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SAFETY EVALUATIONS OF ADAPTIVE AUTOMATION

Suitability of Existing Review Guidance

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ABSTRACT

The staff of the U.S. Nuclear Regulatory Commission (NRC) uses the human factors engineering (HFE) guidance in NUREG-0711 and NUREG-0700 to perform safety reviews of control room designs and technologies. Since new technologies continually evolve, the NRC is committed to keeping its guidance up-to-date with these advances. One such advance is the emerging use of adaptive automation (AA). The objective of this report was to evaluate whether the NRC's HFE guidance is sufficiently comprehensive to support AA system reviews; and when it is not, to identify what additional guidance is needed. To do so, we evaluated the guidance in NUREG-0711 and NUREG-0700 for reviewing the allocation of functions to AA systems, AA system design, and the evaluation and validation of AA systems. The results revealed that the available guidance is sufficient to review some aspects of AA, such as the monitoring of AA systems, detection of AA system failure, and the general evaluation/validation of AA systems. However, there are numerous areas where the guidance is insufficient to review the unique design characteristics of AA systems, such as the design of AA configurations and triggering conditions. Additional research is needed to provide more comprehensive guidance that can be used to evaluate these unique characteristics.

This RIL should be used as a companion piece to RIL-2020-05 (O'Hara & Higgins, 2020). The conclusions of this report rely heavily on the results from RIL-2020-05.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

AA	adaptive automation
DOA	degree of automation
EID	ecological-interface design
FA	function allocation
FRA	functional requirements analysis
HFE	human factors engineering
HSI	human-system interface
I&C	instrumentation and control
IEEE	Institute of Electrical and Electronics Engineers
ISV	integrated system validation
LOA	level of automation
MUX	multiplexer
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission (U.S.)
OFS	operator functional state
SA	situation awareness
SRP	Standard Review Plan
T&E	test and evaluation
U.S.	United States

1 INTRODUCTION

The Reactor Oversight Process is based on a regulatory framework that describes how best to protect the public health and safety (NRC, 2000). It identifies human performance as a "cross-cutting" area to be addressed. The U.S. Nuclear Regulatory Commission (NRC) addresses human performance, in part, by conducting human factors engineering (HFE) safety reviews of the HFE programs of applicants for construction permits, operating licenses, standard design certifications, and combined operating licenses for nuclear power plants (NPPs). The purpose of these reviews is to verify that acceptable HFE practices and guidelines are incorporated into an applicant's HFE program. This helps to ensure that personnel performance and reliability are appropriately supported.

The HFE review methodology is based on a systems engineering approach (e.g., IEEE, 2005) and embodies two key principles for addressing the HFE aspects of design: a "top-down" methodology and "life-cycle" considerations. "Top-down" refers to an approach that starts at the "top," (i.e., with the plant's high-level mission and goals). These are divided into the functions necessary to achieve the goals which are then allocated to human and system resources. Functions are broken down into tasks and analyzed to identify the human-system interfaces (HSIs), (e.g., alarms, displays, and controls that will be needed to support operator performance). Tasks are arranged into work activities to be performed by individual crewmembers and teams. The detailed design of the HSI, procedures, and training represents the "bottom" of the top-down process. HFE should be addressed over the plant life-cycle (e.g., concept planning through operations).

Reflecting these principles, the NRC's safety review methodology examines the applicant's HFE design process, as well as its products (e.g., the main control room). Chapter 18 of the *Standard Review Plan,* SRP, (NUREG-0800) provides high-level guidance for conducting HFE reviews (NRC, 2016). Chapter 18 directs the reviewer to the detailed review criteria in the *HFE Program Review Model* (NUREG-0711) (O'Hara et al., 2012) for evaluating an applicant's HFE design process and the *Human System Interface Design Review Guidelines* (NUREG-0700, Revision 3) (NRC, 2020) for evaluating the products, specifically the control room and HSI design. NUREG-0711 and NUREG-0700 are described in greater detail in Section 2 of this report.

Over time, new technologies evolve and are incorporated into plant and control room designs. Similarly, new HFE methods and tools are developed to analyze, test, and evaluate them. Given the important role HFE review guidance plays in the staff's review process and in meeting its mission of ensuring public safety, it is imperative for the NRC to keep its guidance up-to-date with these advances.

One advance in technology that impacts operational practices and, potentially, plant safety is the emerging use of adaptive automation. Adaptive automation (AA) is the dynamic, real-time change in the degree of automation (DOA) a system employs that is triggered by conditions such as poor task performance and high operator workload. AA has been discussed in the literature as a promising means of mitigating human performance issues that often arise in highly automated systems, such as loss of situation awareness, complacency, and degrading of manual skills. RIL-2020-05 (O'Hara & Higgins, 2020)[1] stated that AA improved task

1 RIL-2020-05 (O'Hara & Higgins, 2020) is the primary reference used throughout this report and was based on a previous report by O'Hara & Higgins, 2017, with the same title.

performance and the operator's understanding of automation. Although the research was limited, it suggested that AA also supported operator recognition of automation failure and recovery. There is limited HFE guidance available to support designers and reviewers of AA systems. Despite recent standards and guidelines acknowledging AA as a design option, relatively few guidelines are available to support the function allocation process and the detailed design of the key aspects of AA systems. Thus, a research need to develop HFE guidance available to support the design and review of AA systems was identified (see RIL-2020-05, Section 8.3.3, HFE Guidance for AA Implementation and Review). For a full detailed description of AA, please review RIL-2020-05, as the details will not be reviewed again here.

Because limited guidance can impact the ability of the NRC staff to conduct thorough reviews of AA systems, this report identifies the specific gaps that exist in NRC's guidance for the review of AA systems.

2 OBJECTIVES AND METHODOLOGY

2.1 Objective

An applicant's AA system is reviewed by the NRC staff using the HFE guidance in NUREG-0711 and NUREG-0700. The objective of this report is to evaluate whether the guidance is sufficiently comprehensive to support AA system reviews; and when it is not, to identify what additional guidance is needed.

2.2 HFE Review Guidance

When reviewing the HFE aspects of NPP designs, the staff focuses on:

- the key design process analyses in the applicant's HFE program that lead to decisions about the technology to be used and its required characteristics
- the key features and functions that describe how the technology is implemented and how operators interface with it

NUREG-0711 is used to review the applicant's design process and NUREG-0700 is used to review the implementation of the technology. NUREG-0711's approach is based on the concept that the HFE aspects of NPPs should be developed, designed, and evaluated based on a structured systems analysis using accepted HFE principles. The reviews address 12 elements of an HFE program as shown in Figure 2-1.

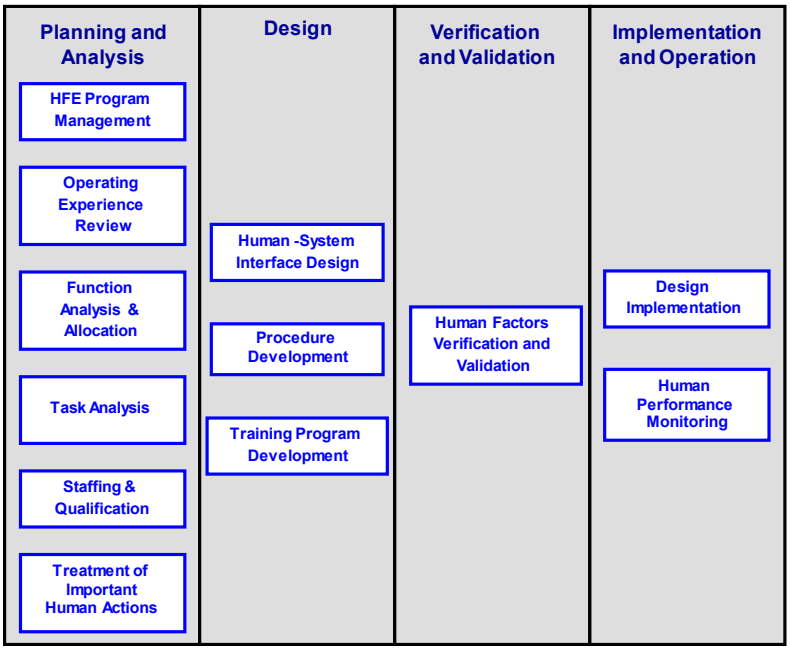

Figure 2-1 NUREG-0711 review elements

The NRC uses NUREG-0700 to evaluate the products of the HFE program, specifically the control room and HSI design. The guidance addresses the physical and functional characteristics of HSIs. The HSI review topics are identified in Table 2-1.

Table 2-1 NUREG-0700 HSI Review Topics

1	Information Display
2	User-Interface Interaction and Management
3	Analog Display and Control Devices
4	Alarm System
5	Safety Parameter Display System
6	Group-View Display System
7	Soft Control System
8	Computer-Based Procedure System
9	Automation System
10	Communication System
11	Workstation Design
12	Workplace Design
13	Maintainability of Digital Systems
14	Degraded HSI And I&C Conditions

2.3 Use of HFE Guidance to Review AA Systems

The guidance evaluation was organized into three topics: Allocation of functions to AA, AA system design, and evaluation and validation of AA systems. Each topic is described below.

