EPRI/NRC-RES Fire Human Reliability Analysis Guidelines—Quantification Guidance for Main Control Room Abandonment Scenarios

Supplement 2

FINAL REPORT

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Office of Nuclear Regulatory Research
Washington, D.C. 20555-0001

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Supplement 2

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FINAL REPORT
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ABSTRACT

Fire probabilistic risk assessments (PRAs) analyze a wide variety of fire-induced scenarios, one of which is fire damage that renders the main control room (MCR) either uninhabitable or ineffective. In this scenario, operators cannot safely shutdown from the MCR, and the command and control (C&C) of the plant is transferred to remote or alternate shutdown panels. This is commonly referred to as main control room abandonment (MCRA).

While EPRI/NRC-RES Fire Human Reliability Analysis Guidelines (NUREG-1921 and also Electric Power Research Institute [EPRI] 1023001) provided methods and guidance to estimate human error probabilities (HEPs) for fire PRAs, the subject of MCRA was reserved for future research. Supplement 1 of NUREG-1921 (EPRI 3002009215) addressed qualitative considerations for fire scenarios resulting in MCRA. In particular, Supplement 1 provided PRA modeling considerations and qualitative human reliability analysis (HRA) guidance including: feasibility assessment, identification and definition, timing, performance shaping factors, and walk-through and talk-through guidance for MCRA scenarios.

This report provides guidance for quantifying the probabilities of human failure events (HFEs) for fire PRA scenarios resulting in MCRA, building upon both NUREG-1921 and Supplement 1. The HRA process for MCRA scenarios remains unchanged from NUREG-1921, but it has been supplemented by additional contextual factors unique to MCRA scenarios.

Guidance is provided based on the specific time phases of the MCRA timeline: 1) the time before abandonment, 2) the time for the decision to abandon, and 3) the time after the decision to abandon has been made. This report provides formal HRA quantification guidance for two categories of HFEs that have not been previously addressed. First, for scenarios where feasibility can be demonstrated, a new decision tree was developed to quantify the failure probability of the decision to abandon upon a loss of control (LOC). Second, additional HRA guidance is also provided to account for possible failures in C&C and/or communications after the MCR is abandoned. HRA quantification guidance also is provided for how to use existing HRA methods for operator actions before abandonment and after the decision to abandon.

Keywords
Command and control (C&C)
Fire human reliability analysis (HRA)
Fire probabilistic risk analysis (PRA)
Main control room abandonment (MCRA)
Quantitative analysis

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EXECUTIVE SUMMARY

PRIMARY AUDIENCE: Fire probabilistic risk assessment (PRA) engineers and fire human reliability assessment (HRA) practitioners who support the development and/or maintenance of fire PRAs.

SECONDARY AUDIENCE: Engineers, utility managers, operators, operator trainers, and operations staff, and other stakeholders who review fire PRAs and who are interested in learning about the human and plant response during a main control room abandonment (MCRA) event.

KEY RESEARCH QUESTION

Fires can render the main control room (MCR) uninhabitable due to diminishing environmental conditions or ineffective due to fire impacting equipment vital to controlling the plant. When these conditions occur, nuclear power plant (NPP) operators may decide to abandon the MCR and perform shutdown from outside the MCR.

NUREG-1921 Supplement 1/Electric Power Research Institute (EPRI) 3002009215 provided guidance to make a qualitative assessment of feasibility, timing and timelines, and performance shaping factors. Since quantification approaches were not addressed in Supplement 1, this report answers the question: How should fire PRAs quantify the human response for fire scenarios resulting in MCRA?

RESEARCH OVERVIEW

Through a joint research effort between EPRI and the Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research (RES), this report builds upon the qualitative guidance provided in NUREG-1921 Supplement 1/EPRI 3002009215. Supplement 1 defines and describes the three time phases of MCRA. Guidance in this follow-on report is provided based on the three time phases: 1) the time period before abandonment, 2) the time for the decision to abandon, and 3) the time period once the decision to abandon has been made.

To the extent practical, the guidance provided here is an extension of existing methods. Early iterations of the guidance started with existing HRA methods, which were revised to fit the unique context of MCRA. As the project developed, expert feedback was sought to provide additional insights and solidify the guidance. The expert feedback provided both qualitative and quantitative insights that helped finalize the guidance.

Similar to the development of NUREG-1921 Supplement 1/EPRI 3002009215, feedback was requested at several points during the project. A first draft was prepared in early 2018 to support a presentation to the Reliability and PRA Subcommittee of the U.S. NRC's Advisory Committee on Reactor Safeguards (ACRS) in April 2018. A second draft supported a peer review that occurred during the summer of 2018. The feedback received from both interactions was folded into the final publication.

KEY FINDINGS

The focus of this report is to provide guidance on the quantification model used in the MCRA HRA. The following key findings and lessons learned include:

- Pre-abandonment (Phase I) actions may be quantified using the guidance provided in NUREG-1921/EPRI 1023001 since these actions are similar to other human actions modeled in the fire PRA and follow the same emergency operating procedures (EOPs) and fire response procedures as non-MCRA scenarios.
- The decision to abandon on loss of control (LOC) (Phase II) actions may be quantified using the decision tree provided in Section 4. A credible scenario and feasibility must be demonstrated to use this quantification tool.
- Post-abandonment (Phase III) actions may be quantified using existing guidance, but analysts must also consider if a command and control (C&C) sequencing failure may exist. Additionally, the Phase III actions should include the time required for communications and coordination as recommended in Section 5.

WHY THIS MATTERS

This report provides quantification guidance for analyzing the human response for fires that result in MCRA. While not many fire scenarios may require abandonment and implementation of the post-abandonment shutdown strategy, the impact of a potential scenario where MCRA takes place could significantly challenge plant response. In past fire risk studies, a legacy screening value was used; however, the National Fire Protection Association (NFPA) 805 transition process in the United States required a more substantial effort to qualify and justify post-abandonment actions. As a result, a closer examination of the strategy, operator insights, and detailed analysis was performed, as part plant-specific FPRA and this fire HRA research. In many cases, plant or procedure changes were recommended to make these actions more reliable.

HOW TO APPLY RESULTS

This report should be applied with the guidance and methodology provided in both EPRI/NRC-RES Fire Human Reliability Analysis Guidelines (NUREG-1921/EPRI 1023001) and EPRI/NRC-RES Fire Human Reliability Analysis Guidelines: Qualitative Analysis for Main Control Room Abandonment Scenarios (NUREG-1921 Supplement 1/EPRI 3002009215). The quantification guidance is structured by the time phases of the scenario (pre-abandonment, the decision to abandon, and after the decision to abandon). Phase I actions may be quantified using the guidance provided in NUREG-1921. Phase II actions are quantified using the decision tree in Section 4, assuming feasibility has been demonstrated. Phase III actions follow NUREG-1921 guidance supplemented with a process to address any C&C-related sequencing failure modes.

LEARNING AND ENGAGEMENT OPPORTUNITIES

Users of this report may be interested in fire PRA training, Module IV – Fire Human Reliability Analysis, sponsored jointly by EPRI and the U.S. NRC-RES.

EPRI's HRA Users Group performs research aimed at improving human reliability analysis and provides technology transfer opportunities. The collaboration site for the user group can be accessed at: https://membercenter.epri.com/collaboration/4000000763/

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In May 2018, a revised draft was provided for independent peer review. The peer review team was composed of stakeholders from the industry, NRC, and members of the human factors and cognitive science community. We thank those who provided comments: Andreas Bye (OECD Halden Reactor Project), Fernando Ferrante (EPRI), Christopher Hunter (NRC-RES), J.S. Hyslop (retired; formerly NRC-NRR), Mark Humphrey (EPM), Michelle Kichline (NRC-NRR), Stuart Lewis (Jensen Hughes), Pierre Macheret (Jensen Hughes), Stephanie Morrow (NRC-RES), Emilie Roth (Roth Cognitive Engineering), Nathan Siu (retired; formerly NRC-RES), Song-Hua Shen (retired; formerly NRC-RES), Harold Stiles (Duke), Jeff Stone (Exelon), Marty Stutzke (NRC-NRO), and Ricky Summitt (RSC Engineers).

ACRONYMS AND ABBREVIATIONS

AC	alternating current
ACRS	Advisory Committee on Reactor Safeguards
ADS	automatic depressurization system
ADV	atmospheric dump valve
AFW	auxiliary feedwater
ANS	American Nuclear Society
AOP	abnormal operating procedures
AOV	air operated valve
ARTCC	air route traffic control center
ASEP	accident sequence evaluation program
ASME	American Society of Mechanical Engineers
ATHEANA	a technique for human event analysis
ATWS	anticipated transient without scram
BWR	boiling water reactor
C&C	command and control
CBDT	cause-based decision tree
CBDTM	cause-based decision tree method
CCSW	containment cooling service water
CCW	component cooling water
CFM	crew failure mode
CRS	control room supervisor
CSR	cable spreading room
CST	condensate storage tank
DOE	U.S. Department of Energy
ECCS	emergency core cooling system
EDG	emergency diesel generator

EDMG	extensive damage mitigation guidelines
ELAP	extended loss of AC power
EOP	emergency operating procedure
EPC	error producing conditions
EPRI	Electric Power Research Institute
ESFAS	engineering safety features actuation system
ESW	emergency service water
FAA	Federal Aviation Administration
FLEX	flexible and diverse mitigation strategies
FPRA	fire probabilistic risk assessment
FRP	fire response procedure
GTT	general task type
HCR/ORE	human cognitive reliability/operator reliability experiment
HEP	human error probability
HFE	human failure event
HI	human interaction
HLR	high level requirement
HMI	human-machine interface
HPCI	high pressure coolant injection
HRA	human reliability analysis
HVAC	heating, ventilating, and air conditioning
IDHEAS	integrated human event analysis system
JHEP	joint human error probability
JPM	job performance measure
LOC	loss of control
LOCA	loss of coolant accident
LOH	loss of habitability
LOOP	loss of offsite power
LPI	low pressure injection
LPSI	low pressure safety injection
MCR	main control room
MCRA	main control room abandonment
MFW	main feedwater

MOU	Memorandum of Understanding
MOV	motor operated valve
MSIV	main steam isolation valve
NARA	nuclear action reliability assessment
NFPA	National Fire Protection Association
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation
PIRT	phenomena identification and ranking table
PORV	power-operated relief valve
PRA	probabilistic risk assessment
PSF	performance shaping factor
PTS	pressurized thermal shock
PWR	pressurized water reactor
RCIC	reactor core isolation cooling
RCP	reactor coolant pump
RCS	reactor coolant system
RES	NRC’s Office of Nuclear Regulatory Research
RHR	residual heat removal
RO	reactor operator
RPV	reactor pressure vessel
RSDP	remote shutdown panel
RWST	refueling water storage tank
SAMG	severe accident management guidelines
SBO	station blackout
SCBA	self-contained breathing apparatus
SG	steam generator
SGTR	steam generator tube rupture
SI	safety injection
SISBO	self-induced station blackout
SLC	standby liquid control
SLCS	standby liquid control system
SM	shift manager

SME	subject matter expert
SOP	standard operating procedure
SPAR-H	standardized plant analysis risk – human reliability analysis
SR	supporting requirement
SRM	staff requirements memorandum
SRO	senior reactor operator
SS	shift supervisor
SSC	structures, systems, and components
SSD	safe shutdown
STA	shift technical advisor
SW	service water
THERP	technique for human error-rate prediction
TSC	technical support center
U.S.	United States

1
INTRODUCTION

1.1 Background

This report provides guidance for quantifying the probabilities of human failure events (HFEs) in fire scenarios that require main control room abandonment (MCRA).

This guidance builds upon the fire human reliability analysis (HRA) guidance provided in previously published reports,[1] with the most recent listed first:

- EPRI/NRC-RES Fire Human Reliability Analysis Guidelines: Qualitative Analysis for Main Control Room Abandonment Scenarios, NUREG-1921 Supplement 1/EPRI 3002009215 [1], which provides guidance for the probabilistic risk assessment (PRA) development of qualitative HRA for fire scenarios leading to MCRA and qualitative guidance for the associated HRA.
- EPRI/NRC-RES Fire Human Reliability Analysis Guidelines, NUREG-1921/EPRI 1023001 [2], which provides guidance for the development of HRA for fire scenarios that do not require MCRA. NUREG-1921 augments (and sometimes replaces) that given in the overall fire PRA methodology report (NUREG/CR-6850) [3].
- EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities Volume 2: Detailed Methodology, EPRI 1011989/NUREG/CR-6850 [3], which primarily develops the fire model and associated plant response (PRA) models.

In particular, this report is a companion document to NUREG-1921, Supplement 1. Both supplements should be used with the original report, NUREG-1921.

1.2 Problem Statement

MCRA refers to “situations in which control room operators are forced to leave due to untenable fire generated conditions” [1]. After abandoning the main control room (MCR), operators implement the MCRA safe shutdown strategy[2] using a specific procedure from a location(s) outside the MCR. The procedure and remote shutdown capability outside the MCR are plant specific.[3] As outlined in NUREG-1921, “actions outside the MCR may be taken at multiple locations, including the remote shutdown panel, or at one or more local control panels, breakers, or pieces of equipment” [2]. Some nuclear power plants (NPPs) may have a control panel to control and monitor key core cooling functions and parameters, while other plants may

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[1] These joint reports were prepared under a Fire Risk Research Addendum to the Memorandum of Understanding (MOU) between NRC and EPRI. These reports are jointly published by both organizations. For simplicity, the NUREG number is used throughout this report.

[2] Note that other phrases might be used equivalently to describe this strategy, such as "alternate shutdown."

[3] For additional discussion on the variations of remote shutdown capability, refer to Appendix A of NUREG-1921, Supplement 1.

have a set of control points and control panels located at various points in the plants, requiring the coordinated actions of several operators. The control panel is commonly referred to in Supplement 1 and this report as a “remote shutdown panel,” or RSDP. In some plants, the control panel may be referred to as an “alternate shutdown panel,” and these two terms are synonymous with respect to the guidance provided in this report.

The MCR can be abandoned due to: 1) loss of habitability[4] (LOH) (e.g., dense smoke, intense heat, and/or toxic gases that prevent operators from monitoring and/or being able to use controls on the MCR panels, or 2) loss of control (LOC) (i.e., loss of significant systems necessary to control the plant. LOH is primarily a concern within the MCR envelope, although it may be possible for smoke to propagate from nearby or adjacent areas. LOC scenarios can initiate from either the MCR or other plant areas where redundant equipment is routed (such as a cable spreading room). The assessment of abandonment scenarios is plant specific and dependent on many factors including the volume of the control room, the capability of the MCR smoke-purge HVAC system, and cable routing.

Fire HRA guidance did not completely address the unique context of MCRA scenarios. Additionally, general fire PRA guidance did not address how to define potential LOC scenarios. This guidance builds upon the quantification guidance in NUREG-1921 and NUREG-1921 Supplement 1 to provide additional quantification factors for MCRA HRA.

1.3 Objectives and Scope

The overall objective of this EPRI/NRC-RES collaboration is to provide guidance on the application of HRA quantification methods, including any adjustments needed to address the context of the fire scenarios leading to MCRA, in order to develop human error probabilities (HEPs) and uncertainty parameters.

