automated aids
Operator and/or automation require input from the other agent to execute the task
Who is the primary agent?
Is the operator aware of the task?
Can this be recovered by the system, another person, or a procedure?
Does operator have the skills/ training/ knowledge necessary to complete the manual task?
Can another crew member or the automation recover?
Successful Performance
FM 7
Is the automaton working properly?
Is the operator aware of the plant process AND the automation?
Optimal Operator and System Performance
Is there sufficient time, information, and low workload to recover SA?
Does operator believe manual action is required?
FM 4
Successful Performance but Operator Out of the Loop
Can manual action achieve success/ recovery of automation?
Is the operator aware of the plant process, the automation, AND the action required to recover?
Is there sufficient time, information, and low workload to recover SA?
Can another crew member or the automation recover?
FM 1
Does the operator choose to use automated aids?
Are the automated aids working properly?
FM 2
Does operator have the resources to complete the task manually?
Successful yet Inefficient Performance
FM 3
Does operator have the skills/ training/ knowledge necessary to complete the manual task?
Can another crew member or the automation recover?
Does the automation or system provide correct information?
Does the operator use the information?
FM 5
Is the operator aware that the information is incorrect?
Can operator obtain/ recover correct information?
Is recovery possible by any mechanism?
Does the operator use the incorrect information?
Is the automation working properly?
Is the operator aware that the automation needs operator input?
Is there sufficient time, information, and low workload to recover SA?
FM 6
Does operator have the knowledge and information necessary to provide correct input to the automation?
Does operator provide incorrect input to the automation?
Can another crew member provide correct input?
Can another crew member or the automation recover?
Can manual action achieve success/ recovery of automation?
Is the operator aware of the plant process, the automation, AND the action required to recover?
Is there sufficient time, information, and low workload to recover SA?
Can another crew member or the automation recover?
Y
N
HAC Failure Modes:
1. Automation fails and operator is unable to recover
2. Operator uses automation when s/he should not (i.e., misuse)
3. Operator does not use automation when s/he should (i.e., disuse)
4. Operator interferes with automation that is working properly (i.e., error of commission)
5. Operator fails to act on good information from properly working automation
6. Operator fails to provide correct input to the automation
7. Operator fails at manual task