Allocation of Functions to AA

For the review of an AA system to become necessary, an applicant must decide to implement AA in their design. Ideally, this occurs in their allocation of function analyses, where AA is identified as the appropriate type of automation for a function or task. An applicant's allocation of functions is reviewed using the guidance in NUREG-0711, Section 4, Functional Requirements Analysis and Function Allocation. To evaluate whether the guidance is sufficiently comprehensive to support the review of the allocation of functions to AA system, that guidance was examined in detail to determine whether it provides a basis to review AA.

AA System Design

If an applicant's function allocation identifies AA as the type of automation to use, the next step is to design the way AA is to be implemented.

To evaluate whether the guidance is sufficiently comprehensive to support the review of an AA system implementation, the characterization of AA developed in RIL-2020-05 was used. A technology characterization is a fundamental aspect of the NRC's guidance development process (O'Hara et al., 2008). The first step in developing guidance for any topic, such as AA, is to develop a characterization in order to identify the aspects of a new technology for which review guidance is needed. To accomplish this, existing and development systems were reviewed, as well as related research, to identify the characteristics and functions along which the topic can be defined. The characterization is important because it provides a structure for developing and organizing the guidance. The characterization also provides a reviewer with a framework for requesting information from applicants during a review. Knowing what questions

to ask is one vital aspect of conducting a design review. The selection of such questions is typically guided by the NRC's primary HFE guidance documents, such as NUREG-0700. However, an understanding of the important aspects of the design that might impact performance can also be provided by technical reports, such as in RIL-2020-05.

In this report, the characterization identified aspects of AA that the NRC staff should review, thus, it provides a good framework with which to determine whether the existing guidance is sufficient to perform a review. A similar approach used to examine the key human performance aspects related to the design and operation of small modular reactors (O'Hara, Higgins & D'Agostino, 2015).

Guidance for the review of automation is contained in NUREG-0700, Section 9, Automation System. The guidelines are organized into subsections, as shown in Table 2-2. Section 9.6 specifically addresses AA. Since AA systems incorporate automation features related to general automation characteristics, such as automation levels, that guidance is applicable as well.

Table 2-2 HSI Review Guidance for Automation Systems

9 AUTOMATION SYSTEM
9.1 Automation Displays
9.2 Alerts, Notifications, and Status Indications
9.3 Interaction and Control
9.4 Automation Modes
9.5 Automation Levels
9.5.1 Shared Control
9.5.2 Operation by Consent
9.5.3 Operation by Exception
9.6 Adaptive Automation
9.7 Computerized Operator Support Systems
9.8 HSI Integration

In addition to Section 9, Section 14 of NUREG-0700 is applicable to the review of AA since it addresses degraded HSI and instrumentation and control (I&C) conditions. Since failure detection and management is applicable to all HSI systems, including automation, the review guidance addressing it are contained in one section. Reviewers are directed to Section 14 in each of the other sections of NUREG-0700 to ensure this aspect of HSI design is addressed for all systems.

Like all HSI systems, AA systems contain general HSI features such as alarms, displays, and soft controls. The general guidance in the other sections of NUREG-0700 is applicable to these characteristics. Thus, the review process of an AA system, or any other HSI system, is based on the multiple sections of NUREG-0700 (see Figure 2-2). However, these general characteristics were not considered in this report. Instead, this review will focus on the unique aspects of AA.

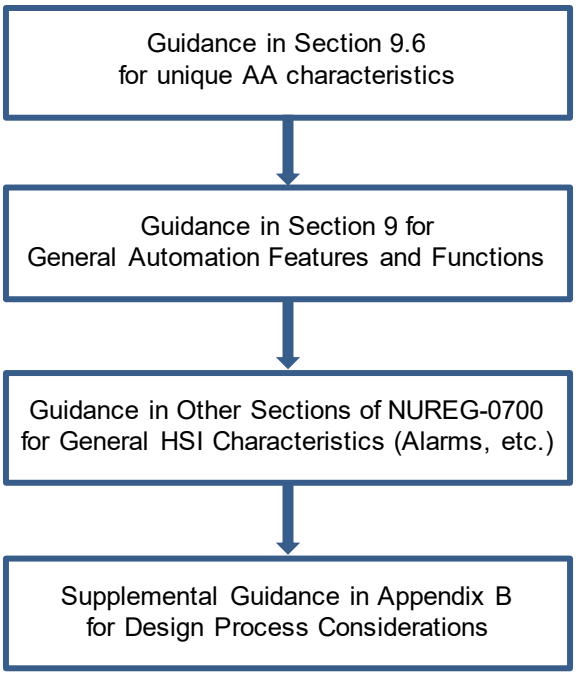

Figure 2-2 Review of an AA system using the guidance in NUREG-0700

The guidelines in the main sections of NUREG-0700 address the physical and functional characteristics of HSIs and not the unique design process considerations that may be important. In the development of review guidelines, aspects of the design process and training that are important to be aware of are identified. Since such considerations are not within the scope of the main design review guidelines, they are contained in NUREG-0700, Appendix B.[2] Supplemental guidance for the design process aspects of automation is contained in Section B.4. For example, in the development of design review guidelines for automation, training emerged as a very significant factor in supporting reliable human-automation interaction. The considerations contained in Appendix B can be addressed by NRC reviewers on a case-by-case basis during specific reviews.

To evaluate whether the guidance is sufficiently comprehensive, the guidance was examined in detail to determine whether it provides a basis to review the characterization of AA system design.

Evaluation and Validation of AA Systems

The applicant performs evaluations and validations of AA systems as they are being designed, once the design is complete, and when it is included in the integrated control room system. An applicant's evaluation and validation are reviewed using the guidance in NUREG-0711, Sections 8, Human-System Interface Design, and 11, Human Factors Verification and Validation.

2 Note that this differs from the more general process review guidance in NUREG-0711. NUREG-0711 does not cover design considerations for specific HSI technologies.

To evaluate whether the guidance is sufficiently comprehensive to support the review of evaluations and validations of AA system, the guidance was examined in detail to determine whether it provides a basis to review AA.

2.4 Categories of Guidance Evaluations

The review guidance in each of the areas described above were evaluated and concluded whether the guideline is:

- sufficient as is for the review of AA systems.
- sufficient at a high-level for the review of AA systems, but the guidance can be improved to better inform the reviewer of specific AA considerations.
- insufficient for the review of AA systems and additional guidance to address the deficiencies (noted in the evaluation) is needed.

3 RESULTS

3.1 Allocation of Functions to AA

In Section 2, it was noted that the review of an AA system becomes necessary when an applicant has decided to implement one in their design. This occurs in their allocation of function, which is reviewed using the guidance in NUREG-0711, Section 4, Functional Requirements Analysis and Function Allocation.

Allocation of function methodologies for AA systems was identified as a research issue in RIL-2020-05 and the lack of guidance in this area was noted (in Section 8.3.1 - Key Enabling Technologies and Issues):

> *Function Allocation* - Prior NRC research has identified an issue on *Function Allocation Methodology to Support Automation Decisions* (O'Hara, Higgins & Pena, 2012). Our evaluation of current advances in FA [function allocation] methodology has not substantially changed the overall conclusion. There remains a need for improvements in the methods available for making AA decisions. While more recent HFE guidance has acknowledged AA has an option and alternative to static allocation, little guidance is available to designers for selecting this alternative or safety reviewers evaluating those decisions.

Thus, while it has already been determined the NRC review guidance is not sufficiently comprehensive to review the allocation of function to AA systems, an evaluation of the detailed guidance will help to identify why and where it needs to be improved. The applicable detailed guidance is in Section 4, Functional Requirements Analysis and Function Allocation, Subsection 4.4, Review Criteria. Each guideline is evaluated below to better understand, specifically, how the guidance is insufficient and what additional guidance is needed.

Review Guideline

(5) Applicants should allocate functions to a level of automation (e.g., from manual to fully automatic) and identify the technical bases for the allocations.

Additional Information: The technical basis for the FA [function allocation] can be any one or combination of the factors (see Figure 4-2). For example:

- Functions, or parts of them, may be allocated based on operating experience. Successful operating experience may suggest keeping allocations the same as in predecessor designs and operating experience issues may suggest changing the allocations to address the issues.

- Functions, or parts of them, may be allocated to automation when their performance requirements exceed human capabilities and human error is likely. Conditions that establish a basis for automation (assuming the acceptability of other factors, such as technical feasibility or cost) include when the required response time is very short, when an action must be performed repeatedly, or when very precise control is required.

- Functions, or parts of them, should be allocated to personnel when human knowledge and judgment is needed to ensure reliable function performance, it is

important to keep personnel involved in the actions so they have good situation awareness should they need to perform the function, or to preclude boredom.