While this report addresses all phases of MCRA scenarios, the primary improvements to the fire HRA were in the following areas:

- HRA quantification guidance for the decision to abandon for LOC scenarios (i.e., Phase II per definitions provided in Supplement 1), which is described in Section 4 (with background development provided in Appendix B).
- HRA quantification guidance for the actions to implement the MCRA procedure following the decision to abandon (i.e., Phase III per Supplement 1), including considerations for communications and command and control (C&C) which is described in Section 5 (with background development provided in Appendix C).

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[4] Early abandonment is not addressed in this report. In an early abandonment scenario, the operators would progress more quickly to the alternate shutdown strategy and any actions that might have been taken in the MCR prior to abandonment would then occur at the RSDP or locally. The existing methods would address such a scenario, so no new guidance is considered necessary.

The guidance and examples presented in the report are derived from interviews and typical plant operating practices of the current fleet of NPPs within the United States (U.S.). In general, this guidance may be applied internationally, but with the understanding that the strategies, RSDP capability, staffing, and procedure progression may differ from those found in the United States.

1.4 Technical Approach

The technical approach for Supplement 2 builds upon the previous guidance developed in NUREG-1921 and NUREG-1921, Supplement 1 and:

- Takes advantage of the joint EPRI/NRC-RES HRA team experience and expertise that includes prior HRA method developments, U.S. and international HRA/PRA experience, non-nuclear HRA/PRA experience, and recent HRA method development and application for some of the newer HRA/PRA contexts (e.g., seismic HRA, Level 2 HRA); and the experience and understanding developed in previous fire HRA/PRA guidance reports
- Leverages the expertise and experience of a variety of subject matter experts (SMEs) during various stages of the report development
- Considers both operational experience as well as the latest advances in cognitive and behavioral science[5]

In particular, the technical approach for developing guidance on how to quantify HFEs associated with actions in MCRA scenarios involved the following steps:

1. General consideration of Supplement 1 with respect to HRA quantification for unique scenario contexts of MCRA, as well as with respect to the driving factors and qualitative analysis foundation provided in Supplement 1
2. For the operator actions related to the decision to abandon and C&C functions after MCRA, development of a list of consequential factors that may affect HRA quantification, including consideration of differentiation points (best case, intermediate, and least favorable), possible compensatory factors, and synergistic effects of the identified factors
3. Comparison of the list of potentially consequential factors with those factors used in existing HRA methods, such as cause-based decision tree method (CBDTM) [4], human cognitive reliability/operator reliability experiment (HCR/ORE) [4], standardized plant analysis risk-human reliability analysis (SPAR-H) [5], and integrated human event analysis system (IDHEAS) at-power [6], including:
    a. Evaluation of HRA method effectiveness for the range of actions and the range of MCRA contexts for critical tasks and sub-tasks
    b. Consideration of the method structure, relevance of the associated underlying data, and sufficiency of the associated guidance for the range of actions and the range of MCRA contexts

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[5] The understanding of the effects of cognition and its failures in responding to events at NPPs has seen increasing improvements since the 1980s, starting with reports such as NUREG/CR-4532 [7]. In turn, there has been a significant effort to incorporate the effects of cognition in the development of HRA methods for use in PRAs. This work has shown that failures in cognition by operators can be significant contributors to failure events in the PRA models. Over time, various HRA methods (e.g., ATHEANA, IDHEAS at-power) have represented such advances, depending on what contexts were the focus of the HRA method.

   c. Consideration of the cognitive activities that are specific to MCRA scenarios before MCRA (e.g., use of emergency operating procedures (EOPs)), after MCRA (including any decision-making required by MCRA procedures), and when making the decision to abandon

4. Use of an expert panel to:
   a. Further refine the list of potentially consequential factors
   b. Refine a new decision tree, and assign HEPs in the decision tree for the HFE representing the decision to abandon in LOC scenarios
   c. Identify the most risk-critical aspects of C&C after MCRA to address in HRA quantification
5. Use of existing HRA methods to develop an HEP for C&C-related sequencing failures

With many plant-specific differences in alternate shutdown capability and a small population of realistic training on the decision to abandon the MCR on LOC as well as subsequent post-abandonment operations, there are few “experts” who have the breadth of experience and knowledge needed to address this area of research. The SMEs were pushed to the bounds of the qualitative and quantitative understanding of the issues, and the scenario/HEPs should appropriately consider the treatment of uncertainties.

Appendix A provides more information on the use of experts and expert judgment in developing this report.

1.5 Summary of Qualitative MCRA HRA

The authors intend that the guidance provided in this report be used in conjunction with that given in NUREG-1921, Supplement 1 on qualitative MCRA HRA. In some cases, crucial guidance provided in Supplement 1 is referenced or repeated in this report.

The guidance developed in NUREG-1921 Supplement 1 provides the elements to develop a qualitative foundation for the human response to fires resulting in MCRA. In addition to the HRA elements, Supplement 1 also provides guidance beyond that in NUREG/CR-6850 for modeling the MCRA scenario-specific success criteria and incorporation of HFEs and equipment failures into the plant response model.

The qualitative analysis process described in NUREG-1921 Supplement 1 serves as an input to the HRA quantification including the following:

- Development of fire PRA scenarios that establish the PRA context for the HRA
- Collection and review of plant-specific information for MCRA including procedures, models, success criteria, and operator action feasibility analyses
- Identification of the operator actions in the fire scenarios to be developed as HFEs as part of the plant response
- Definition of three time phases for MCRA scenarios
- Definition of operator actions based on the relevant procedure steps associated with scenarios leading to MCRA
- Feasibility assessment for MCRA scenarios as well as individual actions
- Timeline development for the MCRA scenario

- Qualitative analysis of operator actions, including:
  - Evaluation of performance shaping factors (PSFs) based on the context of the fire scenarios for MCRA and other influences on operator performance observed during walk-/talk-throughs and simulator exercises of the MCRA process
  - Initial data collection and assessment of C&C in terms of existing plans, training, and communication requirements
  - Dependency analysis considerations for multiple HFEs that occur in the same cutset
  - Identification of sources of uncertainty
- Documentation of the analysis in sufficient detail to allow the basis for the qualitative analysis to be understood and the input parameters to quantification to be clearly identified

1.6 Relevant Supporting Requirements from the PRA Standard

Appendix D of NUREG-1921 [1] discusses the relationship between the fire HRA guidance provided in that report and the high level and supporting requirements contained in the 2009 version of the ASME/ANS PRA Standard [8].

The PRA Standard high level requirement (HLR) HR-G provides the quantification requirements for post-initiator HFEs, and implementation of this report's (Supplement 2) guidance is expected to meet HLR-HR-G.

As stated in Section 10.5 of Supplement 1, the fire HRA section of the PRA Standard does not specifically discuss requirements for MCRA HRA. The requirements for fire HRA in the PRA Standard refers back to the internal events HRA Standard requirements.

Supporting requirements (SRs) that are particularly relevant to MCRA actions are:

- HR-E3 (HRA-A1) on conducting talk-throughs of procedures
- HR-E4 on using simulator observations or talk-throughs to confirm the response models used for scenarios
- HR-G3, G4, and G5 on basing the available time on thermal/hydraulic analyses, and basing the required time to complete actions for significant HFEs on action time measurements from either procedure walk-/talk-throughs or simulator observations
- HR-G6 (HRA-C1) on requirements for performing a consistency check by: (a) developing a timeline for all the MCRA actions (as discussed in Section 2), and (b) comparing all HFEs and their HEPs to assess the relative reasonableness given the HFE characteristics and scenario(s) to which they pertain
- HR-G8 on the use of mean values for quantification of HEPs and their associated uncertainty in the risk analysis (as discussed in Section 6)
- HR-H2 on requirements for crediting operator recovery actions only if:
  - A procedure is available, and operator training has included the action as part of the crew's training, or justification for the omission for one or both is provided.
  - There are "cues" (e.g., alarms) to alert the operator to the recovery action if a procedure, training, or skill-of-the-craft exists.
  - Attention is given to the relevant PSFs listed in HR-G3.

- There is sufficient manpower to perform the action.

1.7 Organization of Report

This report is structured to address the additional guidance needed for the quantification of HFEs in fire scenarios leading to MCRA beyond that provided in NUREG-1921 and NUREG-1921 Supplement 1. The general report is structured to provide the guidance to the analyst in the main report sections. The process used to develop the guidance, technical approach, and discussion with SMEs is documented in the appendices.

Also, because timing is especially important for MCRA HRA, this report is organized such that guidance on timing and timelines is provided first. Then, HRA quantification is provided with respect to the three different time phases defined in Supplement 1.

In particular, this report is arranged in the following sections and appendices:

- Section 1 (i.e., this section) identifies the objectives and scope of this report, summarizes the qualitative MCRA report (NUREG-1921 Supplement 1), and provides an overview of this report.
- Section 2 summarizes the discussion of time phases from Supplement 1 and provides additional guidance on how to develop the timing inputs needed for MCRA HRA quantification.
- Section 3 provides guidance on how to treat pre-abandonment (Phase I) actions.
- Section 4 provides guidance on how to quantify the decision to abandon (Phase II) using a newly developed decision tree.
- Section 5 provides guidance on how to quantify post-abandonment shutdown (Phase III) actions and address coordination between actions associated with C&C.
- Section 6 discusses recovery, dependency, and uncertainty.
- Section 7 provides a summary of lessons learned and concluding remarks.

The appendices are presented in order of expected usage. Specifically:

• Appendix A	The use of experts and expert judgment in the development of the MCRA HRA guidance
• Appendix B	Technical approach and summary of discussion with SMEs for the decision to abandon (i.e., Phase II)
• Appendix C	Technical approach and summary of discussions on C&C in Phase III
• Appendix D	Considerations for potential future quantification approaches for the decision to abandon on LOC

In addition, a draft of this report was presented to the Advisory Committee on Reactor Safeguards (ACRS) Reliability and PRA Subcommittee and peer reviewers provided comments. Responses to both ACRS PRA Subcommittee comments and peer review comments are given in ML19162A379 [9] and ML19176A541 [10], respectively.

1.8 References

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2

ESTIMATING TIMING PARAMETERS USED IN MCRA HRA QUANTIFICATION

NUREG-1921, Supplement 1 [1] identified the importance of developing a MCRA timeline that combines the fire progression, plant response, and operator response. Specifically, Section 7 in Supplement 1 [1] provides full details on the construction of the MCRA timeline. An overall timeline is necessary to support the evaluation of individual HFE feasibility and is a direct input to the quantification in terms of:

- Demonstration of feasibility, through the development of time available and time required (also parameters that are called for in the ASME/ANS PRA Standard [2] supporting requirements HR-G3, HR-G4, and HR-G5)
- Input to HEP evaluation using HRA quantification methods
- Performing the reasonableness check of the HEPs by reviewing the timeline and timing parameters
- Supporting sensitivity studies

The MCRA timeline is divided into three phases, as discussed in NUREG-1921, Supplement 1 [1] and as represented in Figure 2-1. This chapter provides guidance on how to estimate or calculate the timing parameters required for the quantification for each phase:

- Section 2.1 addresses timing for Phase I actions
- Section 2.2 addresses timing for Phases II and III
  - Section 2.2.1 provides the process for assessing parameters for LOH scenarios
  - Section 2.2.2 provides the process for assessing parameters for LOC scenarios

While the phases have been identified as time phases, the important characteristics of the phases are: 1) the procedures that govern the plant response, and 2) the location of C&C for the plant response.

A brief description of the phases is found below, which provides additional information that clarifies the initial development in Supplement 1. Particularly, as shown in Figure 2-1, Phase I actions are more likely to start before the MCR team becomes involved with the decision to abandon (i.e., some Phase I actions may overlap with Phase II).

- ***Phase I*** – Time period before the operators make the decision to abandon (see Section 2.1 for exceptions). During this phase, the plant response is governed by the EOPs, and C&C is in the MCR. Fire response procedures (FRPs) may or may not be implemented in parallel with the EOPs.
- ***Phase II*** – Time period associated with the decision to abandon. During this phase, the plant response for the decision to abandon is governed by the FRPs, and C&C is in the MCR. EOPs may or may not be implemented in parallel with the FRPs, depending on the plant's response strategy.
- ***Phase III*** – The time period after the decision to abandon has been made, during which the transitional actions for transferring control from the MCR to the RSDP (or local control stations) are performed, and the post-abandonment shutdown actions are performed. During this phase, the plant response following the decision to abandon is governed by the alternate shutdown procedure (typically, one of the FRPs or an abnormal operating procedure (AOP)), and C&C is at the RSDP.

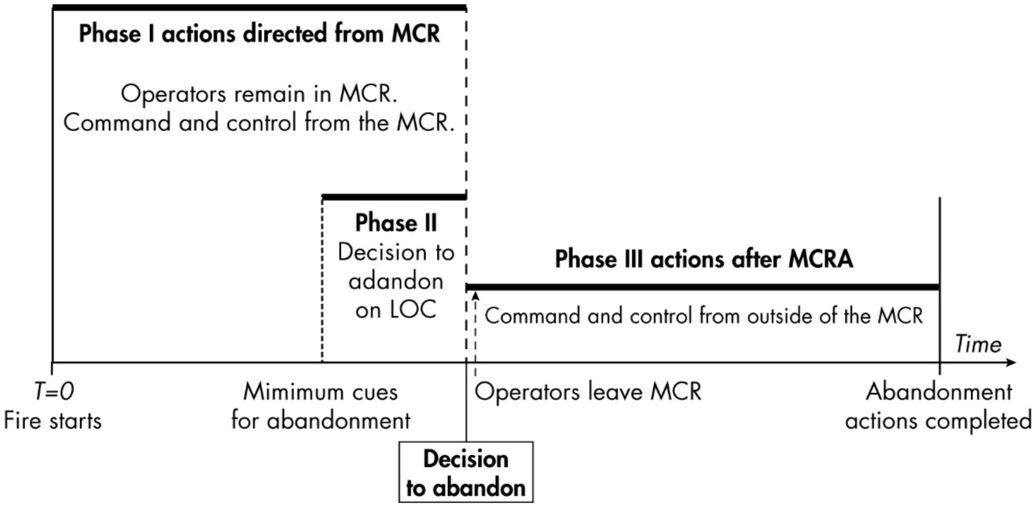

Figure 2-1
Three phases of MCRA

2.1 Timing for Phase I Operator Actions

The only additional guidance for Phase I beyond that published in NUREG-1921 [3], Section 4.6.2, is that if a Phase I HFE occurs simultaneously with the Phase II decision to abandon, then the context for the Phase I HFE needs to reflect the conditions, extra workload, and timing delays associated with the concurrent activities. For example, the time required for cognition of a Phase I HFE may be longer if the Phase I HFE overlaps with the Phase II decision to abandon (e.g., the operators may be in multiple procedures). In addition, it may be appropriate to add time for cue recognition for the Phase I operator action (i.e., T_{delay}) or add cognitive processing time for the Phase I operator action (i.e., Tcog) because operator attention is distracted by the fire effects, including fire brigade activities and communications.

2.2 Development of Timing Parameters for Phase II and Phase III

This section discusses the timing parameters for Phases II and III. A brief discussion is provided highlighting the differences between the MCRA timelines for LOH and LOC scenarios, followed by subsections describing the different processes for determining the timing parameters for LOH and LOC scenarios, respectively. Figures 2-2 and 2-3 show the timelines for typical progression of LOH and LOC scenarios, and Table 2-1 provides a summary of the similarities and potential differences between the timing progressions for the two scenarios.