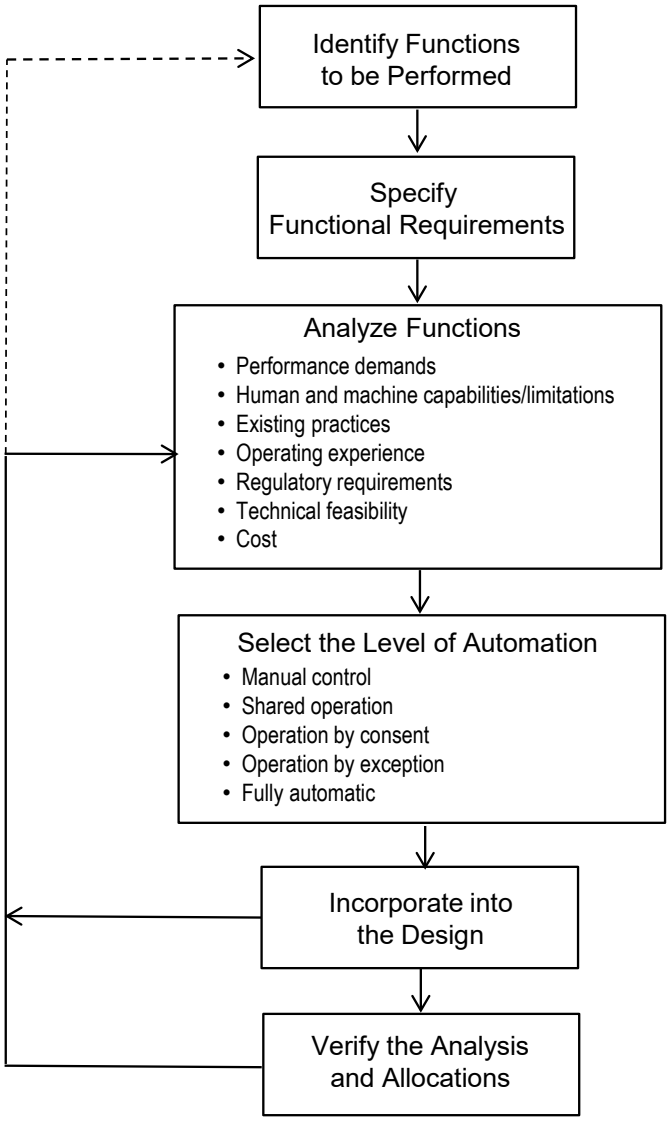

Figure 3-1 Allocation of functions to personnel and automatic systems
(Source is NUREG-0711, Figure 4-2)

Evaluation

This review guideline does not include a technical basis that would reflect the need for AA. The figure only depicts allocation of function options involving static levels of automation. It does not identify AA as an option where the DOA may be variable and where other aspects of automation may change, such as tasks performed by automaton. Thus, this guideline is insufficient for the review of AA systems and additional guidance to address the deficiencies noted above is needed.

Review Guideline

(6) The applicant's FA should consider not only the primary allocations to personnel (those functions for which personnel have the primary responsibility), but also their responsibilities to monitor automatic functions, detect degradations and failures, and to assume manual control when necessary.

Evaluation

This guideline is stated at a fairly high level in that it identifies primary allocations and failure detection in general. As such, it can be applied to AA systems. A slight change is suggested to better accommodate the review of AA systems. The guideline identifies the "primary responsibility" of personnel. In AA systems, the primary responsibilities may change depending on the DOA configuration in effect at a given time. That possibility can be acknowledged in the review guideline. Thus, this guideline is sufficient at a high-level for the review of AA systems, but the review guidance can be improved to better inform the reviewer of specific AA considerations.

Review Guideline

(7) The applicant should describe the overall role of personnel by considering all functions allocated to them.

Additional Information: The FA to personnel and automation is considered on a function-by-function basis. However, the overall personnel role is an aggregate of all functions allocated to them. While on an individual basis, a single function allocation to personnel may be justified, allocations should also be considered in the context of other responsibilities personnel have to help ensure that together all functions allocated to personnel are acceptable and do not interfere with each other.

Evaluation

This guideline assumes that the operator's role and responsibilities are static and does not address the possibility that the role of personnel (and automation) in AA systems may dynamically change. Thus, this guideline is insufficient for the review of AA systems and additional guidance to address the deficiencies noted above is needed.

Review Guideline

(8) The applicant should verify that the FRA [functional requirements analysis] and FA accomplish the following:

- all the high-level functions needed to achieve safe operation are identified.
- all requirements of each high-level function are identified.
- the allocation of functions to humans and automatic systems assures a role for personnel that takes advantage of human strengths and avoids human limitations.

Evaluation

The key consideration in this guideline that is related to AA is the third bullet, and the consideration applies to any automation system, including AA. Thus, this guideline is sufficient, as is, for the review of AA systems.

It should also be noted, however, that reviewers should carefully consider FRA and FA when multiple levels of automation are employed. There may be situations when a shift in automation strategy may put operators in situations that require human intervention in a manner inconsistent with their strengths or limitations. This effect may be more pronounced with more complex AA systems such as ones that use multiple LOA.

3.2 AA System Design

As discussed in Section 2, once functions are allocated to AA, the applicant's next step is to design the way the automation will be implemented. To evaluate whether the guidance is sufficiently comprehensive to support the review of an implemented AA system, the characterization of AA developed in RIL-2020-05 was used as a surrogate for the aspect of AA to be reviewed. The characterization has three main elements: Configurations, Triggers, and HSI. Each is briefly described below. The reader is referred to the earlier report for additional detail. Then, the review guidance available to address the characteristics are identified and evaluated.

3.2.1 Configurations

A configuration is a DOA that defines the roles and responsibilities of both operators and automation. AA configuration changes involve changes in automation dimensions, such as levels of automation and generic tasks. There are several decisions that are important to the design of configurations that have potential consequences for human performance; hence they should be addressed in an HFE safety review. They are:

1. Configuration Definition - Should the configurations be predefined or defined in real time?

2. DOA Change Selection - What type of DOA changes should be used to support operator task performance?

3. Number of Configurations - How many individual configurations should be designed?

4. Configuration Timing - What is the minimum length of time configurations should remain in effect?

These aspects of configurations are discussed below.

It is noted that these aspects of AA system design were identified in RIL-2020-05 as a technical issue (in Section 8.3.1 - Key Enabling Technologies and Issues):

> *Configurations* – While AA systems provide configurations offering operators different DOAs, we do not know how many are appropriate or what the minimum length of time configurations should remain in effect before shifting them becomes disruptive. An

additional area to be addressed is the potentially disruptive effects of configuration changes, especially when triggered by conditions other than operator command.

Thus, while it was already determined the NRC review guidance in not sufficiently comprehensive to fully review the configurations of AA systems; an evaluation of the detailed guidance will help to identify why and where it needs to be improved.

3.2.1.1 Configuration Definition

Issue

The issue here is whether configurations should be defined by designers and built into the AA system or by operators to give them the flexibility to define role changes in real time. There is a tradeoff between these options. When predefined, operator and automation roles can be clearly defined, and operators can be trained for each configuration. Further, the DOA configuration options can be designed into the HSI so they can be easily changed. However, the configurations will be somewhat general and may not be exactly tailored to the current situation. Providing operators the flexibility to define changes in real time would enable such precise tailoring. However, the workload to do so might be high and training on the changes in operator responsibilities would not address every possible configuration change.

Review Guidance

NUREG-0700, Guideline 9.6-1 addresses this aspect of AA design:

> 9.6-1 Predefined Roles and Responsibilities
> Adaptive automation should use predefined definitions of the roles and responsibilities of human and machine agents.
>
> *Additional Information*: This will minimize the workload due to changing the automation configuration and will support the operator's understanding of automation by limiting the number of available options.

Evaluation

This guideline states that predefined configurations should be used. This is reasonable from a workload position. However, the guideline should acknowledge the potential benefits of providing flexibility to help operators better tailor AA to the demands of the current situation. Thus, this guideline is sufficient at a high-level for the review of AA systems, but the review guidance can be improved to better inform the reviewer of specific AA considerations for giving operators the flexibility to define role changes in real time.

3.2.1.2 DOA Change Selection

Issue

Configuration changes can reflect changes in levels of automation, generic task performed, or some other aspect of automation. Designers need to identify the aspects of automation that will underlie DOA changes.

Review Guidance

This aspect of AA design is not addressed in the review guidance in NUREG-0700, Section 9, Automation System. It is addressed in the supplemental guidance in NUREG-0700, Section B.4. As discussed in Section 2, this supplemental guidance identifies aspects of the design process and training that are important to consider. The considerations contained in Appendix B can be addressed by NRC reviewers on a case-by-case basis during specific reviews.

Section B.4 contains the following supplemental guideline (only the applicable portion of the guideline is shown):

(2) *Automation Design Characteristics* – The following considerations should be addressed in the detailed design of automation.

- *Adaptive Automation* - Adaptive automation (AA) has a positive effect on the operator's understanding of automation, situation awareness, and ability to recover when the automation fails. AA is known to help support task performance and manage workload, especially for lower-level cognitive functions (information acquisition and action implementation functions). The situation is more complex when it is applied to higher-level cognitive functions (information analysis and decision making), and performance may be disrupted.

Evaluation

Since this aspect of AA design is not addressed in the review guidance in NUREG-0700, Section 9, the guidance is insufficient for the review of AA systems and additional guidance is needed on employing DOA configuration changes that go beyond levels of automation (LOA).

The supplemental guidance in Appendix B of NUREG-0700 also does not adequately address the complexity of DOA changes. Generally, it does address the potential differential effects of automating generic tasks. However, as noted above, DOA changes can be based on other aspects of automation as well. RIL-2020-05 emphasized how these changes should be tied to the task demands and operator needs, but these considerations are not adequately addressed.

3.2.1.3 Number of Configurations

Issue

If an AA system has too many configurations, it may lead to potential issues (e.g., it becomes difficult for operators to keep track of the different configurations and the relative responsibilities when each is in effect).

Review Guidance

The NRC review guidance does not address this aspect of AA design.

Evaluation

Since this aspect of AA design is not addressed in the review guidance in NUREG-0700, Section 9, the guidance is insufficient for the review of AA systems and additional guidance is needed on the number of configurations employed in AA systems.

3.2.1.4 Configuration Timing

Issue

Configurations are operative for a period and stay in effect until another trigger either changes the configuration or terminates the automation. What is the minimum length of time configurations should remain in effect? It is likely that too many rapid changes will be disruptive and confusing and lead to difficulty keeping track of the relative responsibilities of all agents. Configurations should remain in effect long enough to not be confusing to operators.

Review Guidance

This aspect of AA design is not addressed in the review guidance in NUREG-0700, Section 9. It is addressed in the supplemental guidance in NUREG-0700, Section B.4 (only the applicable portion of the guideline is shown):

(2) *Automation Design Characteristics* – The following considerations should be addressed in the detailed design of automation.

- *Adaptive Automation* - In adaptive automation, there can be a cognitive cost to switching between LOAs that can disturb ongoing task performance. Thus, the design of the triggering mechanisms must be addressed carefully to minimize this issue and should be easily accomplished with the HSI.

Evaluation

Since this aspect of AA design is not addressed in the review guidance in NUREG-0700, Section 9, the guidance is insufficient for the review of AA systems and additional guidance is needed on DOA changes beyond LOA.

The supplemental guidance in Appendix B of NUREG-0700 also does not adequately address the complexity of DOA changes which involve more than LOA changes. Further, the guidance does not directly address configuration length. Thus, this guideline is insufficient for the review of AA systems and additional guidance is needed.

3.2.2 Triggers

Triggers are the conditions that initiate changes in AA configurations. They include:

- *Operator commanded* – a configuration change is made when commanded by the operator. Plant start-ups and mode changes are typically performed in this manner.

- *Operator functional state* – a configuration change is made when an operator state threshold is reached (e.g., high workload level, low situation awareness (SA), and fatigue). This class of triggers requires monitoring of operator state (e.g., using physiological measures).

- *Operator performance* – a configuration change is made based on a change in operator task performance, such as when an operator fails to perform a task or when performance falls below a threshold for acceptability.

- *System state* – a configuration change is made when a system state change is detected or needed based on the current configuration.

- *Event based* – a configuration change is made when specific situations are detected.

- *Hybrid* – more than one class of the above triggers is used, such as when a configuration change is made when specific situations are detected.

There are several decisions that are important to the design of triggers that have potential consequences for human performance; hence they should be addressed in an HFE safety review. They are:

1. Appropriateness of Trigger Categories - Which category of trigger or combination of categories is appropriate for the specific AA system?

2. Invoking Thresholds - When should the trigger cause a shift in AA's configuration, the "invoking threshold?"

These aspects of triggers are discussed below.

It should be noted that this aspect of AA system design was identified RIL-2020-05 as a technical issue (in Section 8.3.1 - Key Enabling Technologies and Issues):

> *Triggers* – While the triggering conditions used in the research studies reviewed were generally effective at switching AA configurations, more research is needed on those using measures to assess operator functional state (OFS). OFS is often predicted using physiological measures. Researchers have used single physiological measures or multiple measures. A question remains as to which measures are best and how they should be integrated to get reliable OFS predictions. Further, some researchers recommend the use of hybrid triggers (i.e., the use of triggers from more than one category). A research question remains as to which ones provide the most reliable triggers and how they should be combined to trigger DOA changes. Finally, a key consideration is the invoking threshold (i.e., the specific point at which the trigger changes). Research is needed on determining these thresholds and on how to implement them so configurations shift in an acceptable manner.

Thus, while it has already been determined the NRC review guidance is not sufficiently comprehensive to fully review triggers for AA systems, an evaluation of the detailed guidance will help to identify why and where it needs to be improved.

3.2.2.1 Appropriateness of Trigger Categories

Issue

Designers must identify which category of triggers or combination of categories is appropriate for their AA applications. Failure to use an appropriate trigger or combination of triggers may result in configurations not changing when they should or configurations changing when they should not. This would minimize the value of the AA system and may detract from operator performance when the DOA does not match current needs or when configurations change unexpectedly.

Review Guidance

The NRC review guidance does not address this aspect of AA design.

Evaluation

Since this aspect of AA design is not addressed in the review guidance in NUREG-0700, Section 9, the guidance is insufficient for the review of AA systems and additional guidance is needed addressing the category of trigger or combination of categories that are appropriate for specific AA system applications. The issue noted above is included here regarding the use of measures needed to get reliable OFS predictions.

3.2.2.2 Invoking Thresholds

Issue

Part of trigger design is defining the invoking thresholds they will use to initiate shifts in the AA systems configurations. To illustrate the issues involved in this aspect of trigger design, consider an adaptive system using task performance as a trigger. The configuration is changed based upon predefined performance setpoints. If performance is drifting above and below this setpoint every few seconds, the automation configuration will shift every few seconds as well. This could be very distracting to the operator and disruptive to performance. The issue can be even more significant with physiological measures. Human physiological parameters can change rapidly which, if they cross the setpoints established to trigger configuration changes, can lead to rapid changes in the DOA.

Review Guidance

This aspect of AA design is not addressed in the review guidance in NUREG-0700, Section 9. It is addressed in the supplemental guidance in NUREG-0700, Section B.4 (only the applicable portion of the guideline is shown):

(2) *Automation Design Characteristics* – The following considerations should be addressed in the detailed design of automation.

- *Adaptive Automation* - In adaptive automation, there can be a cognitive cost to switching between LOAs that can disturb ongoing task performance. Thus, the design of the triggering mechanisms must be addressed carefully to minimize this issue and should be easily accomplished with the HSI.

Evaluation

Since this aspect of AA design is not addressed in the review guidance in NUREG-0700, Section 9, the guidance is insufficient for the review of AA systems and additional guidance is needed on defining invoking thresholds.

The supplemental guidance in Appendix B of NUREG-0700 does not directly address the design of invoking thresholds.

3.2.3 HSIs

HSIs provide the link between the operator and automation. HSIs are made up of the alarms, displays, controls, and communications necessary for operators to interact with the AA system. There are several decisions that are important to the design of HSIs that have potential consequences for human performance; hence they should be addressed in an HFE safety review. They are:

1. Monitoring - How is situation awareness (SA) and the detection of degraded conditions supported?

2. Control - How do operators configure and control automation and how is workload managed?

3. Communication - How is communication between operators and automation fostered?

These aspects of HSI design are discussed below.

It should be noted that HSIs for AA systems was identified in RIL-2020-05 as a technical issue (in Section 8.3.1 - Key Enabling Technologies and Issues):

> *HSIs* – HSIs provide the link between the operator and automation. We discussed the work on EID (ecological-interface design) displays to support monitoring and failure detection and delegation-style interfaces to support configuration awareness and workload management. We also discussed the work on automaton etiquette to help make automation's communication with its human teammates more acceptable and less disruptive. While all this research is promising, much more needs to be done, especially in light of the fact that automaton is becoming more interactive. In addition, the use of adaptive HSIs to support interface management and reduce the workload associated with it looks promising. Additional research is needed to identify applications in the nuclear plant operations and to ensure that automation's performance of these tasks does not disrupt operator tasks or create confusion.

Thus, it has already been determined that the NRC review guidance in not sufficiently comprehensive to fully review the HSIs for AA systems, an evaluation of the detailed guidance will help to identify why and where it needs to be improved. Each guideline is evaluated below to better understand specifically how the guidance is insufficient and what additional guidance is needed.

3.2.3.1 Monitoring

Issue

Monitoring is a key task that nuclear plant operators perform using control room HSIs. They monitor overall plant performance as well as systems and subsystems supporting that performance. A long-standing issue that operators have in highly automated system is the monitoring of automation. One factor contributing to this issue is poorly designed HSIs. The work on EID interfaces identified in the "HSIs" issue above, reflects the need to design better means to monitor automation performance.