In Figure 2-2, a LOH scenario, the unsuppressed fire grows, and smoke and heat begin to accumulate in the MCR. As the environment conditions in the MCR begin to deteriorate, operators may don SCBA. The heat and/or buildup of smoke directly leads the operators to pursue abandonment, as it is no longer tenable to remain in the MCR. At this point, operators will prepare to abandon the MCR including tripping the reactor (if not already tripped), completion of immediate post-trip actions, and transfer control from the MCR to one or more shutdown panels. After leaving the MCR, C&C is established outside the MCR and actions are undertaken to restore the necessary systems and functions to reach a safe, stable end state.

In Figure 2-3, the LOC scenario progression may be less obvious. If the fire begins outside the MCR (e.g., CSR), smoke may not be observed in the MCR. The first indication of fire may be a fire alarm or component failures. The operators will be monitoring the “cues” as the scenario develops which may include fire-induced component failures, reactor trip, or fire detection/suppression alarms. As these cues appear, operators will need to detect and diagnose the LOC condition. Once the diagnosis of the LOC occurs, the scenario will progress similar to Figure 2-2 (e.g., complete MCR actions, transfer control outside of the MCR, establish C&C outside the MCR, and restore systems and functions necessary to reach a safe, stable end state).

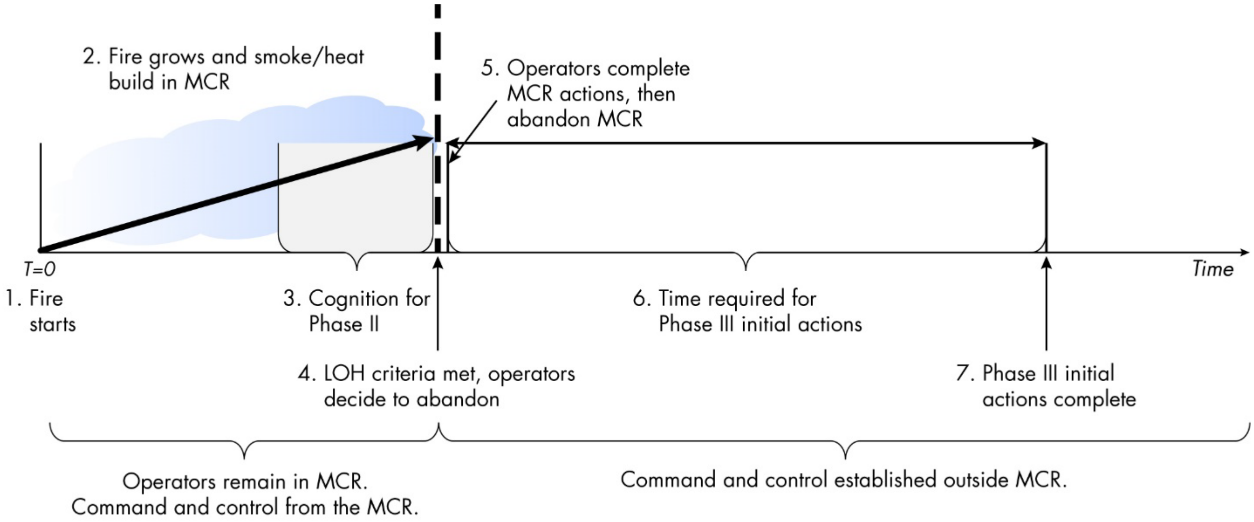

Figure 2-2
Typical MCRA LOH scenario progression

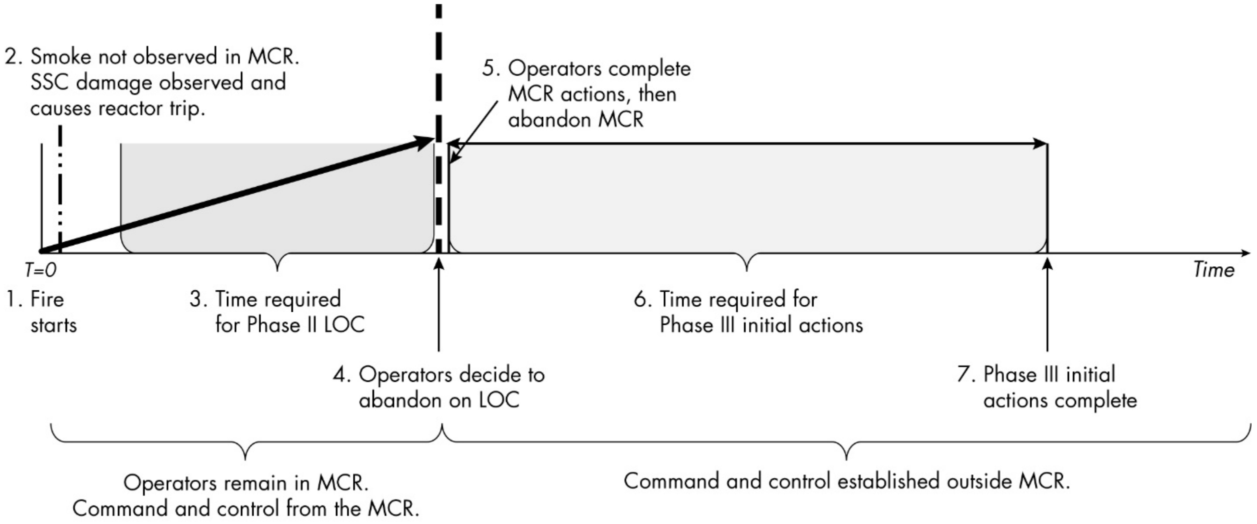

Figure 2-3
Typical MCRA LOC scenario progression

Table 2-1
Comparison of MCRA LOH and LOC timelines (see Figures 2-2 and 2-3)

Time Step*	LOH	LOC
1 – Fire starts	Fire starts at T=0.	
2 – Initial fire growth	Smoke and heat builds in the MCR. The shaded area and arrow in Figure 2-2 show an incremental fire growth and associated smoke buildup. While the fire is detected, it is not suppressed. Structure, system, and component (SSC) damage may prompt Phase I actions and may lead to reactor trip.	The fire grows and is detected in the MCR, and/or SSC damage is observed. Often, the fire damage is modeled as causing a reactor trip at T=0 or shortly thereafter due to failed SSCs.
3 – Cognition for Phase II	As the fire grows, physical cues (e.g., heat, smoke) accumulate, and the operators' understanding of the seriousness of the scenario increases; this represents "cognition" for Phase II in LOH scenarios. During this time period, the MCRA procedure may be reviewed, and operators may don self-contained breathing apparatus (SCBA), in parallel with EOP response.	As the fire grows, cues from systems accumulate and the operators start understanding the seriousness of the scenario. Phase II starts when the minimum set of cues (that correspond with the definition of LOC) are available (T_{delay}). Operator detection and diagnosis starts at this time too. During this time, operators review the MCRA procedure. (Typically, operators will complete the necessary steps in the reactor trip procedure (e.g., E-0) before transitioning to the MCRA procedure.) Also, during this time, additional SSC failures are likely, and the severity of the condition becomes increasingly apparent.

Table 2-1 (continued)
Comparison of MCRA LOH and LOC timelines (see Figures 2-2 and 2-3)

Time Step*	LOH	LOC
4 – Operators decide to abandon (start of Phase III)	LOH criteria are reached, and the operators are forced to abandon. Once the LOH criteria have been met, the time required for the decision to abandon is not zero, but it is expected to be short.	Operators decide to abandon the MCR due to LOC.
5 – Operators complete MCR actions and abandon the MCR	A manual reactor trip may have occurred earlier (e.g., at T=0); it may be performed as the operators leave the MCR; or may occur at any point in between. The time of the reactor trip is used as input to thermal hydraulic calculations that determine the system time window. Operators complete MCR actions (e.g., post-trip actions, transfer control to RSDP), then abandon MCR.	SSC damage causes reactor trip earlier in the scenario. Operators complete MCR actions (e.g., post-trip actions, transfer control to RSDP), and then abandon MCR.
6 – Phase III duration	Time required to perform initial (short-term) Phase III actions.	
7 – Phase III complete	Phase III initial actions are complete.	

*The numbers in this column correspond to time points on Figures 2-2 and 2-3.

The primary difference between determining the timing parameters for LOH and LOC scenarios is driven by the fact that, in an LOH scenario, there is a set time at which the operators will abandon because they cannot physically continue to inhabit the MCR. Whereas, in a LOC scenario, there is no similar function to force the decision, so it is possible that the operators take too long to make (or otherwise delay) the decision past the point where there is sufficient time for Phase III actions to be successful. This difference leads to different approaches to calculating the Phase II and III timing parameters for LOH and LOC.

2.2.1 Development of Phase II and III Timing Parameters for LOH Scenarios

Calculating timing parameters for LOH scenarios follows the same general process typically used for HFEs. The timing parameters for LOH are primarily driven by when the reactor trip occurs, as illustrated in Figures 2-4 and 2-5 (see Table 2-2 for a summary of timing parameters and associated guidance) and as summarized below:

- **Delayed reactor trip**. For scenarios with little or no SSC damage, typically, the reactor trip does not occur until the decision to abandon has been made. Figure 2-4 illustrates the timing parameters for LOH with no SSC damage. In particular, the reactor trip and the decision to abandon are essentially coincident because the operators will trip the reactor before leaving the MCR. This group of LOH scenarios provides the most time available for Phase III actions (i.e., the system time window is measured from when the decision is made to abandon the MCR).
- **Reactor trip caused by SSC damage**. For LOH scenarios that involve SSC damage, the reactor trip may occur when the first SSC is damaged or when sufficient SSCs are damaged

that lead to the reactor trip. A simplifying or an initial modeling assumption is to model the reactor trip at time T=0 since this leaves the least amount of time available for Phase III actions. Figure 2-5 illustrates the timing parameters for LOH with SSC damage close to the start of the fire. In particular, a reactor trip (shown as item #2 in Figure 2-5) can occur at any time between T=0 and when operators decide to abandon the MCR. In this case, there is a time delay from when reactor trip occurs until operators decide to abandon the MCR. Consequently, T_{delay} is equal to the "cognition time" shown in Figure 2-5 (which is the time until LOH criteria are met).

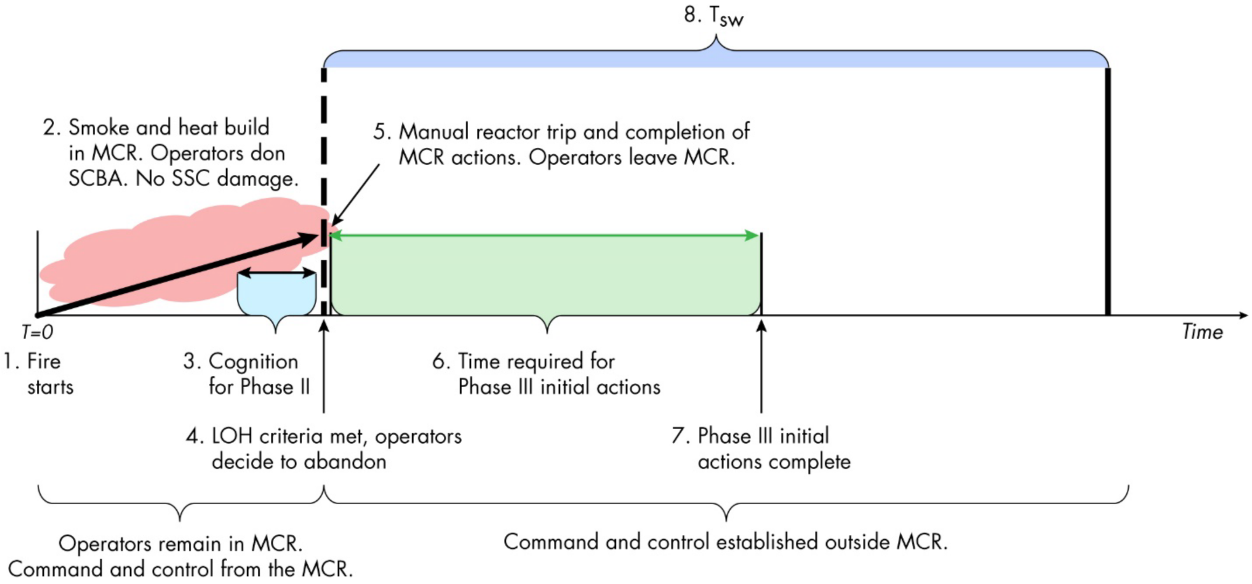

Figure 2-4
Timing parameters for Phase II and III LOH scenarios with no SSC damage (delayed reactor trip)

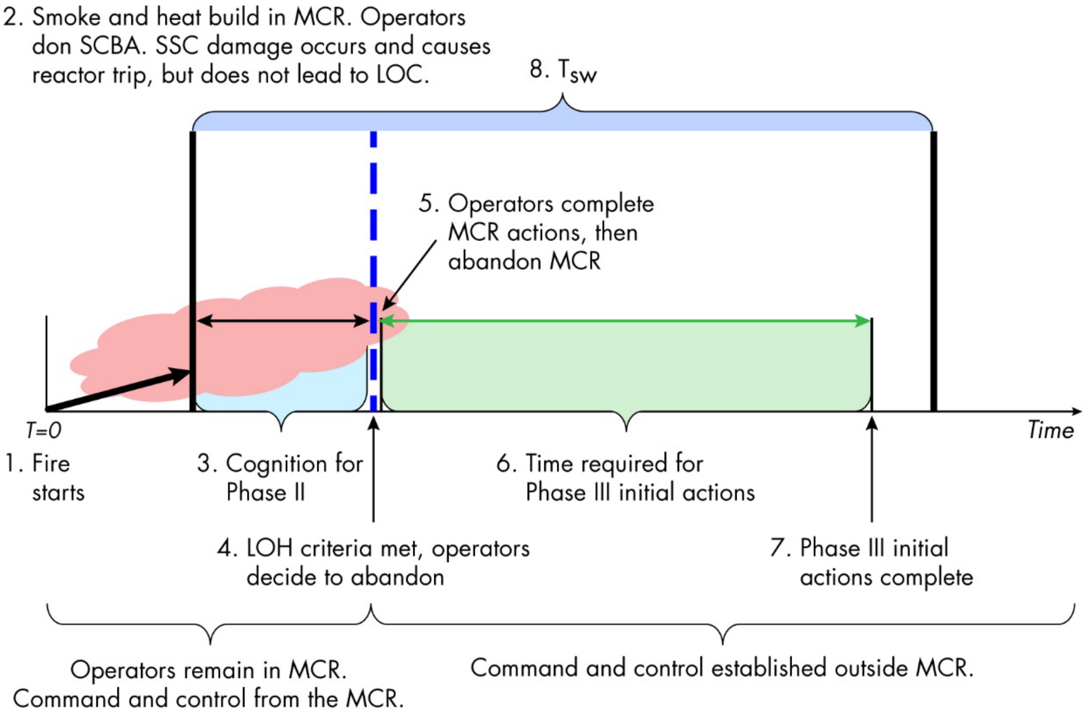

Figure 2-5
Timing parameters for Phase II and III LOH scenarios with limited SSC damage

Table 2-2
Guidance for estimating Phase II and III timing parameters for LOH

LOH Parameter	Guidance
T_{SW}: System time window for the overall MCRA scenario	Section 7.4.2 of NUREG-1921 Supplement 1 [1] provides the definition of a system time window (T_{SW}) for the MCRA scenario. This is the same for both LOH and LOC scenarios (see Section 2.2.2.1 in this report for additional discussion). Delayed reactor trip is more likely for LOH scenarios where the fire may cause no or limited SSC damage. The manual reactor trip may have occurred at T=0, but it is often performed just before the operators leave the MCR (or may occur at any point in between). When the reactor trip is delayed, the time of the reactor trip is used as input to thermal hydraulic calculations that determine the system time window.
$T_{delay,LOH}$: Criteria for abandoning the MCR is met for LOH	Although no HFE is modeled for Phase II in LOH scenarios, the time when operators abandon the MCR (i.e., time delay) is needed for timing calculations performed for Phase III operator actions. $T_{delay,LOH}$ is determined from fire modeling calculations as described in NUREG-1921 Supplement 1, Section 4.1 [1].
$T_{reqd,III}$: Time required for Phase III actions	The time required ($T_{reqd,III}$) to perform initial Phase III actions starts when the operators make the decision to abandon, and ends once safe shutdown conditions have been established (or re-established). This is the same for LOC (see Section 2.2.2.2 for additional discussion).

Table 2-2 (continued)
Guidance for estimating Phase II and III timing parameters for LOH

LOH Parameter	Guidance
$T_{avail,III}$: Time available for Phase III actions	The time available for initial Phase III operator actions in LOH scenarios depends on when the reactor trip occurs: For scenarios when reactor trip occurs at T=0, the time available is calculated as: $T_{avail,III} = T_{SW} - T_{delay,LOH}$ When the reactor trip occurs immediately after the decision to abandon the MCR (e.g., Figure 2-4, numbered item 5), the time available for the initial Phase III actions becomes: $T_{avail,III} = T_{SW}$

2.2.2 Development of Phase II and III Timing Parameters for LOC Scenarios

For LOC scenarios (for which an HFE is modeled for Phase II), the same system time window (T_{sw}) is used for both Phase II and Phase III operator actions; therefore, these two phases must be addressed together (because they are coupled). Also, because of this coupling and because timing parameters associated with Phase II may be difficult to determine, the process used to develop these timing parameters may be iterative and involve allocation (especially for Phase II), rather than an actual calculation of time.

The general approach recommended is to, first, allocate time from the overall scenario to Phase III and then allocate the remaining time to the Phase II decision to abandon (see Figure 2-6). Initially, it is recommended to estimate the time available for Phase III as being equal to the time required for Phase III. However, iterations in this allocation of time may be needed if, for example, recovery (such as self-check or peer check as described in Section 9.2 of Supplement 1) is credited in Phase III. It is important to remember during the development of timing parameters that any adjustments to the Phase III timing will impact the Phase II timing.

For LOC scenarios, the timing evaluation to support Phase II and Phase III HFE quantification should be performed using the process steps listed below, which are graphically depicted in Figure 2-6. The first five steps are accomplished to develop the input needed for Phase II quantification. The last step is accomplished in order to independently check the feasibility based on the time required for Phase II.

1. Calculate the system time window (T_{SW}) for the overall MCRA scenario (i.e., for both Phase II and Phase III).
2. Develop the time required ($T_{reqd,III}$) to perform the initial Phase III actions.
3. Initially, set the time available for Phase III actions ($T_{avail,III}$) equal to the time required ($T_{reqd,III}$) for Phase III actions (i.e., equate the time required with the time available for Phase III actions).
4. Determine the time delay for Phase II (i.e., the time at which the minimum set of cues needed for the decision to abandon on LOC become available) ($T_{delay,LOC}$).
5. Calculate the time available ($T_{avail,LOC}$) for Phase II (i.e., the decision to abandon).
6. Estimate the time required ($T_{reqd,LOC}$) for Phase II to confirm feasibility.

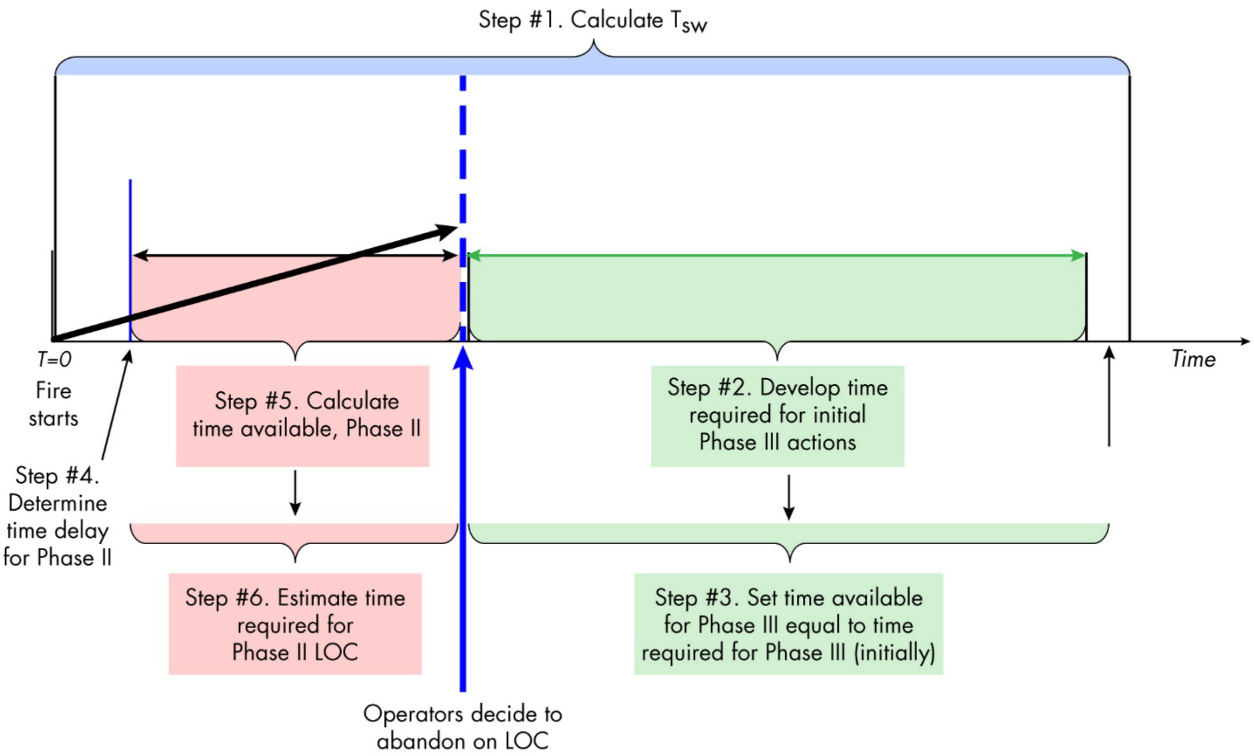

Figure 2-6
Key timing parameters in Phase II and Phase III MCRA LOC scenarios with extensive SSC damage

2.2.2.1 Step 1: Calculate the System Time Window (T_{SW}) for the MCRA Scenario

Definition. Section 7.4.2 of NUREG-1921 Supplement 1 provides the definition of a system time window (T_{SW}) for the MCRA scenario. The system time window is defined from T=0 (if reactor trip is assumed at T=0) until the point where the action is no longer beneficial (typically, when actions must be completed to avoid irreversible damage, such as core or component damage).

Initial actions taken in Phase III are those operator actions needed in the short term to establish (or re-establish) safe shutdown conditions. The system time window for Phase III should be based on the success criteria for the plant functions, system, and equipment associated with these initial actions. This same system time window should also be used to establish the endpoint for the time available for Phase II. Additional actions required to maintain safe shutdown conditions over the long term (e.g., condensate storage tank refill) should be considered separately with a different time window.

Process. The process to determine T_{SW} is the same for both LOH and LOC scenarios. The system time window is established from deterministic calculations such as thermal-hydraulic analyses, room heat-up calculations, or component damage calculations. If the system time window is based on a thermal-hydraulic calculation that was developed for the internal events PRA, then the timing basis should be reviewed to ensure that it remains applicable given the fire damage in the MCRA scenario, such as the fire-induced initiating event and/or spurious operations. For example, if the fire-induced initiating event leads to multiple primary relief valve openings, the T_{SW} can be shorter than for a loss of coolant accident (LOCA) based on one relief valve opening. In all cases, the system time window for the MCRA scenario should be consistent (either realistic or bounding) with the PRA scenario that was modeled, as described in Section 3 of NUREG-1921 Supplement 1.

Depending on the fire characteristics (such as LOH, LOC, limited damage, or severe damage), the development of the timing associated with the system time window may need to be adjusted for the MCRA scenario. Examples of such cases include:

- Delayed reactor trip. Delayed reactor trip is more likely for LOH scenarios where the fire may cause no or limited SSC damage. This can also occur in LOC scenarios such as in a cable spreading room (CSR), depending on the layout of cables in the CSR and the location of the ignition source relative to pertinent cables and components which could produce a trip upon being damaged.
- Time of component damage. Sometimes, the system time window is based on completing an action before component damage or before a vessel is over-filled. These system time windows may be more restrictive than those for core uncovery or core damage.
- Timing of fire damage. The baseline MCRA scenario is often based on a simplified, bounding model where all fire damage occurs at T=0, and the worst-case fire damage is assumed (e.g., all components operated from the MCR are failed). However, in some fire scenarios, the damage may be delayed, or the fire may not damage a running system. Depending on the fire damage and the components that are running prior to operators leaving the MCR, there can be significant variations in the system time window. This is discussed in Sections 7.3.2 and 7.4.2 of Supplement 1.

2.2.2.2 Step 2: Develop the Time Required ($T_{reqd,III}$) to Perform Initial Phase III Actions in LOC Scenarios

Definitions. The time required ($T_{reqd,III}$) to perform Phase III actions starts when the operators make the decision to abandon and ends once safe shutdown conditions have been established (or re-established). This includes: 1) starting the required support systems and front-line systems, and 2) re-establishing control over spurious operations including those that cause a breach in reactor coolant system (RCS) integrity or secondary integrity.

Discussion. Note that the time required at this step is only for the initial Phase III actions needed in the short term to establish (or re-establish) safe shutdown conditions. Once the safe shutdown conditions have been re-established, then subsequent actions may be required to maintain the long-term safe and stable plant condition (e.g., actions to refill the condensate storage tank (CST) or emergency diesel generator (EDG) fuel oil tank). Since these actions occur after the successful restoration of safe shutdown conditions and have a different system time window, these HFEs are not included in the calculation of the time required for Phase III. Instead, these actions are developed using NUREG-1921 Section 4.6.2 models of timing.

Within the collective set of initial actions, the following time parameters (representing a variety of actions), should be considered in the development of Phase III time required:

- Time to travel to the RSDP(s) and other locations where local actions are performed as defined in Section 4.6.2 of NUREG-1921
- Time to transfer control from the MCR to the RSDP or local control station(s)
- Time to electrically isolate the MCR

- Time to implement Phase III actions as defined in Sections 7.4.4 and 7.4.5 of NUREG-1921 Supplement 1,[6] including the following:
  - T_{cog} and T_{exe} for individual HFEs following MCRA
  - Time required for critical communications and coordination among operators (as part of C&C), as defined in Section 5.2.2.2 of this report
  - Time to verify the success of the operator action, including recovery opportunities (if credited)

Depending on the plant MCRA strategy, some Phase III operator actions may be performed sequentially, and some may be performed in parallel. Regardless of how they are performed, the time available for Phase III needs to address the collective set of actions in Phase III that is needed to establish (or re-establish) safe shutdown conditions.

If recovery, including recovery by self-review, is credited in Phase III, then the $T_{reqd,III}$ should be expanded to include the time modeled for the crew to perform that recovery. Additionally, if the reliability of a time-critical Phase III action needs to be ensured by adding a time margin to the time required, then the time available $T_{avail,III}$ equals the $T_{reqd,III}$ (including recovery) plus that time margin.

In Figure 2-7,[7] an example is depicted of the Phase III time required to re-establish feedwater and to re-establish injection. The yellow box shows the overall time available for Phase III, which consists of the time required to establish injection and feedwater plus some margin.

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[6] The discussion in Sections 7.4.4 and 7.4.5 of Supplement 1 focuses on individual actions, and provides examples, but does not discuss the collective set of actions which is what this parameter represents.

[7] Figure 2-7 (adapted from NUREG-1921 Supplement 1), is intended to show the time required for Phase III actions. This figure is not intended to address initial actions versus long-term control actions that may occur after reaching a safe, stable end state.

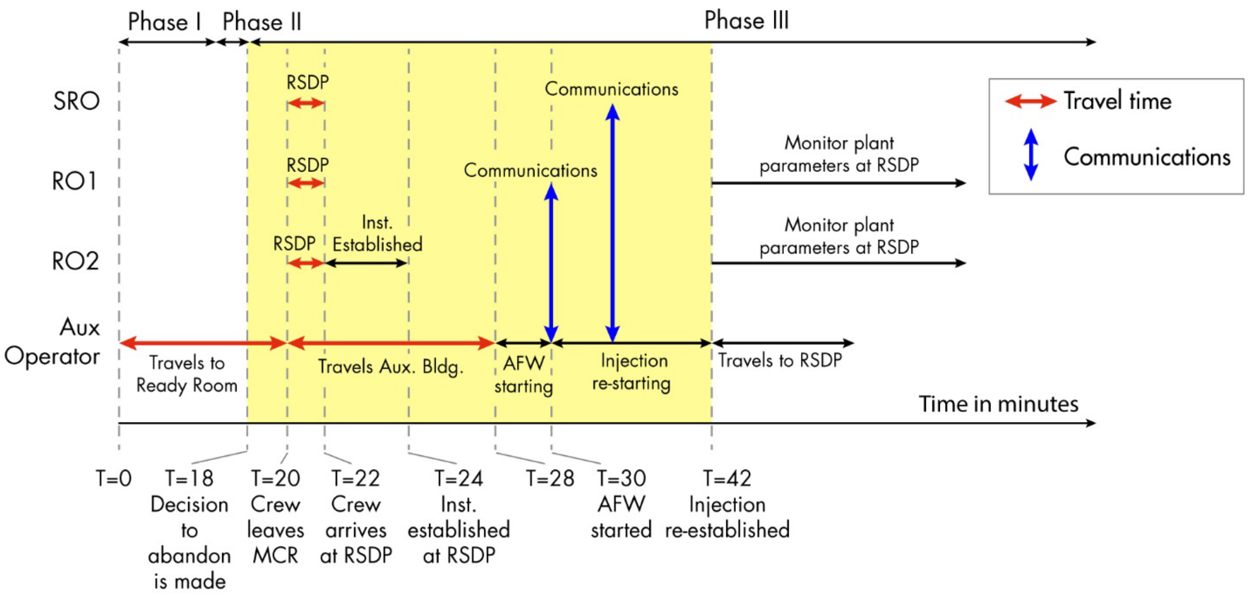

Figure 2-7
Time required to perform short-term Phase III MCRA actions

Process. The process to determine $T_{reqd,III}$ is the same for both LOH and LOC scenarios. The time required for Phase III actions is a best estimate time and, to the extent possible, is determined by timing validation reports, timed walk-through data, and/or talk-throughs of Phase III actions to establish (or re-establish) safe shutdown conditions. As discussed in NUREG-1921, in collecting timing information, developing a range of times is a good practice. Data sources include job performance measures (JPMs) and Appendix R/National Fire Protection Association (NFPA) 805 timing walkdowns. Currently, U.S. NPPs have detailed timing on T_{exe} for individual actions as documented in JPM and training exercises, but these times are generally trained on for a single action conducted in isolation and may represent only part of the set of actions modeled by the fire HRA/PRA. On the other hand, Appendix R or NFPA 805 timed walkdowns may consider all of the actions represented by the fire HRA/PRA, including, for example, time for C&C functions such as the coordination of multiple operator actions. For MCRA HRA, it is important to understand how the actions are related following MCRA (i.e., since not all actions are performed in isolation). Additionally, the time required for Phase III actions may be longer due to communications, coordination, travel time, equipment manipulation, etc.