With respect to AA, monitoring may be more significant because the roles and responsibilities of both operators and automation will change, unlike the case with static automation. Ensuring operator awareness of the current configuration and when configuration shifts are triggered are key considerations in the design of HSIs for AA systems

An important consequence of monitoring issues is that operators are less likely to be aware of automation degradations and failures. While HSIs provide alerts, alarms, and displays to support monitoring, how well HSIs support SA and the detection of degraded conditions is a significant consideration in the review of an AA system.

The evaluation is divided into two parts. In the first part, the review guidance for general monitoring is evaluated. In the second part, the review guidance for detection of degraded conditions will be evaluated.

Guidance for the Review of General Monitoring

There is considerable guidance for the review of automation monitoring in NUREG-0700, specifically:

- Section 9.1, Automation Displays
- Section 9.2, Alerts, Notifications, and Status Indications
- Section 9.6, Adaptive Automation

Review Guideline

9.1-7 Current Responsibilities of Each Agent
When a task is not fully automated, the HSI should identify the roles and responsibilities of human and automation agents.

Additional Information: Within a human-automation team, an agent is the one responsible for performing some portion of the task. A clear delineation of the responsibilities of the human and automation agent is important to successful performance. For example, in an automatic system to start-up the plant, some tasks will be performed by the automation and others by the operators, such as opening a manual valve. The task steps requiring operator action should clearly indicate the need for the operator to take the action.

Evaluation

This review guideline identifies the need for operators to maintain awareness of relative roles and responsibilities. This applies to the changing roles and responsibilities that come with configuration changes in AA systems. Thus, this guideline is sufficient, as is, for the review of AA systems.

Review Guideline

9.6-3 Notification of Impending Changes to Automation
If automation can change for reasons other than user's request, the operators should be notified of the impending change with adequate time to override the change if necessary.

Additional Information: Operators should be alerted to impending changes in automation (approach to triggering condition) so they are not surprised and have time to block or override it, if appropriate.

Evaluation

This review guideline addresses the need to make operators aware of configuration shifts that are about to occur with an emphasis on those that are triggered by the system rather than operator request. Thus, this guideline is sufficient, as is, for the review of AA systems.

Review Guideline

9.6-4 Identification of Triggering Conditions
If automation can change for reasons other than by the user's request, the triggering conditions and how automation has changed should be identified.

Additional Information: Adaptive changes can be made based on factors such as measured workload indicators, performance decrements, or other criteria.

Evaluation

This review guideline addresses the need to make operators aware of the causes for configuration shifts. This is important for the operators understanding of why a shift takes place. Thus, this guideline is sufficient, as is, for the review of AA systems.

Review Guideline

9.6-5 Shift Confirmation of Automation Change
The HSI should confirm that a change in automation has taken place.

Additional Information: Adaptive changes should be confirmed positively by the system to prevent operators becoming confused about their current roles and responsibilities.

Evaluation

While the prior review guidelines are intended to ensure operator awareness that a shift will take place and why, this guideline supports awareness that the shift has taken place. Thus, this guideline is sufficient, as is, for the review of AA systems.

<u>Guidance for the Review of the Detection of Degraded Conditions</u>

Review guidance for the detection of degraded conditions in provided in Section 9.2, Alerts, Notifications, and Status Indications, and Section 14, Degraded HSI and I&C Conditions. For the guidance in Section 14, only the guideline titles are provided. See NUREG-0700 for the complete text of these guidelines. Collectively, this guidance will be evaluated for its support of AA system degradation and failure.

Section 9.2, Alerts, Notifications, and Status Indications

9.2-3 Notification of the Failure of Automation Initiation
When automation can be automatically actuated, operators should be alerted to the failure of automation to start.

Section 14, Degraded HSI and I&C Conditions

14.1 HSIs for Monitoring I&C System Conditions
- 14.1-1 Overall Representation of the I&C System
- 14.1-2 Hierarchal Access to Information
- 14.1-3 Indicate Important Status and Performance Parameters
- 14.1-4 Indication of Proper HSI Operation
- 14.1-5 User Requested Status Check

14.2 HSI Response to I&C System Changes
- 14.2-1 Notification of Important Changes
- 14.2-2 Indication of Information Inaccuracy
- 14.2-3 Alarm to HSI and I&C System Failure
- 14.2-4 Information on Failure Cause

14.3 Information Source and Validity
- 14.3-1 Identify Information Source
- 14.3-2 Data Validation
- 14.3-3 Invalid Data
- 14.3-4 Unvalidated Data
- 14.3-5 Display of Data Reliability/Validation

14.4 Backup of HSI and I&C Failures
- 14.4-1 Backup System Availability
- 14.4-2 Support Failure Recovery and Transition to Backup Systems

Evaluation

Section 14 is a new NUREG-0700 section that contains guidance for reviewing the operator's ability to detect and manage degraded HSI and I&C conditions, such as the degradation of an automation system. Any unique degradation and failure modes that distinguish AA systems from other automated systems nor specific conditions that need to be addressed were not identified in a review. Thus, this guidance is sufficient, as is, for the review of AA systems.

3.2.3.2 Control

Issue

HSIs need to provide controls for all operator interactions with automation (e.g., to configure automation and control what it does). AA has some unique control considerations:

- change AA's current configuration (an operator-commanded trigger).
- override a configuration change triggered by a non-operator commanded trigger.

- interactions with functions provided by delegation-type interfaces.
- some AA system may also have controls to modify configurations in real time.

Operator interaction with automation imposes workload. A key consideration is how this workload is managed. If automation control is simple and imposes minimum workload, operators are likely to use it effectively. If the control of automation is cumbersome and imposes high workload, operators may refrain from interacting with it in an effort to manage overall workload. The work on delegation-type interfaces identified in the "HSIs" issue above, reflects the need to design better means to interact with AA.

Review guidance for the control of AA is provided in Section 9.6, Adaptive Automation. General guidance for the control of automation is contained in NUREG-0711, Section 9.3, Interaction and Control. However, Section 9.3 does not address the unique control requirements for AA; thus, it was not evaluated.

Review Guidance

9.6-2 Operator Control of Automation Shifts
The HSI should provide controls for implementing changes in automation.

Evaluation

This guideline addresses the unique AA control requirement for changing AA's current configuration through an operator-commanded trigger, the first unique control requirement identified above. Thus, this guidance is sufficient, as is, for the review of AA systems.

However, NUREG-0700 guidance does not address the last three of four unique AA control considerations. The last two unique control requirements will require further definition before generic review guidance can be developed and some of the required controls may be system specific. The latter two bullets involve more complex controls where workload issues are more likely to arise. Since these aspects of AA design are not addressed in the review guidance in NUREG-0700, Section 9, the guidance is insufficient for the review of AA systems and additional guidance is needed to address the override of configuration changes triggered by non-operator commanded triggers, interactions with functions provided by delegation-type interfaces (noted in the "HSIs" issue above), and controls to modify configurations in real time, if applicable.

3.2.3.3 Communication

Issue

In RIL-2020-05, the importance of human-automation interaction from the perspective of teamwork was discussed. AA systems are likely to be more interactive with operators than static automation and can be viewed a part of a multi-agent system. The current limitations of using teamwork models to identify the dimensions important to human-automation interaction and to define issues addressing them was also discussed (in Section 8.3.1, Key Enabling Technologies and Issues):

Teamwork - If automation is part of a multi-agent team, then what model of teamwork should be used to specify its characteristics? There is currently no answer to this question.

Additional work is needed to identify appropriate teamwork models that incorporate an understanding of the differences between human and automation agents.

Despite the absence of a comprehensive teamwork model to guide the design of how automation agents interact with their human teammates, the key consideration for any team is communication. Communications should be timely with respect to the importance of the information and not distracting and disruptive to the crew's ongoing task performance. The designer's challenge is to design communication to be minimally disruptive given the importance of the information to be communicated.

RIL-2020-05 suggested that modeling communication based on human teamwork may be appropriate. That is, communication design should follow the rules of etiquette found in the communication between operator teammates. However, it may be premature to recommend such an approach until further research is conducted. Thus, at the present time, HFE guidance for communications should ensure it is effective and non-disruptive.

This issue is not unique to AA systems. AA systems differ from other forms of automation because of the amount of communication that is likely. Since AA systems may dynamically change DOA configurations in real-time, it can be expected that they will require more communication between human and automation agents.

General review guidance for communications between operators and automation is provided in Section 9.3, Interaction and Control. Since the guidance is not specific to AA, it will be collectively evaluated.

Review Guidance

9.3-5 Feedback for Operator Inputs
Automated systems should provide clear feedback about the receipt of user's inputs and the confirmation that resulting actions are complete.

9.3-6 Support for Operator Queries
The HSI should enable users to query automation about the basis for its actions and recommendations to support the tracking, interpreting, and verifying of automation's recommendations.

9.3-7 Provide User Control of Level of Detail
When automation explanations are lengthy, the HSI should support users in adjusting the level of detail.

9.3-8 Automation Communications with Operators
The HSI should support communications from the automation when necessary, such as when an obstacle to completing a goal is encountered or when information is needed from users (e.g., data that the automation cannot access through the I&C system).