2.2.2.3 Step 3: Set Time Available for Initial Phase III Actions ($T_{avail,III}$) as Equal to Time Required ($T_{reqd,III}$)

For LOC scenarios, the available time to make the decision to abandon and perform the initial Phase III actions is treated as one block of time that is then allocated by the analyst to Phase II and Phase III for quantification purposes. This is because it is difficult to estimate a time required to make the decision to abandon. Initially, the analyst allocates the minimum amount of time to Phase III by setting the time required for Phase III as equal to the time available for Phase III (i.e., $T_{reqd,III} = T_{avail,III}$). However, iteration may be necessary to increase the time available for Phase III to ensure that these HFEs are reliable and that sufficient time is available for recovery.

2.2.2.4 Step 4: Determine the Time at Which the Minimum Set of Cues for the Decision to Abandon on LOC Becomes Available ($T_{delay,LOC}$)

Definition. Section 4.6.2 of NUREG-1921 defines time delay. For MCRA, this is the time at which the minimum set of cues to satisfy the criteria for abandoning the MCR are present in the MCR. For LOC scenarios, the minimum set of cues typically consists of failed systems or functions and marks the start of Phase II.

Process. For LOC scenarios, this parameter is one of the more difficult parameters to estimate since 1) the cue(s) may not be well defined, 2) the time estimates are not available as a direct result of an engineering calculation or existing measurements, and 3) there are uncertainties regarding how fast the scenario may progress. Insights from fire modeling, operator interviews, and the procedure path should be reviewed to estimate an appropriate $T_{delay,LOC}$. Estimation of this parameter can be done using the following steps:

1. Define the minimum set of cues based on the definition of LOC.
2. Determine the time when those cues are manifested.

The first step, definition of the minimum set of cues, is described in Section 4.2.1 of this report and Section 4 of NUREG-1921 Supplement 1 [1].

The second step determines when those cues are present in the MCR. While fire modeling may indicate that damage can occur quickly following ignition, there may be other activities, such as EOP response occurring in the MCR that may delay when the impact of the damage is detected by the operators in the MCR. $T_{delay, LOC}$ is established by either (whichever is later):

- When the minimum set of alarms or indications are available, or
- The earliest time at the point when the operators acknowledge the cues

Section 4.2.1 of this report discusses, in detail, how to evaluate cues for the decision to abandon, including consideration of when cues occur and when the operators may attend to the cues per procedural guidance.

2.2.2.5 Step 5: Calculate the Time Available ($T_{avail,LOC}$) for the Decision to Abandon

Section 7.4.6 of NUREG-1921 Supplement 1 defines $T_{avail,LOC}$ time as the time available to perform the action. For LOC scenarios, this timing parameter is used to determine which Phase II timing regime is selected when applying the decision to abandon quantification tool (see Section 4.2.4).

The time available for the decision to abandon on LOC is calculated as:[8]

$$T_{avail,LOC} = T_{SW} - T_{delay\ LOC} - T_{avail,III} \qquad \textbf{Equation 2-1}$$

Depending on the time available for Phase II (i.e., the decision to abandon) calculated with the above equation and the resulting HEP obtained with the HRA quantification tool given in Section 4.2.4, the analyst may decide to make further adjustments to the time available allocated to Phase III and, ultimately, Phase II. However, the analyst must be certain that Phase III actions remain feasible and reliable.

2.2.2.6 Step 6: Estimate the Time Required ($T_{reqd, LOC}$) for the Decision to Abandon to Confirm Feasibility

Note: The time required for the Phase II decision to abandon is not explicitly used in this quantification approach; however, it is needed in order to establish the feasibility of the Phase II HFE and to satisfy supporting requirement HR-G5 of the PRA Standard. In particular, $T_{reqd,LOC}$ must be smaller than the time available for Phase II for the decision to abandon in LOC scenarios to be feasible.

Definition. The time required for Phase II ($T_{reqd,LOC}$) is defined as the time needed to recognize, evaluate, and formulate a response to the cues for the Phase II HFE. Specifically, this is the time required for cognition (detection, diagnosis, and decision-making) for the decision to abandon the MCR following a LOC scenario.

Process. Estimate the $T_{reqd,LOC}$ in order to confirm feasibility. For LOC scenarios (based on the current operator training on MCRA), U.S. NPPs do not typically run LOC MCRA scenarios in the simulator, especially the decision to abandon (i.e., MCRA simulator scenarios typically start with the assumption that the decision to abandon has been made). To confirm the feasibility of the HFE for the decision to abandon on LOC scenarios, operator interviews need to be conducted to understand the process used by the operating crew to detect, diagnose, and make the decision to abandon upon LOC. These same interviews can be used to confirm the abandonment criteria and other feasibility information described in Section 4.2 of this report.

2.3 Review Timeline as Part of the HEP Reasonableness and Potential Sensitivity Studies

Once the timeline has been established, it can be used to support the following:

- HEP reasonableness check
- Sensitivity studies

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[8] Note: this formula is a minor change to the one provided in Section 7.3.3.2 of Supplement 1:

$$Maximum\ time\ available\ for\ decision\ to\ abandon = T_{SW} - T_{Delay} - T_{reqd,III}$$

The difference is, that the Supplement 1 formula uses $T_{reqd,III}$, while this report uses $T_{avail,\ III}$. This change was made to reflect that, while the process typically starts by setting $T_{avail,III}$ equal to $T_{reqd,III}$, there is room for iteration in the allocation of time available between Phases II and III. Particularly, it may be appropriate to adjust and increase $T_{avail,III}$ to account for the recovery margin; in which case, the larger of the two numbers should be used to determine the time allocation for the decision to abandon.

2.3.1 Reasonableness Check

Developing a single timeline integrating the modeled operator actions in a scenario is an important tool that lays out each of the HFEs on a common axis to check for overlap between actions and to provide for an allowance for communication and coordination. Ultimately, however, it is done to ensure consistency across the set of MCRA HFEs. The development of an integrated timeline also applies to the reasonableness check portion of the PRA Standard (SR HR-G6) and is useful to identify sources of uncertainty for potential quantification as sensitivity cases.

Suggested areas to be addressed by the reasonableness review include:

- System time window allocation, resulting in the time available for Phase II and the time available for Phase III
- Ensuring that any recovery of initial Phase III restoration actions fits within the time available for Phase III
- Process for assessing the time delay for Phase II
- Interaction between the fire cues physically present versus any delays attending to those cues due to being in the EOPs
- Process for assessing the time required for the decision to abandon
- Selection of the parameters used in the timeline development

2.3.2 Timing Sensitivity

Some of the key timing parameters involved in the quantification of MCRA operator actions can be subjective and, therefore, include a potentially large variability (i.e., a source of uncertainty in the quantification of MCRA operator actions). Sensitivity studies should be particularly considered for the timing parameters that lead to inflection (turning) points in the quantification, including:

- $T_{delay, LOC}$
- Amount of time in $T_{reqd,III}$ (particularly any time allotted for recovery) and its impact on $T_{avail,LOC}$

2.4 References

1. EPRI/NRC-RES Fire Human Reliability Analysis Guidelines—Qualitative Analysis for Main Control Room Abandonment Scenarios: Supplement 1. U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Washington, DC, and Electric Power Research Institute (EPRI), Palo Alto, CA: 2017. NUREG-1921 Supplement 1 and EPRI 3002009215.
2. ASME/ANS RA-Sa-2009, Addenda to ASME/ANS RA-S-2008, Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications. The American Society of Mechanical Engineers, New York, NY, February 2009.
3. EPRI/NRC-RES Fire Human Reliability Analysis Guidelines – Final Report. U.S. Nuclear Regulatory Commission, Rockville, MD, and the Electric Power Research Institute (EPRI), Palo Alto, CA: July 2012. NUREG-1921, EPRI 1023001.

3

PHASE I – PRE-ABANDONMENT ACTIONS

3.1 Introduction

In Phase I, C&C is still located in the MCR, and the operators will be interacting with the fire brigade and performing any necessary actions in the MCR. Up until the time that the minimum set of cues is presented that indicate to the operators that MCRA should be considered, the operators will be following a set of EOPs as well as the FRPs. Due to the severity of the fire, they may also be reviewing the MCRA procedure(s).

While the detection of fire will occur in Phase I, the fire PRA typically gives very little credit for the operators performing many actions. This is because it is generally assumed that, as severe fire conditions are beginning to present themselves, the operators discontinue use of the EOPs and focus on the FRPs. Consequently, in the most rapidly developing scenarios, the Phase I timeframe is expected to last only a matter of minutes based on either LOC or LOH conditions.

Table 3-1 lists the types of actions that have been indicated in the procedures as potential Phase I actions for both pressurized water reactors (PWRs) and boiling water reactors (BWRs).

Table 3-1
Potential Phase I actions taken prior to abandonment

Reactor Type	Potential Phase I MCRA Actions
BWR & PWR	Reactor trip
	Turbine trip
	Start of the EDG – either remotely or from the MCR.
	Align service water (SW) and/or cooling to the EDGs.
	Isolate main steam.
	Start standby train of support system (e.g., component cooling water (CCW)/ emergency service water (ESW)/SW).
	Bus alignments to recover power
	Transfer control from the MCR to the RSDP by manipulating switches/breakers in the MCR
BWR	Anticipated transient without scram (ATWS) – standby liquid control (SLC) or boron injection
	Start reactor core isolation cooling (RCIC)/high pressure coolant injection (HPCI) – either remotely or from the MCR.
	Actuate engineered safety features actuation system (ESFAS) signal if it failed to actuate automatically.

Table 3-1 (continued)
Potential Phase I actions taken prior to abandonment

Reactor Type	Potential Phase I MCRA Actions
BWR (continued)	Control reactor pressure vessel (RPV) level – Throttle back HPCI/RCIC to avoid a high level trip.
	Close the containment isolation valves.
PWR	Trip the RCPs - either remotely or from the MCR.
	Start safety injection (SI) after the auto start signal fails.
	Start auxiliary feedwater (AFW)/main feedwater (MFW) – either remotely or from the MCR.
	Actuate charging/align charging pump suction to the refueling water storage tank (RWST).
	Place all non-running charging pumps in pull-to-lock.

A reactor trip prior to abandonment is usually credited. Unless specific procedural direction is given for equipment manipulation prior to MCRA (e.g., starting an EDG from the MCR or locally, or starting a system that failed to auto start), the HRA usually credits such actions as part of the Phase III execution. This places more operational burden on Phase III and gives less credit to actions prior to abandonment due to the constrained MCR capability and timeframe for response.

The success or failure of Phase I actions can define the plant conditions following abandonment. For example, if the operators recover the EDGs before abandonment, then alternating current (AC) power will be available following abandonment.

3.2 Quantification Guidance for Phase I HFEs

Phase I is considered to be similar to non-MCRA fire events in terms of procedure use, C&C location, and types of operator actions. Any ex-MCR operator actions performed during Phase I are directed from the MCR, similar to other fire scenarios. The recommended guidance for quantification of Phase I HFEs is provided in NUREG-1921 [1] for evaluating the context under which operators are performing any actions prior to leaving the MCR.

However, the evaluation of Phase I actions needs to carefully account for the environment and the stress the crew is likely to be facing. Consideration should be given to environmental effects (e.g., smoke, heat), increasing the stress level, and time for cue recognition (i.e., T_{delay}) or cognitive processing time (i.e., T_{cog}) because operator attention is distracted by the fire effects, including fire brigade activities and communications. These modifications should be based on input from operator interviews.

3.3 References

1. EPRI/NRC-RES Fire Human Reliability Analysis Guidelines – Final Report. U.S. Nuclear Regulatory Commission, Rockville, MD, and EPRI, Palo Alto, CA: July 2012. NUREG-1921, EPRI 1023001.

4

PHASE II – DECISION TO ABANDON

This section provides guidance on how to develop the HEP for the HFE that represents the decision to abandon the MCR following a fire-induced scenario. This HFE is the only HFE explicitly modeled in Phase II of the MCRA timeline. The fire PRA analyzes two types of scenarios where the operators would need to abandon the MCR:

1. Scenarios that result in the MCR environment becoming untenable due to heat or smoke, referred to as LOH scenarios
2. Scenarios that result in a loss of the ability to successfully operate and monitor safe shutdown equipment from the MCR such that core damage is prevented, referred to as LOC scenarios.[9]

For LOH scenarios, the operators are driven from the MCR by high heat and smoke (including lack of visibility). Consequently, the failure probability for the decision to abandon is considered negligible in the fire PRA. This is discussed in Section 4 of NUREG-1921 Supplement 1 [1].

For LOC scenarios, the decision to abandon the MCR is modeled as an HFE. This HFE consists of the cognitive aspects associated with the assessment of the situation including:

- The detection of cues
- The diagnosis of the need for abandonment
- Making the decision to abandon

Once the decision has been made to abandon the MCR, Phase II ends and Phase III, which represents those operator actions and associated HFEs that model the execution following the decision to abandon, begins.

4.1 Development of the Quantification Approach for Phase II

This section summarizes how the quantification approach for Phase II was developed. The technical basis for the quantification approach is described in Appendix B of this report. Six HRA methods (CBDTM [2], HCR/ORE [2], SPAR-H [3], IDHEAS [4], NARA [5], and CREAM [6]) were reviewed to see if these methods provide adequate guidance or could be modified to provide adequate guidance to address LOC scenarios. Several LOC scenarios were reviewed and tested against these methods to determine if existing, current quantification methods could directly address the challenges and potential failure mechanisms identified in Tables 8-1 and 8-2 of NUREG-1921 Supplement 1 [1].

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[9] The LOC may occur from fire-induced failures or from fire-induced failures plus one or more random failures. An example would be hot shorting of control cables during a fire in the CSR. The operators would have no way to make the distinction between these two scenarios. The operators only know that they have lost control and are unable to re-establish control from the MCR. Therefore, their decision to abandon the MCR is unaffected by why the LOC occurs. As a practical matter, however, the LOC scenarios that include additional random failures are typically lower frequency scenarios and, consequently, are less likely to significantly impact the overall risk from MCRA scenarios.