9.3-9 Minimize Queries of the Users
Automation's queries of the user for information should be minimized.

9.3-10 Unobtrusive Communication
Communications from automation should not be intrusive and should not disrupt the user's ongoing tasks unless necessary.

9.3-12 Monitoring of Personnel Actions
To the extent possible, automation should monitor operators' activities and the HSI should alert operators to potential errors of commission (taking an incorrect action) and omission (failing to take a needed action).

Evaluation

This review guidance addresses the general need for effective and non-disruptive communication between human and automation agents. Thus, within this scope, the guidance is sufficient, as is, for the review of AA systems.

However, as noted above, there is a broader issue of team characteristics that will require additional research to develop the technical basis on which additional review guidance can be developed.

3.3 Evaluation and Validation of AA Systems

The applicant performs evaluations and validations of AA systems as they are being designed, once the design is complete, and when it is included in the integrated control room system. An applicant's evaluations and validations are reviewed using the guidance in NUREG-0711, Sections 8, Human-System Interface Design, and 11, Human Factors Verification and Validation.

To evaluate whether the guidance is sufficiently comprehensive to support the review of evaluations and validations of AA system, that guidance was examined in detail to determine whether it provides a basis to review AA.

3.3.1 Test and Evaluation

Section 8, HSI Design

8.4.6 HSI Tests and Evaluations

NUREG-0711 states that tests and evaluations (T&Es) of concepts and detailed design features are conducted during the process of developing HSIs to support design decisions. The section provides review guidance for two types of T&Es:

- Trade-off evaluations are comparisons between design options, based on aspects of human performance that are important to successful task performance, and to other design considerations.

- Performance-based tests involve assessing personnel performance, including subjective opinions, to evaluate design options and design acceptability.

8.4.6.1 Trade-off Evaluations

Review Guideline

(1) In comparing design approaches, the applicant should consider those aspects of human performance important to performing tasks. The applicant should take into account the following factors when developing criteria to apply in selecting one design approach over another:
- personnel-task requirements
- human-performance capabilities and limitations
- HSI-system performance requirements
- inspection and testing needs
- maintenance demands
- use of proven technology and the operating experience of predecessor designs

Additional Information: Including selection criteria for human performance will help to ensure that the differential effects of design options on human performance can be assessed, along with other considerations. For example, when analyzing trade-offs between using either a mouse or a touch screen as a computer-input device, the fatigue caused by using the device and the time required to perform actions using each device should be considered.

Evaluation

A limitation of this review guideline when considering automation systems in general, and AA systems in particular, is their potential impact on human performance (e.g., SA and workload). Human performance demands and the potential for automation to impact performance should be identified. This consideration should include managing conditions where the automated system degrades or fails. Thus, this guideline is insufficient for the review of AA systems and additional guidance addressing human performance demands and impacts is needed.

Review Guideline

(2) The applicant should state explicitly the relative benefits of design alternatives and the basis for the design approach selected.

Evaluation

There are no unique considerations of AA systems that are needed to apply this review guideline. Thus, this guideline is sufficient, as is, for the review of AA systems.

8.4.6.2 Performance-Based Tests

Review Guideline

(1) The applicant should identify the specific objectives of the tests.

Additional Information: Performance-based tests have many different purposes, such as choosing between design alternatives or verifying that an aspect of the HSI meets performance criteria.

Evaluation

There are no unique considerations of AA systems that are needed to apply this review guideline. Thus, this guideline is sufficient, as is, for the review of AA systems.

Review Guideline

(2) The applicant should base the general approach to testing on the test's objective(s). The following aspects of the tests should be described (note that not all items are applicable to every type of test):
- participants
- testbed
- design features or characteristics of the HSI being tested
- tasks or scenarios used
- performance measures
- test procedures
- data analyses

Evaluation

There are no unique considerations of AA systems that are needed to apply this review guideline. Thus, this guideline is sufficient, as is, for the review of AA systems.

Review Guideline

(3) The conclusions from the tests and their impact on design decisions should be described.

Evaluation

There are no unique considerations of AA systems that are needed to apply this review guideline. Thus, this guideline is sufficient, as is, for the review of AA systems.

3.3.2 Validation

NUREG-0711, Section 11, Human Factors Verification and Validation, contains review guidance for integrated system validation. While the main guidance is in Section 11.4.3, Integrated System Validation, relevant guidance is also presented in Section 11.4.1, Sampling of Operational Conditions. The latter identifies the scenarios to be used for validating the design. A preliminary evaluation was conducted of these two sections to identify which may have implications for AA systems. The results are presented in Table 3-1. Sections 11.4.1.1, Sampling Dimensions, and 11.4.3.5, Performance Measurement were determined to have potential implications for the review of AA systems. Others, while providing guidance for the review of various aspects of the test methodology, would not be impacted by AA. For example, the guidance on review of plant personnel participating in validation tests will not be affected by the fact that an AA system is part of the integrated system.

Table 3-1 Implications of AA for NUREG-0711 Validation Review Guidance

NUREG-0711 Section	AA Implications
11.4.1 Sampling of Operational Conditions	
11.4.1.1 Sampling Dimensions	Yes
11.4.1.2 Identification of Scenarios	No
11.4.1.3 Scenario Definition	No
11.4.3 Integrated System Validation	
11.4.3.1 Validation Team	No
11.4.3.2 Test Objectives	No
11.4.3.3 Validation Testbeds	No
11.4.3.4 Plant Personnel	No
11.4.3.5 Performance Measurement	Yes
11.4.3.6 Test Design	No
11.4.3.7 Data Analysis and HED Identification	No
11.4.3.8 Validation Conclusions	No

Based on this assessment, the guidance in Sections 11.4.1.1, Sampling Dimensions and 11.4.3.5, Performance Measurement was evaluated.

Section 11.4.1.1, Sampling Dimensions

Review Guideline

(1) The applicant should include the following plant conditions:

- I&C and HSI failures and degraded conditions that encompass:
  - The I&C system, including the sensor, monitoring, automation and control, and communications subsystems; (e.g., safety-related system logic and control unit, fault tolerant controller, local "field unit" for multiplexer (MUX) system, MUX controller, and a break in MUX line).

Evaluation

Failures and degradations of an AA system will be identified by this guideline which comprehensively includes these conditions in the sampling process. Thus, this guideline is sufficient, as is, for the review of AA systems.

Review Guideline

(2) The applicant should include the following types of personnel tasks:

- *Automatic System Monitoring* – The sample should include situations in which humans must monitor a risk-important automatic system.

- *Range of Human Cognitive Activities* – The sample should include the range of cognitive activities that personnel perform, including:

- situation assessment (e.g., interpreting alarms and displays to diagnose faults in plant processes and in automated control and safety systems).
- response implementation (e.g., in-the-loop control of plant systems, assuming manual control from automatic control systems, and carrying out complicated control actions).

Evaluation

Personnel tasks associated with an AA system and their associated cognitive demands will be identified by this guideline which comprehensively includes these conditions in the sampling process. Thus, this guideline is sufficient, as is, for the review of AA systems.

Section 11.4.3.5, Performance Measurement

Review Guideline

(1) The applicant should identify the specific plant performance measures applicable to each ISV [integrated system validation] scenario.

Additional Information: They may address the performance of functions, systems, or components.

Evaluation

There are no unique considerations of AA systems that are needed to apply this review guideline. Thus, this guideline is sufficient, as is, for the review of AA systems.

Review Guideline

(2) The applicant should identify the primary task measures applicable to each ISV scenario.

- For each scenario, the applicant should identify the primary tasks operators must perform to accomplish scenario goals, so that such measures can be developed.

  Additional Information: The primary tasks are those involved in carrying out the functional role of the operator in supervising the plant; i.e., monitoring, detection, situation assessment, response planning, and response implementation. Primary tasks should be assessed at a level of detail appropriate to the task's demands. For example, for some simple scenarios, measuring the time to complete a task may suffice. For complicated tasks, especially those described as knowledge-based, it may be appropriate to undertake a fine-grained analysis, such as identifying the task's components, seeking specific data, making decisions, taking actions, and obtaining feedback.

- The measures chosen to evaluate personnel task performance should reflect those aspects of the task that are important to system performance, such as:
  - time
  - accuracy
  - frequency
  - amount achieved or accomplished

- consumption or quantity used
- subjective reports of participants
- behavior categorization by observers

• The analysis of primary tasks will support the identification of errors of omission (primary tasks not performed). Also, any actions and tasks that operators *actually* perform that deviate from the primary tasks should be identified and noted. These actions should be used to identify errors of commission.

Evaluation

AA poses some unique considerations for the identification of primary tasks. Where AA systems are used to support operator performance of primary tasks, the operator's roles and responsibilities will change as AA configurations are dynamically changed. This complicates the identification of primary tasks since they will change based on the current configuration. At a minimum, this situation should be noted in the guidance. A better solution is to address how primary task identification should be addressed when AA systems are deployed. Thus, this guideline is insufficient for the review of AA systems and additional guidance to address changing primary tasks of operators in response to AA configuration changes is needed.

Review Guideline

(3) The applicant should identify the secondary task measures applicable to each scenario.

Additional Information: Secondary tasks are those personnel must perform when interfacing with the HSI, such as navigating through computer screens to find a needed display and to configure HSIs. The measurement of secondary task performance should reflect the demands of the detailed HSI implementation (e.g., time to configure a workstation, navigate between displays, and manipulate them (e.g., changing display type and scale settings)).

Evaluation

While this guidance should pick up secondary tasks imposed by AA, the increased interaction between operator and automation in AA systems may present some unique features. Thus, this guideline is sufficient at a high-level for the review of AA systems, but the review guidance can be improved to better inform the reviewer of specific AA secondary task considerations.

Review Guideline

(4) The applicant should identify the measures of situation awareness applicable to each scenario.

Additional Information: Situation awareness is the degree to which personnel's perception of plant parameters and understanding of the plant's condition corresponds to its actual condition at any given time and influences predictions about future states.

Evaluation

An applicant's SA measure should be sensitive to automation implications. However, AA systems pose increased demands on SA due to their dynamically changing nature. Further, as plants become more automated, a focus on awareness of the automation's status should be included in the guidance. Thus, this guideline is sufficient at a high-level for the review of AA systems, but the review guidance can be improved to better inform the reviewer of specific AA considerations for awareness of automation performance and automation changes.

Review Guideline

(5) The applicant should identify the workload measures obtained for each scenario.

Additional Information: Workload is comprised of the physical, cognitive, and other demands that tasks place on plant personnel. The impact of one or many of these aspects of workload should be considered in the performance measures.

Evaluation

Like SA, an applicant's workload measure should be sensitive to automation implications. However, AA systems pose increased workload demands due to the dynamically changing nature and the increased level of interaction required. Thus, this guideline is sufficient at a high-level for the review of AA systems, but the review guidance can be improved to better inform the reviewer of specific AA considerations for workload demands imposed by automation.

Review Guideline

(6) The applicant should identify the anthropometric and physiological measures obtained for each scenario.

Additional Information: Anthropometric and physiological factors include such concerns as visibility of displays, accessibility of control devices, and ease of manipulating the control device. Many of these design aspects are assessed as part of verifying the HFEs design. Therefore, attention should focus on those areas of the design that only can be addressed by testing the integrated system (e.g., the ability of personnel to effectively use the various controls, displays, workstations, or consoles while performing their tasks).

Evaluation

There are no unique considerations of AA systems that are needed to apply this review guideline. Thus, this guideline is sufficient, as is, for the review of AA systems.

3.4 General Conclusions

The review guidance evaluation was divided into three topics:

- allocation of functions to AA
- AA system design
- evaluation and validation of AA systems

For many of these topics, AA research issues that needed to be addressed to support guidance development were previously identified. Since this report will address the guidance needs in this summary, these issues will be repeated. The evaluation of the detailed guidance enabled a specific identification of what the deficiencies are and what new guidance is needed for AA system review.

Conclusions regarding each are summarized below.

3.4.1 Allocation of Function to AA

In RIL-2020-05, an issue regarding a lack of HFE guidance for the function allocation process regarding AA systems was identified:

> *Function Allocation* - Prior NRC research has identified an issue on "Function Allocation Methodology to Support Automation Decisions" (O'Hara, Higgins & Pena, 2012). Our evaluation of current advances in FA methodology has not substantially changed the overall conclusion. There remains a need for improvements in the methods available for making AA decisions. While more recent HFE guidance has acknowledged AA has an option and alternative to static allocation, little guidance is available to designers for selecting this alternative or safety reviewers evaluating those decisions.

Four detailed review guidelines in NUREG-0711 were pertinent to the allocation process. One was evaluated as sufficient, as is, for the review of function allocation verification. One guideline was identified as sufficient at a high level but can be improved to better inform the reviewer that in AA systems, the operator's primary responsibilities may change depending on the DOA configuration in effect at a given time.

Two guidelines were identified as insufficient for the review of AA systems. Guidance is needed to address:

- AA as an allocation option where the DOA may be variable and where other aspects of automation may change, such as tasks performed by automation.

- operator roles and responsibilities that can dynamically change (in contrast to typical static allocations that are characteristic of other human-automation systems).

Improved guidance addressing these aspects of AA systems will help regulators to review the basis for design decisions about how human and automation responsibilities are determined.

3.4.2 AA System Design

The characterization of AA systems has three main elements: Configurations, triggers, and HSIs. The status of the review guidance available for each is briefly described below.

3.4.2.1 Configurations

A configuration is a DOA that defines the roles and responsibilities of both operators and automation. To better understand guidance needs, guidance for aspects of configurations with human performance consequences were evaluated:

- defining configurations.
- DOA change selection.
- number of configurations.
- configuration timing.

In RIL-2020-05, the issue addressing AA configurations was identified:

> *Configurations* – While AA systems provide configurations offering operators different DOAs, we do not know how many are appropriate or what the minimum length of time configurations should remain in effect before shifting them becomes disruptive. An additional area to be addressed is the potentially disruptive effects of configuration changes, especially when triggered by conditions other than operator command.

This issue identifies the last two of these aspects of configurations.

With respect to the detailed guidance in NUREG-0700, one guideline addresses configuration definition, which stated that predefined configurations should be used. This guideline is sufficient at a high-level for the review of AA systems, but the review concluded that the review guidance can be improved to better inform the reviewer of specific AA considerations to give operators the flexibility to define role change in real time.

The remaining three aspects of configurations (DOA change selection, number of configurations, and configuration timing) are not addressed in NUREG-0700 and additional guidance is needed to review:

- DOA configuration changes that go beyond LOA.
- the number of configurations employed in AA systems.
- the time configurations remain in effect.

3.4.2.2 Triggers

Triggers are the conditions that initiate changes in AA configurations. To better understand guidance needs, guidance for aspects of triggers with human performance consequences was evaluated: appropriateness of trigger categories and invoking thresholds.

An issue addressing AA triggers was identified RIL-2020-05:

> *Triggers* – While the triggering conditions used in the research studies reviewed were generally effective at switching AA configurations, more research is need on those using measures to assess OFS (operator functional state). OFS is often predicted using physiological measures. Researchers have used single physiological measures or multiple measures. A question remains as to which measures are best and how they should be integrated to get reliable OFS predictions. Further, some researchers recommend the use of hybrid triggers, i.e., the use of triggers from more than one category. A research question remains as to which ones provide the most reliable triggers and how they should be combined to trigger DOA changes. Finally, a key consideration is the invoking threshold; i.e., the specific point at which the trigger changes. Research is needed on determining these thresholds and on how to implement them so configurations shift in an acceptable manner.

This issue identifies these two aspects of trigger design as in need of additional guidance. That conclusion is supported by a detailed review of NUREG-0700 guidance. These two aspects of trigger design are not addressed. Thus, additional guidance is needed for:

- addressing the category of trigger or combination of categories that are appropriate for specific AA system applications, including the use of measures needed to get reliable OFS predictions.
- defining invoking thresholds.

3.4.2.3 HSIs

HSI provide the link between the operator and automation. To better understand guidance needs, guidance for aspects of HSI design related to monitoring, control, and communication was evaluated.

HSI design was identified in RIL-2020-05 as a technical issue:

> *HSIs* – HSIs provide the link between the operator and automation. We discussed the work on EID (ecological-interface design) displays to support monitoring and failure detection and delegation interfaces to support configuration awareness and workload management. We also discussed the work on automaton etiquette to help make automation's communication with its human teammates more acceptable and less disruptive. While all of this research is promising, much more needs to be done, especially in light of the fact that automation is becoming more interactive. In addition, the use of adaptive HSIs to support interface management and reduce the workload associated with it looks promising. Additional research is needed to identify applications in the nuclear plant operations and to ensure that automation's performance of these tasks does not disrupt operator tasks or create confusion.

This issue identifies two general guidance needs, the first related to monitoring and the second to control:

- identifying design characteristics for EID displays to support monitoring and failure detection.
- identifying design characteristics for delegation-style interfaces to support configuration awareness and workload management.

<u>Monitoring</u>

Operators use HSIs to monitor overall plant performance as well as systems and subsystems supporting that performance. In addition, operators monitor AA to be aware of the current configuration and when configuration shifts are triggered. Operators must also monitor automation HSIs so they became aware of automation degradations and failures.

Of the four review guidelines that were evaluated for automation monitoring, all were found to be sufficient, as is, for the review of AA systems. These guidelines addressed the need for operators to be aware of:

- the relative roles and responsibilities of automation and operators.
- configuration shifts that are about to occur.

- the causes for configuration shifts.
- shifts that have taken place.

In addition, the general guidance in NUREG-0700 Sections 9.2 and 14 were sufficient for reviewing degraded HSI and I&C conditions for AA systems.