After examination and review of these methods, it was concluded that the existing, current HRA methods did not adequately address the operators' reluctance to abandon the MCR. Reluctance was considered to be an important factor for many NPPs. Reluctance can cause a delay in abandonment while the operators confirm the impact on plant systems and indications to the point where it may be too late to abandon and still safely shutdown the plant. Thus, the HRA team developed a new quantification approach. This new decision tree is based on: 1) a list of issues important to the decision to abandon developed by the author team, 2) confirmation and additional prioritization of issues by an expert panel, 3) the structure and content of the original cause-based decision trees (CBDTs) (as well as HCR/ORE), and 4) specific adaptations to account for variations in the time available for operators to make the decision to abandon the MCR. The authors found through discussions with SMEs that operator reluctance could not be quantified as an explicit factor (i.e., a separate heading on the decision tree) and, instead reluctance is implicit in the assigned HEPs for all relevant PSFs. However, it was judged that reluctance can be somewhat offset by procedure quality and effective training. Consequently, these impacts are modeled explicitly.

The impact of reluctance was considered during the expert elicitation process and implicitly incorporated into the end point HEP values shown on the decision tree in Section 4.2.4. The experts were asked to provide best estimate HEPs for end points on the decision tree starting with the worst case (end state 24, given feasibility) and then the best case (end state 1). Following the extreme scenarios, then the expert panel addressed the mid-range scenarios. Because of the process followed to generate the HEPs, there are many scenarios which the experts believed have the same HEP because the individual factors could not be evaluated independently.

Appendices A and B provide additional details on the expert elicitation panel and the process used to develop the decision tree and the endpoint HEPs (shown in Section 4.2.4). Appendix D provides an overview of the current understanding and HRA modeling practices for decisions with serious consequences.

4.2 Quantification Guidance

The quantification process starts with the identification, definition, and qualitative analysis described in NUREG-1921 Supplement 1. This process includes the definition of the scenario context, specifying the fire-induced initiating event, the fire-damaged components, and the successes and failures of components and systems before the decision to abandon is made. The context also includes environmental factors (e.g., smoke) and staffing considerations such as whether some MCR staff may leave the MCR in order to join the fire brigade. The LOC scenarios can be caused by fires in the MCR front panel area, MCR back panel area, or in a separate room that impacts controls or indications in the MCR. CSRs often include fire scenarios that lead to LOC. In some cases, the fire that causes a LOC may cause smoke in the MCR, but not enough smoke and heat to cause abandonment on LOH.

Inputs to the Phase II HFE quantification are summarized in the following bullets:

- Definition, context, and qualitative assessment. Section 3.2.4 and Section 4 of NUREG-1921 Supplement 1 develop the HFE definition, including scenario context, and provide guidance on the qualitative assessment of the HFE associated with the decision to abandon.
- Timing parameters
  - Definitions. Section 7.3.3 of NUREG-1921 Supplement 1 defines timing parameters associated with Phase II within the context of the combined MCRA scenario timeline.
    - Section 7.6.2 of NUREG-1921 Supplement 1 provides an example timeline for a LOC scenario.
  - Timing parameters for quantification. Section 2 of this report describes the further development of the MCRA timeline and develops guidance for the selection of timing parameters used for quantification.

Once the context is established, the quantification process for the decision to abandon consists of the following steps:

1. Evaluation of the MCR indications and alarms that are used as cues for the decision to abandon (e.g., how do these cues support operators' situation assessment for abandonment?),
2. Development of timing parameters,
3. Feasibility verification, and
4. HEP assessment.

4.2.1 Evaluation of Indications as Cues for Abandonment

Overall, the collective set of cues must first be defined by the HRA/PRA team and evaluated for how and when the operators will be able use the cues for diagnosis of the decision to abandon the MCR during an LOC scenario. There could be a wide variation between operators on definitions of what the collective set of cues will be for abandonment and, in these cases, the HRA should work to define the consensus definition for LOC scenarios. If a consensus opinion cannot be defined, then the decision to abandon HEP is 1.0.

As noted in Section 3.2.4 of NUREG-1921 Supplement 1, for LOC, fire modeling may only provide fire-induced failures and inputs to the thermal-hydraulic analysis that determines when the LOC conditions are reached, given those failures. Before the decision to abandon can be considered, the scenario must progress to the point where there is a set of cues and indications associated with MCRA that the operators must observe.

Typically, there is no single indicator or explicitly defined parameter-based cue that is used to determine when the MCR must be (or would be) abandoned for LOC scenarios. The “cue” for abandonment is, in reality, a progression of indications about the fire, including fire-induced failures and fire growth. Different fire locations and different fire growth progressions will result in variations in how the LOC scenario will progress and when associated indications occur. Regardless of scenario-specific progression, operators will continuously evaluate information as plant conditions and associated indications change. To credit abandonment for LOC scenarios, the operators' understanding of the plant conditions and associated indications needs to reach a “tipping point” that operators equate with a sufficiently severe situation to satisfy the abandonment criteria. Also, as noted in NUREG-1921, Supplement 1, Section 4.2, such abandonment criteria must be defined, either through explicit procedural guidance or from a consensus opinion from operator interviews.

In all cases, some level of judgment is required in the decision to abandon for LOC scenarios, and operators must rely on their training to think critically and integrate their overall understanding of the plant state and plant response. The required pieces of information can include confirmation of a fire, confirmation of fire damaged equipment, and reaching procedure steps that provide the abandonment criteria. The set of cues and indications needed for the decision to abandon will be plant-specific and are defined by existing procedure guidance, training, operator interviews, simulator observations, and/or talk-throughs.

The HRA determines the following, and each of these items is independent of fire modeling:

- The time needed for the operators to detect the plant conditions expected in an LOC scenario
- The time needed for the operators to determine that the conditions correspond with an LOC scenario
- The time needed for the operators to decide to abandon, given that LOC conditions exist, and for the operators recognize that it is an LOC scenario

Before one can determine how long it takes for any of the items above, one must first understand "how the operators assess the situation." For existing U.S NPPs, the cues for a LOC do not usually come directly from the abandonment procedure in the same way as they emerge from AOPs and EOPs. The abandonment procedure does not typically provide unambiguous cues for abandonment (i.e., when parameter x reaches value y, and alarm z occurs) that are typical for most accident conditions. Some guidance along these lines may appear in the procedure, but, in the end, there is always a certain amount of discretion given to the final decision maker (i.e., shift supervisor (SS) or shift manager (SM)) to declare when it is no longer possible to successfully reach a safe and stable condition from the MCR.

For this reason, the determination of the cues for LOC requires significant interaction between the PRA analyst, fire modelers, and HRA analysts, since (as noted above and confirmed by operator interviews) the MCRA procedures generally do not contain the same specificity of cue-response as do AOPs and EOPs. It will be necessary for the logic modeling and fire modeling analysts to provide insights into the expected fire-induced failures that will dominate the LOC scenario(s). LOC scenarios are those that will lead directly to core damage if the operators remain in the MCR (i.e., in the absence of operator actions taken following abandonment). For each LOC scenario (or group of scenarios that share the same characteristics) that would lead to core damage in the absence of abandonment actions, the HRA analysts will need to conduct operator interviews to determine if the abandonment procedures and equipment cover these situations and also whether the operators would interpret the conditions as LOC. The HRA team would then define the specific cues/conditions that the operators would interpret as LOC, and the PRA analyst would implement logic in the model that would allow MCRA credit when (and only when) those cues/conditions exist. The details of the interview process and how it is used to determine the cues that may lead operators to abandon are contained in Section 4.3.3 of NUREG-1921 Supplement 1. Also, Section 4.6.2 in NUREG-1921 provides basic definitions for HRA timing parameters.

The following steps describe the systematic process for the HRA analyst to evaluate the operator's assessment of the indications and alarms used as cues during LOC situations.

1. Define the minimum set of indications that would lead to MCRA based on the criteria specified in the procedures. This step includes a check of the operator's understanding and interpretation of these criteria based on their training. While it is useful to know what the procedures say, they may not be specific regarding the criteria, so it is critical to understand how the operators develop or assess a consensus definition of the MCRA criteria to model the "as-operated plant." Because of the potential variability between operators, it is suggested that the HRA analyst interview multiple operators or operator trainers.
2. Identify the indications and alarms associated with each LOC scenario, across the range of all LOC scenarios. For example, some scenarios may have limited fire damage and other scenarios may have extensive fire damage. These alarms and indications may be the direct result of fire damage or may follow from the fire impact such as a reactor trip or spurious component operation. See Table 2-2 in Section 2 of NUREG-1921 for the range of fire-impacts. For example, each LOC scenario may consist of one, several, or all of the following types of fire-induced initiating events, depending on the fire impacts and the cable layout and routing information:
   - Loss of decay heat removal
   - Loss of primary and/or secondary integrity leading to a safety injection actuation
   - Inadvertent safety injection actuation
   - Loss of offsite power and/or station blackout
   - Loss of support systems
3. Evaluate the earliest time when the alarms and indications identified in Step 2 meet the criteria established in Step 1 and start to be evaluated by the MCR operating crew. This is the time that the set of cues is available for the operator to evaluate, and is the timing parameter $T_{delay,\ LOC}$. As described in Section 2.2.2.4, there are two parts to this evaluation:
   a. Identify when the minimum set of alarms and indications is available.
   b. Identify the earliest time that the operators start attending to the cues, typically after completing the reactor trip procedure. See Section 2.2.2.4 for additional details.
4. Determine what checks or confirmations the operators might perform to verify that LOC criteria have been met. For example, checks might be conducted of local indications on systems that appear to be inoperable or non-responsive to controls in the MCR.

Figures 4-1 through 4-4 show several different timelines depicting how the indications leading to the decision to abandon might present themselves. In all cases, there is a time delay (T_{delay}) that is defined as the earliest time at which the collective set of cues is available and the plant staff are available to evaluate the indications.

While fire modeling often suggests that fire-induced component damage occurs quickly following ignition, the component failures may not fail the critical systems associated with the MCRA criteria immediately. For example, the fire can cause valves to close that fail cooling to a pump, but the pump can continue to run for some time after the support system failure.

The impact of the fire damage is initially detected in the MCR and is usually locally confirmed by a plant operator. Specifically, the fire damage leading to LOC is typically modeled as sufficiently large to cause a reactor trip. Operators typically focus on the reactor trip response and the associated fire procedures are not entered until the reactor trip response is complete. Consequently, operator recognition of fire-damaged components may be delayed until after the reactor trip.

Each plant will have a unique definition of what the collective set of cues is for the decision to abandon on LOC. To illustrate this concept, four different scenarios are presented in Figures 4-1 through 4-4, along with the defined collective set of cues for each scenario.

In scenario 1, the alarm response procedure directs the operators to consider abandoning the MCR for a fire in the CSR after local confirmation of a fire. Operator interviews confirmed that they will not consider abandonment until major systems and instrument failures are identified, the immediate memorized actions of procedure E-0 are completed, and local confirmation of the fire is obtained.

Figure 4-1 shows a timeline identifying key events for Scenario 1 (variation 1).

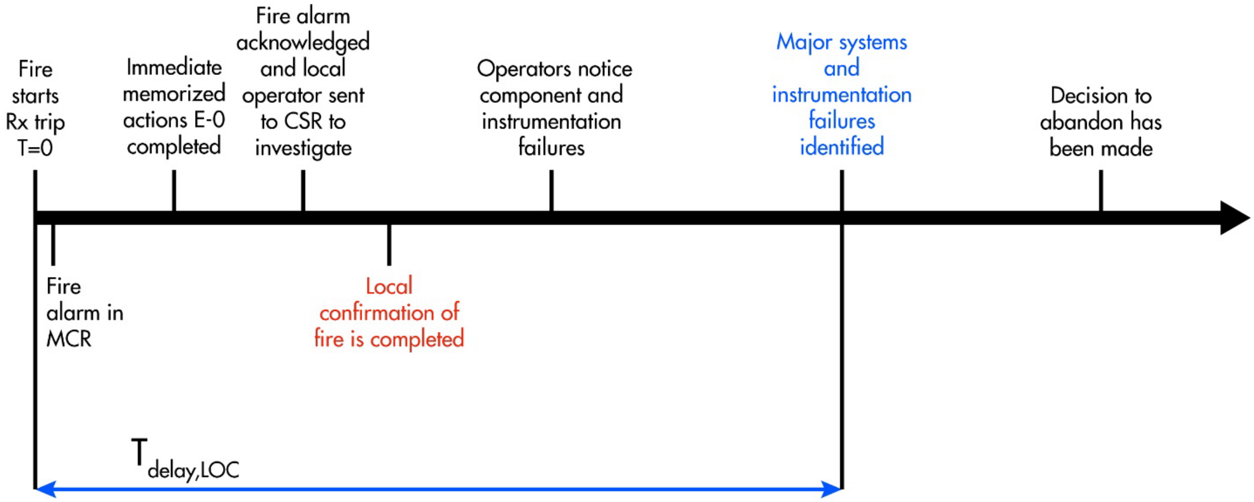

Figure 4-1
Scenario 1: Cable spreading room fire (variation 1)

Figure 4-1 shows that the first indication of the fire is an annunciated alarm on a fire alarm panel. For severe fires, such as those that would lead to MCRA, the fire alarm and equipment trouble indications could be simultaneous or could occur in a different order.

Figure 4-2 shows an example timeline for a second variation of this CSR fire where the first indication of the fire is component and instrumentation failures (rather than fixed fire detection).

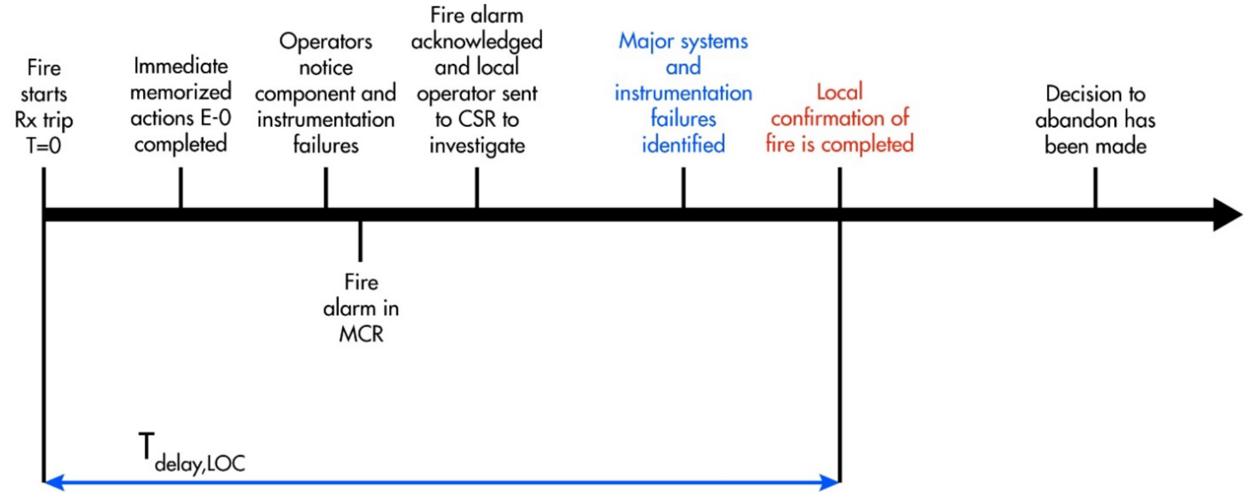

Figure 4-2
Scenario 1: Cable spreading room fire (variation 2)

In scenario 1, the minimum set of cues needed before the decision to abandon would be:

1. Immediate memorized actions following reactor trip are completed,
2. Local confirmation of the fire is obtained, and
3. Major systems and instrument failures are identified.

For both variations of scenario 1, the T_{delay} for the decision to abandon would be the time at which the latest cue occurs, which, in both cases, is major system/instrumentation failures.

Scenario 2 represents a fire in the MCR, but the fire location is not detected until after the reactor trip occurs. For this particular example, the procedure guidance directs the operators to abandon any time there is a fire in the MCR that damages a SSC and potentially leads to a loss of plant control. In scenario 2, the cue for the decision to abandon is the confirmation of fire that impacted at least one SSC, such that other damage may have also occurred and because the extent of damage is unknown the operators are trained to abandon the MCR. Figure 4-3 shows a timeline identifying the key events for Scenario 2.

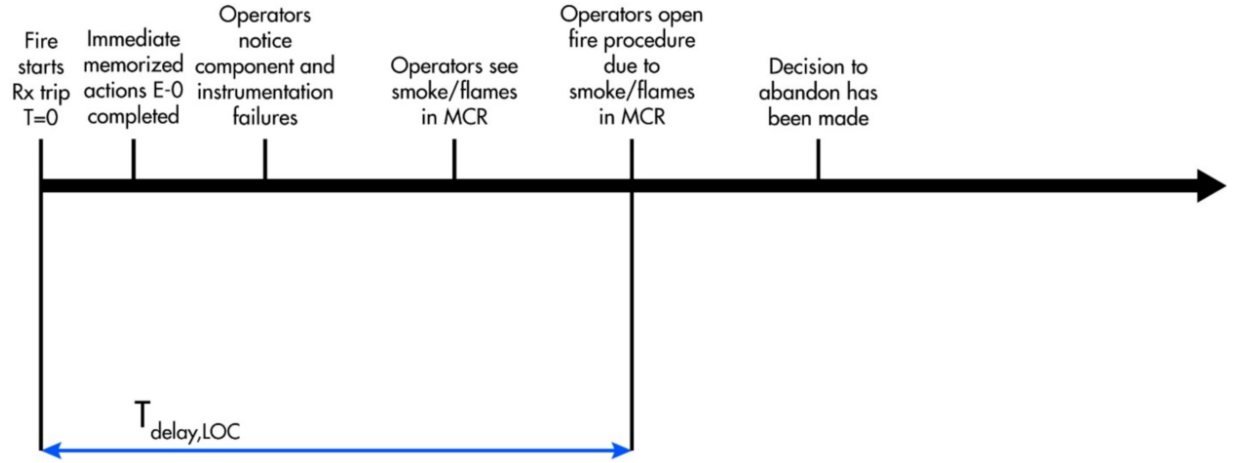

Figure 4-3
Scenario 2: Fire in the MCR (reactor trip occurs before operators identify fire)

In Figure 4-3, the operators are trained to leave the MCR for fires that cause SSC damage regardless of whether the MCR remains habitable. While verification of the fire in the MCR is the primary cue, the decision to abandon may not occur until after operators have identified damage to component and instrumentation failures in the MCR.

In Figure 4-3, the minimum set of cues needed before the decision to abandon would be:

1. Operators visually confirm fire inside the MCR,
2. Operators confirm that at least one SSC is impacted.

In Scenario 2, unlike the first scenario, the immediate memorized actions will have been completed, but they are not considered a cue for abandonment. In addition, the operator may notice fire impacts to components before they have visual confirmation of a fire, but again, this is not a requirement for abandonment.

Scenario 3 is similar to Scenario 2 in that procedure guidance directs the operators to abandon any time there is a fire in the MCR. However, based on operator interviews and their training, the crew will not abandon the MCR for LOC conditions until after SSC damage has been identified. Figure 4-4 shows a timeline identifying the key events for Scenario 3.

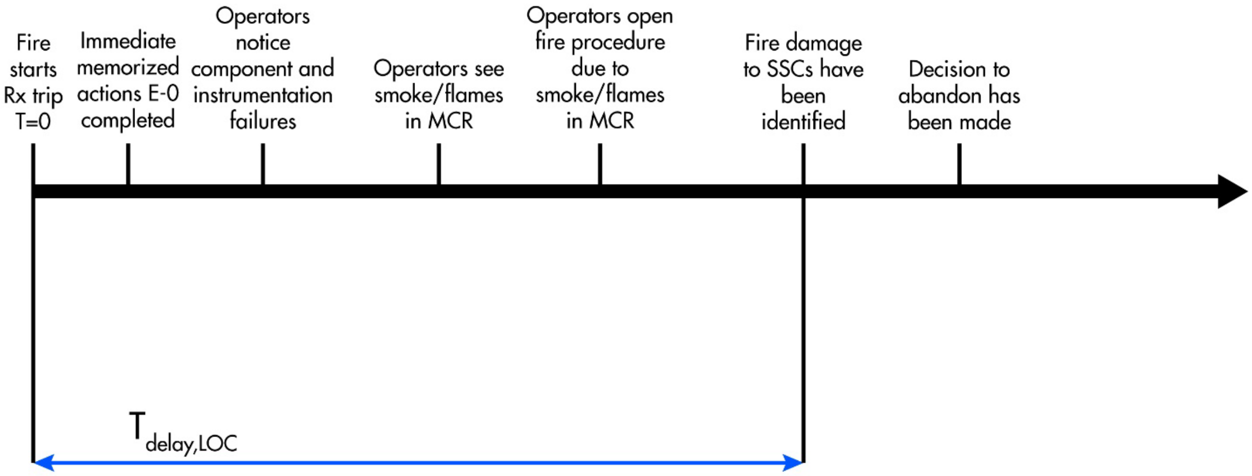

Figure 4-4
Scenario 3: MCR fire with confirmed damage to SSCs

In Figure 4-4, the collective set of cues does not exist until the shift supervisor confirms damage to SSCs. This point will occur after several major systems are determined to be unavailable from the MCR.

In Figure 4-4, the minimum set of cues needed before the decision to abandon would be:

1. Operators see smoke inside the MCR,
2. Fire damage to SSCs in several major systems has been confirmed.

As noted at the beginning of Section 4.2.1, there could be a wide variation from one operator (or operating crew) to another on definitions of what the collective set of cues will be for abandonment, and, in these cases, the HRA should work to define the consensus definition for LOC scenarios. If a consensus opinion cannot be defined, then the decision to abandon HEP is 1.0. This is because there is not a predicable response from the operating crews.

4.2.2 Timing Parameters for Phase II

The timeline for the decision to abandon (Phase II) is highly coupled with the timeline for Phase III. This is because Phase II must end early enough such that all of the Phase III operator actions can be completed in time to satisfy the PRA success criteria (typically, safe shutdown avoiding core damage). See Section 2.2.2 of this document for the definition and the description of the process to develop the Phase II and Phase III timeline.

Development of the timeline will produce the following timing parameters that are used in the qualitative analysis and the quantification of the associated decision to abandon HEP, including:

1. Time at which the minimum set of cues needed for the decision to abandon on LOC becomes available ($T_{delay, LOC}$). See Section 4.2.1 for a description of the progression of cues and indications, and other factors potentially leading to delay.
2. The time available ($T_{avail, LOC}$) for the decision to abandon.
3. The time required to make the decision to abandon ($T_{reqd,LOC}$), which may also be called $T_{cog, LOC}$ (to confirm feasibility).

4.2.3 Verification of Feasibility for Phase II

Section 6.4 of NUREG-1921 Supplement 1 describes the feasibility assessment for MCRA scenarios. Table 4-1 identifies additional feasibility criteria applicable to the decision to abandon HEP. Sections 4.2, 6.2, and 6.4 of NUREG-1921 Supplement 1 are also helpful references.

Table 4-1
Decision to abandon feasibility criteria

Item	Topic	Criteria
1	Information available for operators to make a decision: Sufficient indications and/or alarms to be a cue	Indications and/or alarms must be available in the MCR to alert the operators that they need to abandon. The indications and/or alarms associated with the scenario must match the plant's criteria (set of cues) or the consensus definition of the cues used by the operators for MCRA. See Section 4.2.1 for a description of the collective set of cues. In addition, there must be sufficient staff available to collect and assess the cues associated with the decision to abandon, including local indications if used or verified. If there are no alarms or indications available to satisfy the abandonment criteria (the LOC criteria in the procedures or the consensus opinion on the LOC definition), then the decision to abandon is not feasible.
2	Sufficient time	The time available for the decision to abandon must be greater than the time required for cognition. See Sections 2.2.2.5 and 2.2.2.6 for guidance on how to calculate the time available and the time required.

Table 4-1 (continued)
Decision to abandon feasibility criteria

Item	Topic	Criteria
3	Operators able to recognize the need to abandon through: Explicit procedure guidance on cues OR Training (basis for operator consensus opinion)	There are separate criteria, depending on which case applies to the NPP being analyzed. There are two cases that may exist. The first case is when the procedures explicitly define the cues used for the decision to abandon the MCR during LOC. The second case is when cues are not explicitly proceduralized, such that operator judgment is the sole basis for the cue, and the operators demonstrate that training and experience provide a set of well-understood and consistent cues. One of the following two criteria must be met; otherwise, the decision to abandon is not feasible as stated in Supplement 1 [1]: 1. The abandonment procedure contains explicit guidance on the "cues" for abandonment, as is typical in other formal operating procedures such as EOPs. (Currently, this case is the least common one for U.S. NPPs.) OR 2. Explicit guidance for abandoning the MCR based on LOC does not exist; thus, a substantial amount of judgment is required. In this case, the identification (or sometimes the development) of a set of well-understood cues is performed through interviews of operators and trainers, and requires that they provide a consistent message on "this is what we understand to be a LOC." (Currently, this case is the most common one for U.S. NPPs.) In U.S. NPPs, the MCRA criteria are stated in procedures, but sometimes this simply reads, “for a fire in this area, consider abandoning the MCR.” Consequently, this decision is left to the discretion and judgment of the SS/control room supervisor (CRS). If there is no explicit procedural guidance **AND** consensus opinion cannot be defined, then the decision to abandon is not feasible and the HEP = 1.0.
4	Sufficient training	There must be some training on “how to make the decision to abandon” for LOC scenarios, or else the decision to abandon is not feasible. This training can be either in the classroom or simulator, but it should be part of the plant-specific training schedule. If there is no formal of training on the decision to abandon for LOC scenarios, then the decision to abandon is not feasible and the HEP = 1.0.
5	Sufficient staffing	In order to make the decision to abandon on LOC, staff are typically needed in the MCR and in the plant. Local operators provide input such as confirmation of the fire and other local indications as described above in item #1 of this table. Additionally, all MCR staff who evaluate the MCR indications, communicate with local operators, and make the decision to abandon must be present. The shift technical advisor (STA) is not typically required for making the decision to abandon; however, the STA may assist in monitoring and evaluating key parameters such as critical safety functions that are likely to be impacted in LOC scenarios. If there are insufficient staff, then the decision to abandon is not feasible and the HEP = 1.0.

4.2.4 Quantification of Decision to Abandon

The final step in the quantification of the decision to abandon the MCR for LOC scenarios is performed when the previously discussed steps are complete.

The assignment of an HEP is produced by using a decision tree. Figure 4-5 presents the decision tree logic, and Table 4-2 provides the guidance associated with each end state. Appendix B describes the process used to develop the decision tree, including the quantitative input (i.e., HEP estimation) obtained during the expert elicitation.

The quantification approach presented in Figure 4-5 is based on current U.S. NPP practice and is implicitly dominated by reluctance. For LOC scenarios, operators are generally considered to be reluctant to leave the MCR because the MCR is the primary location of instrumentation and control for plant equipment. This was identified during interviews of operators and operations staff who represent experience at a variety of NPPs. Operator reluctance to leave the MCR is related to various factors including the capability, or perceived capability, of the RSDP, the quality of training, the quality of procedures, and/or the operator confidence in the post-abandonment strategy.

While "reluctance" is considered the dominant influence on the decision to abandon in LOC scenarios for current U.S. NPPs, there may be ways to reduce the influence of reluctance in the future through, for example, significant changes to plant training, procedures, and/or design. Appendix D provides a discussion on the underlying research regarding reluctance as it relates to making decisions with serious consequences as well as the underlying assumptions to the method described in Section 4.