Control

HSIs need to provide controls for all operator interactions with automation (e.g., to configure automation and control what it does). AA has some unique control considerations:

- change AA's s current configuration (an operator-commanded trigger).
- override a configuration change triggered by a non-operator commanded trigger.
- interactions with functions provided by delegation-type interfaces.
- some AA system may also have controls to modify configurations in real time.

AA control was one review guideline that was evaluated. It addresses the requirement for changing AA's current configuration through an operator-commanded trigger and is sufficient, as is, for the review of AA systems.

However, NUREG-0700 does not address the remaining three unique AA control considerations identified above and additional guidance is needed addressing the override of configuration changes triggered by non-operator commanded triggers, interactions with functions provided by delegation-type interfaces, and controls to modify configurations in real time, if applicable.

Communication

A key consideration for any team is communication, even for human-automation teams. Communications should be timely with respect to the importance of the information and not distracting and disruptive to the crew's performance of ongoing tasks.

NUREG-0700 provides review guidance on the need for effective and non-disruptive communication between human and automation agents that is sufficient, as is. It is noted that modeling communication based on human teamwork may be appropriate (i.e., designing communication to follow the rules of etiquette found in the communication between operator teams). However, it may be premature to recommend such an approach until further research is conducted.

Communication is one aspect of a broader issue: teamwork. This issue was previously identified:

> *Teamwork* - If automation is part of a multi-agent team, then what model of teamwork should be used to specify its characteristics? There is currently no answer to this question. Additional work is needed to identify appropriate teamwork models that incorporate an understanding of the differences between human and automation agents.

Nuclear plant operations are accomplished through teamwork; the coordinated activity of multi-person teams. In multi-agent operations, where humans work with automation teammates, the dimensions that characterize effective teamwork may be somewhat different than when human-only teams are considered. Understanding human-automation teams is especially important for

AA systems that are more interactive and where roles and responsibilities are shifted between human and automation teammates. A comprehensive model of human-automation teamwork is needed to improve the design of automaton as a team player. But the issue above points out that no such model is currently available to support guidance development.

3.4.3 Evaluation and Validation of AA Systems

NUREG-0711's approach to HFE evaluation and validation provides a systematic and thorough framework to guide AA system reviews. Such an approach helps promote standardization of reviews and ensures that important factors are not overlooked.

Of the 13 guidelines evaluated, eight were found to be sufficient, as is, for the review of AA systems. Three guidelines were found to be sufficient, at a high-level, for the review of AA systems, but improvements were identified to better inform reviewers about the following considerations:

- specific AA secondary task considerations.
- Situation awareness of automation performance and automation changes.
- workload demands imposed by automation.

Two guidelines were found to be insufficient and additional guidance needs were identified to address:

- the changes to operator's primary tasks in response to AA configuration changes
- the human performance demands and impacts of AA systems

Thus, while the evaluation found the review guidance to be generally appropriate for AA systems, several improvements summarized above were identified.

An evaluation of human-automation interaction in previous reports (O'Hara & Higgins, 2010, 2017 (RIL-2020-05); O'Hara, Higgins, & Pena, 2012) has highlighted the need to consider performance measures that go beyond those currently identified in NUREG-0711. Specifically, "teamwork" and "known human performance issues" should be included in the performance measurement framework.

The importance of teamwork in characterizing human-automation interaction has been discussed. It is also an important consideration is performance measurement, yet it is not currently addressed in NUREG-0711. Performance measures for teamwork should reflect a model that identifies dimensions that are important to NPP team performance. While a specific model is currently unavailable, it is likely to include dimensions such as communication, coordination, and collaboration.

Trust in automation is an example of one dimension that research has shown is an important determining factor in an operator's use of automation. Operators must have trust in automation to use it effectively (O'Hara & Higgins, 2010). If trust is miscalibrated, operators may not use automation when they should or may overly rely on it when they should not. Moreover, their workload may significantly increase by overly verifying automation's behavior. Similarly, failures of automation can remain undetected if operators trust automation too much and hence, become complacent. These situations can lead to performance problems. Measuring trust in automation may provide valuable information for understanding overall performance and the crew's use of automation.

Another category of measures not currently addressed in NUREG-0711 is “known human performance issues.” With respect to automation, there are well known issues that should be assessed when evaluating or validating human-automation performance. While these include loss of SA and workload issues, which are already included in NUREG-0711, there are other issues that are not, such as skill degradation. In highly automated systems, looking at skills degradation can be a very important consideration if operators are expected to perform automation’s tasks when it fails.

Looking more broadly, this category of measurement extends beyond automation issues. It should include any known issues for the type of integrated system operations being evaluated. For example, in multi-unit small modular reactor operations, it’s important to assess neglect time (focusing operator attention on one unit and the expense of another) and change detection/blindness (failing to see large, salient changes in the environment) (O’Hara, Higgins & Pena, 2012).

The inclusion of measures for teamwork and known human performance issues will contribute the overall comprehensiveness of system evaluations and an understanding of integrated human-system performance.

4 DISCUSSION

The NRC staff uses the guidance in NUREG-0711 and NUREG-0700 to perform safety reviews of control room designs and their base technologies. Using the HFE guidance, the reviewer makes a safety determination of the design's acceptability. Since new technologies continually evolve, the NRC has remained committed to keeping its guidance up-to-date with these technological advances. One such advance that impacts both operational practices and plant safety is the emerging use of AA.

In RIL-2020-05, limited HFE guidance available to support designers and reviewers of AA systems was found. Thus, a research need to develop additional HFE guidance for AA systems was identified (see Section 8.3.3, HFE Guidance for AA Implementation and Review). Limited guidance can impact the ability of the NRC staff to conduct a thorough review of an AA system. Thus, while there is a general lack of guidance, the specific gaps in the NRC's guidance for the review of AA systems need to be identified.

The objective of this report was to evaluate whether the NRC's HFE guidance is sufficiently comprehensive to support AA system reviews; and when it is not, to identify what additional guidance is needed. To do so, the suitability of the guidance in NUREG-0711 and NUREG-0700 for reviewing the allocation of functions to AA systems, AA system design, and the evaluation and validation of AA systems was evaluated.

The results revealed that the available guidance is sufficient to review some aspects of AA, such as the monitoring of AA systems, detection of AA failure, and the general evaluation/validation of AA systems. However, there are numerous areas where the guidance is insufficient. Table 4-1 illustrates some of the topics for which guidance improvements are needed.

Table 4-1 Examples of Guidance Improvement Needs

Topic	Improvement
Function Allocation	addressing AA as an allocation option where the DOA may be variable and where other aspects of automation may change
	addressing operator roles and responsibilities that can dynamically change
AA System Design	
Configurations	addressing DOA configuration changes that go beyond LOA
	addressing the number of configurations employed in AA systems
	addressing the time configurations remain in effect
Triggers	addressing the category of triggers or combination of categories that are appropriate for specific AA system applications
	defining invoking thresholds
HSIs	identifying the characteristics of EID displays that are needed to support monitoring and failure detection
	identifying the characteristics of delegation-style interfaces that are needed to support configuration awareness and workload management
	identifying the characteristics of controls to change AA's s current configuration (an operator-commanded trigger)

	identifying the characteristics of controls to override a configuration change triggered by a non-operator commanded trigger
	identifying the characteristics of controls for interactions with functions provided by delegation-type interfaces
	identifying the characteristics of controls to modify configurations in real time
	identifying the characteristics of rules of etiquette for effective communication
	developing models of human-automation teamwork to support the identification of dimensions of teamwork that can be used to improve AA design
Evaluation & Validation	assessing changes to operator's primary tasks in response to AA configuration changes
	assessing human performance demands and impacts of AA systems in tradeoff studies
	including measures of teamwork in evaluations
	including measures of known human performance issues in evaluations

While this report identified guidance needs, the NRC's HFE review process is sufficiently robust to provide reviewers with a variety of strategies that can be used to conduct reviews of advanced and innovative technology until additional guidance is developed (O'Hara & Higgins 2004; O'Hara, Higgins & D'Agostino, 2015).

Knowledge of important design characteristics and human performance issues provides reviewers with information about what questions to ask applicants about their AA systems. While the identification of such questions is typically guided by the NRC's primary HFE guidance documents, an understanding of these aspects of AA systems can be provided by technical reports (e.g., RIL-2020-05).

Until specific detailed guidance is developed, the information provided by applicants in response to the NRC staff's questions can be evaluated in a variety of ways:

- adapting existing criteria, e.g., from NUREG-0711 and NUREG-0700.
- extrapolating best practices from general HFE principles, such as those contained in NUREG-0700, Appendix A.
- reviewing an applicant's T&E (test and evaluation) to ensure that it demonstrates the acceptability of a new technology or operational approach (T&E is built into the NUREG-0711 HFE review process; test results can be used in lieu of deterministic review criteria).
- ensuring the applicant's ISV addresses all issues for which limited guidance is available, so they are evaluated in an integrated manner using comprehensive performance measurement.

Flexibility is essential in a safety-review process to accommodate design innovations that may impact safety. Review strategies, such as those described above, provide a means for an HFE reviewer to address such innovations and applications of new technologies and operational strategies.

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