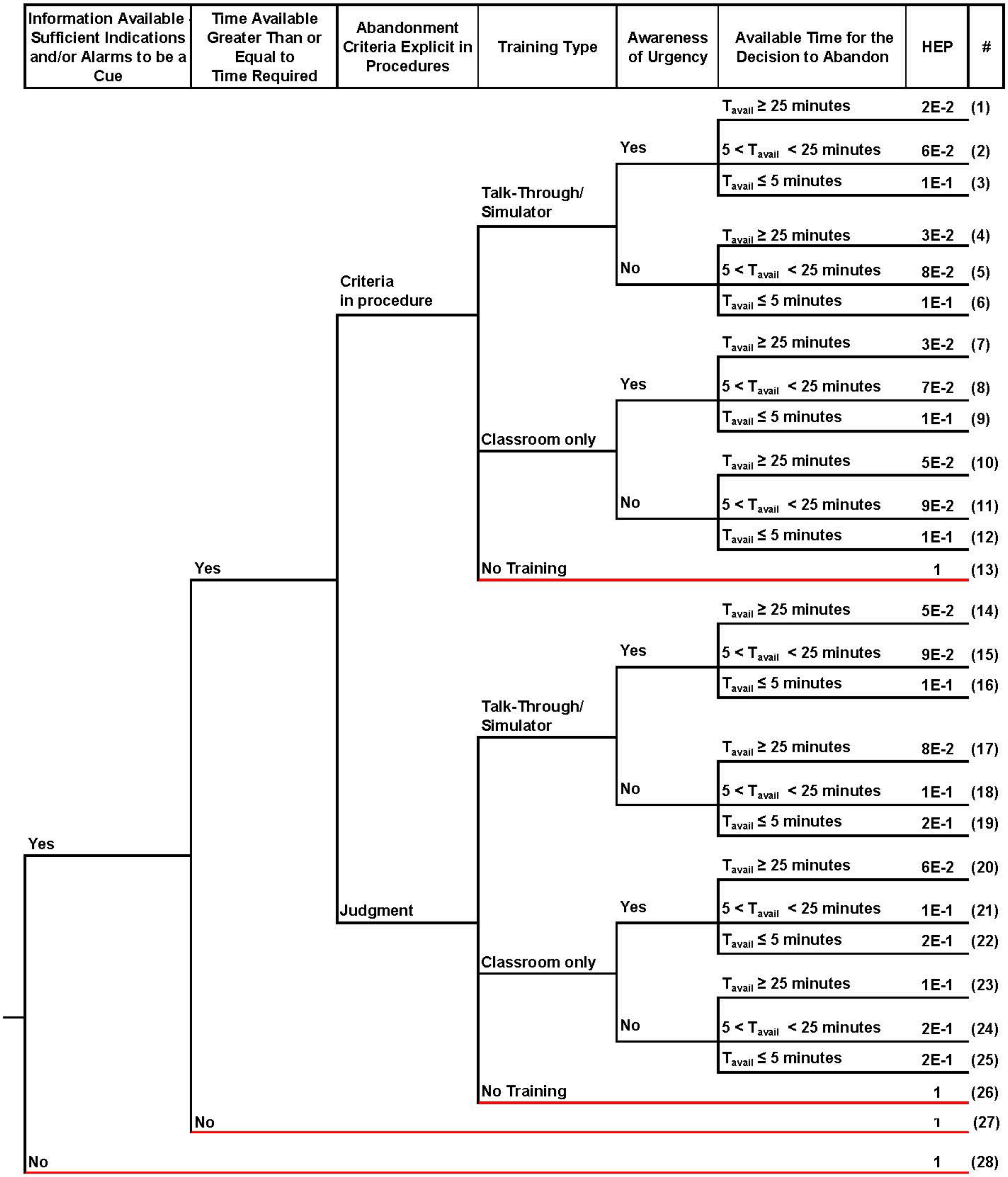

Figure 4-5
HEP quantification for the decision to abandon on LOC

Table 4-2
Guidance for decision to abandon HEP quantification for LOC scenarios

Heading	Guidance for HRA Analyst in Making Assessment
Information available for operators to make a decision: Sufficient indications and/or alarms to be a cue	See item #1 in Table 4-1 for feasibility criteria and the guidance in Section 4.2.1 for an understanding of what information is available and how it becomes available to the MCR staff. This branch assesses if a sufficient set of cues is available to the MCR staff in the fire scenario. These can be either the explicit cues defined in procedures or a consensus definition across the operating crews. The **yes** branch is selected when the minimum set of cues is available. The **no** branch is selected when the minimum set of cues is not available, then the HEP is 1.0.
Time available greater than time required	See item #2 in Table 4-1 for feasibility criteria and the guidance in Section 4.2.2 on how to develop the timing parameters. Sections 2.2.2.5 and 2.2.2.6 provide additional information on how to determine the Phase II time available and time required associated with Phase II. This branch compares the time available for the decision to abandon with the time required. The **yes** branch is selected when the time available for the decision to abandon is greater than or equal to the time required. The **no** branch is selected when the time available for the decision to abandon is less than the time required, and the resulting HEP is 1.0.
Abandonment criteria explicit in procedure	See item #3 in Table 4-1 for feasibility criteria, and the guidance provided in Section 4.2.1 for an understanding of what information is available and how it becomes available to the MCR staff. This branch point assesses how the information that is available is assessed, specifically which criteria are used for the decision to abandon. The **up** branch represents the following: The abandonment procedure contains explicit guidance on the "cues" for abandonment, as is typical in other formal operating procedures such as EOPs. In the best case, there is detailed guidance explicitly telling the operators after what equipment failures or under what operational conditions they should leave. The **down** branch represents the following: When explicit guidance for abandoning the MCR based on an LOC scenario does not exist, a substantial amount of judgment is required. In this case, the identification (or, sometimes the development) of a set of well-understood cues is performed through interviews of operators and trainers and requires that they provide a consistent message on "this is what we understand to be an LOC scenario."

Table 4-2 (continued)
Guidance for decision to abandon HEP quantification for LOC scenarios

Heading	Guidance for HRA Analyst in Making Assessment
Training type	See item #4 in Table 4-1 for feasibility criteria and guidance in Section 4.2.1 for the type of training provided, either classroom or simulator. This branch point distinguishes between the different types of training provided on how to make the decision to abandon. One of the primary ways to improve the reliability for the decision to abandon the MCR following an LOC scenario is to conduct simulator training and/or talk throughs to discuss MCRA criteria and how the criteria match the cues that are available. Therefore, this heading focuses on the type and quality of training related to the decision to abandon. The up branch represents the following: Simulator or talk-through training that is conducted on “how the decision to abandon is made” for each LOC scenario. This training can either be through simulation or as a table-top exercise, but it should include a discussion or simulation of: • LOC criteria and how to monitor or check • Cues/information/plant effects/indications that would lead the operator to understand that the LOC criteria have been met • Checks or confirmations that the operators might perform to verify that the LOC criteria have been met – Do the operators have an immediate way to know whether the MCRA criteria are satisfied based on the information they have available? – Is it obvious or not? For example, for standby systems (residual heat removal (RHR), low pressure injection (LPI)), how do the operators know if these systems are failed until they try to actuate them? • Relevant procedural guidance as applicable (how they would get to the MCRA procedure from the initial fire/EOP response and use of the MCRA procedure itself). It may be that there is not a direct transfer from the EOP/fire procedure, but the operators are relying on their situational awareness training to understand whether the LOC criteria have been met and decide whether to transfer to the MCRA procedure. If this is the case, the training should specifically cover entry into the MCRA procedure based on the LOC criteria and place emphasis on situational awareness and agile thinking. The **middle** branch represents the following: Classroom training is general training that: a) simply lists the criteria for the decision to abandon in LOC scenarios, or b) presents the MCRA criteria for an LOC scenario in general terms. There may be simulator training, but for simulation that begins after the abandonment decision has been made, the simulator exercises do not explicitly address the LOC criteria. Alternatively, there may be talk-throughs that only discuss actions after the decision to abandon has been made. Because neither the simulator training nor the talk-throughs explicitly address the decision to abandon, this type of training is classified as classroom training. In other words, classroom training is selected when simulator exercises or talk-throughs do not discuss how the operators obtain the cues and apply them to the criteria in order to make a decision. The **bottom** branch represents the situation where there is no training on either the procedure or the collective set of cues, such that a consistent definition does not exist across all crews.

Table 4-2 (continued)
Guidance for decision to abandon HEP quantification for LOC scenarios

Heading	Guidance for HRA Analyst in Making Assessment
Awareness of urgency	This branch point characterizes the operator’s sense of time urgency (or understanding of time limitations or constraints on making the decision to abandon). This heading questions whether the crew has an assessment of how long the operator can remain in the MCR and still complete the Phase III actions and meet the PRA success criteria. Operator interviews can be used to establish the operator’s sense of urgency by asking the following questions (taken and updated from NUREG-1921 Supplement 1, Table C-3): • What indicators or parameters will you check once it is first recognized that abandonment may be required? • How quickly (or unhurriedly) do you have to make the decision to abandon? • Are there any timing requirements covered in training that are related to the decision to abandon? The **up** branch on the decision tree is used when: 1) the operators are aware of the time pressure to leave the MCR, or 2) operator training includes a timing requirement to leave the MCR by a specified time, and this timing agrees with the modeled PRA scenario. If they are not aware of the time pressure, the **down** branch is used. If operators do not have an awareness of urgency, then they may delay so long in making the decision such that Phase III would no longer be successful. The decision tree and the associated HEPs assume a general level of reluctance to leave the MCR for LOC scenarios. If the operators are aware of the timing requirements to leave the MCR, they would be more likely to leave and overcome this general reluctance. In general, most U.S. NPP operator crews do not have much information about the amount of time available before they must leave the MCR for LOC scenarios. This is because in general, the decision to abandon has not been explicitly trained and the guidance has not yet been provided to operators. However, there are other PRA scenarios that have timing requirements such as isolation of steam generator tube rupture (SGTR) or tripping the RCPs after a loss of CCW, and the operators are well aware of these timing requirements. More importantly, the operators do have a sense of urgency associated with key plant parameters, for example, rapidly decreasing primary pressure or level indications. In the future, if plants improve their training, there may be situations in which the crew will know that given a fire in a specific area, they must leave within X number of minutes. In these cases, the up branch would be used.

Table 4-2 (continued)
Guidance for decision to abandon HEP quantification for LOC scenarios

Heading	Guidance for HRA Analyst in Making Assessment
Available time for the decision to abandon	There are three different timing regimes for the time available for the decision to abandon (see the equation in Section 2.2.2.5 for how to quantify the time available for Phase II): • $T_{\text{avail, LOC}} \leq 5$ minutes • $T_{\text{avail, LOC}} > 5$ minutes and < 25 minutes • $T_{\text{avail, LOC}} \geq 25$ minutes The breakpoints for the time available for the decision to abandon were determined based on reviews of LOC scenarios currently modeled in fire PRAs. The short time frames are due to uncertainties and assumptions in the fire PRA modeling that limit the overall T_{SW} for the MCRA scenario. The time available for the decision to abandon is highly coupled to the time at which component damage occurs and how much time the operators would need to complete Phase III actions. Current fire PRA models generally assume that, for LOC scenarios, all component damage occurs at T=0. This assumption typically results in a short T_{SW} for the overall MCRA scenario (generally less than 1 hour). In addition, most MCRA strategies take considerable time to implement following the decision to abandon; therefore, the time available for the decision to abandon is generally short (less than 30 minutes). If scenarios with greater than 25 minutes are identified and defined, the time available would not be a dominant contributor; instead, reluctance and the operator's situational assessment would dominate the HEP, and these factors are built into the floor HEP of 2E-2 used for the greater-than-25-minute case.

4.3 Examples of Abandonment Decision Criteria in Procedures

As discussed in Table 4-2, there is a range of procedural guidance throughout the U.S. NPP industry on criteria for the decision to abandon, varying from vague to explicit. Three examples are provided to assist the analyst in determining how to select the branch associated with the heading "Abandonment criteria explicit in procedure" in Figure 4-5.

4.3.1 Example 1 – Explicit, Clear Procedural Guidance

Example 1 provides an instance of explicit procedural guidance. This example was taken from an existing U.S. NPP and represents a best case of procedural guidance. This example procedure lists specific systems that the crew must determine to be unavailable before deciding to abandon the MCR. In this case, the **up** branch under "Abandonment criteria explicit in the procedures" would be used (i.e., "Criteria documented in procedure").

Enter into AOP-XXXX, “Shutdown from outside the main control room” under the following conditions:

If the fire is located in cable spreading room, MCR or plant computer room
AND any of the following exists

- a. RPV Level
  - i. Is unable to be maintained within normal band using high pressure systems (or RPV level is unknown) AND
  - ii. Depressurization capability is unknown OR no Low Pressure subsystems are available.
- b. Containment Cooling
  - i. Both Divisions of CCSW or LPCI are unavailable from the MCR
- c. IF at any time, based on plant conditions, trends and equipment availability, the shift manager or shift supervisor determines that the EOPs or AOPs will be ineffective in maintaining the Unit in hot shutdown

THEN enter AOP-XXXX and proceed to leave the MCR.

Figure 4-6
Excerpt from fire procedure: Explicit procedure guidance

4.3.2 Example 2 – Limited Procedural Guidance

Example 2 provides some guidance, but there is still considerable decision-making required by the SS. In this case, the **up** branch for the decision tree is used, because the entry conditions for this fire procedure also indicate that critical safety function status trees are also used to evaluate the plant functional state.

Note: IF the fire is in the Control Room/Cable Spreading Room, and evacuation is required, THEN go to the Control Room Evacuation (Fire) procedure.

Steps 1 and 2 of the Control Room Evacuation (Fire) procedure provide two symptoms that are expected to lead to MCR evacuation. These are:

1. A catastrophic fire as evidenced by flames or smoke in the Control Room and/or Cable Spreading Room that requires evacuation due to either of the following:

   - Environmental conditions (smoke/heat).

   OR

   - A loss of Control Room control of critical plant functions which cannot be adequately addressed by Alarm Response Procedures, Abnormal Operating Procedures, Instrument Failure Guides, or Emergency Response Procedures.

2. Actuation of fire detection and suppression in other fire areas which indicates conditions i.e., (smoke, fumes) that require Control Room evacuation

Figure 4-7
Excerpt from fire procedure: Limited procedure guidance

4.3.3 Example 3 – Judgment Only in Procedure Guidance

Example 3 is a case where there is no guidance explicitly stated in the procedure for making the decision to abandon, and the decision would be based on judgment only (see Figure 4-8). However, the question about procedure guidance is asked only in Figure 4-5 if the operators can define what the collective set of cues for the decision would be. So, in this case, the crew knows what conditions they need to look for in a fire in the given area, but there is no procedure guidance reminding them of the criteria to be used in this evaluation.

For this case, the **down** branch of the decision tree would be selected.

> When a fire alarm is present in this fire area consider abandoning the MCR.

Figure 4-8
Excerpt from fire procedure: Judgment only procedure guidance

4.4 References

1. EPRI/NRC-RES Fire Human Reliability Analysis Guidelines—Qualitative Analysis for Main Control Room Abandonment Scenarios: Supplement 1. U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Washington, DC, and Electric Power Research Institute (EPRI), Palo Alto, CA: 2017. NUREG-1921 Supplement 1 and EPRI 3002009215.
2. An Approach to the Analysis of Operator Actions in Probabilistic Risk Assessment. EPRI. Palo Alto, CA: 1992. TR-100259.
3. The SPAR-H Human Reliability Analysis Method. U.S. NRC, Washington, DC: 2005. NUREG/CR-6883.
4. An Integrated Human Event Analysis System (IDHEAS) for Nuclear Power Plant Internal Events At-Power Application: Volume 1. U.S. NRC, Washington, DC: March 2017. NUREG-2199.
5. B. Kirwan, H. Gibson, R. Kennedy, J. Edmunds, and G. Cooksley. "Nuclear Action Reliability Assessment (NARA): A Data-Based HRA Tool," Probabilistic Safety Assessment and Management (PSAM) Proceedings, June 14–18, 2004, Berlin, Germany.
6. E. Hollnagel, Cognitive Reliability and Error Analysis Method (CREAM). Elsevier, 1998.

5

PHASE III - ACTIONS FOLLOWING THE DECISION TO ABANDON

This section provides MCRA HRA guidance for the quantification of HFEs for operator actions that occur during Phase III. The quantification guidance:

- Is built on the guidance given in NUREG-1921 [1] (i.e., fire HRA guidelines)
- Expands upon the HFE identification, definition, and qualitative analysis guidance given in NUREG-1921 Supplement 1 [2] (i.e., qualitative analysis guidance for MCRA scenarios)
- Is consistent with qualitative insights on operator performance in MCRA scenarios that were obtained from HRA/PRA and operations experts in a formal workshop
- Is informed by new research and author recommendations on qualitative treatment of C&C beyond that given in NUREG-1921 Supplement 1

Appendix C documents the underlying details of this guidance, including the technical approach used for its development and how issues and considerations identified from the development of NUREG-1921 Supplement 1 (i.e., guidance for qualitative analysis for MCRA scenarios) were addressed. Appendix C also discusses aspects of C&C that may affect HFE quantification.

This section starts with a high-level summary of the HRA quantification guidance for Phase III operator actions, especially focused on differences from existing guidance (such as NUREG-1921). It should be noted that portions of NUREG-1921 Supplement 1 are referenced in this section because the qualitative analysis guidance given in this report is crucial to the development of inputs needed for the Phase III HRA quantification. In some cases, guidance from NUREG-1921 Supplement 1 is repeated because of its importance. In very few cases, qualitative analysis guidance from NUREG-1921 Supplement 1 is updated in this section.

5.1 High-Level Summary of Issues to Consider During Phase III HRA Quantification

For Phase III HFEs, the authors have developed a consensus perspective on the important issues that HRA quantification should address. This perspective also is specific to existing U.S. NPPs, the associated range of RSDP capabilities, associated MCRA procedures and training, and the manner in which MCRA procedures are expected to be implemented.

Typically, the HRA analyst must consider a variety of factors with respect to operator actions, including who performs the action, what tasks are required for the action, where the actions take place, what procedures are used, what equipment and indications are used, and so on. In particular, most U.S. NPPs have a MCRA safe shutdown strategy that involves a supervisor at the RSDP who uses the MCRA procedure and coordinates (as needed) the actions of multiple operators who are located at multiple local control panels. If the HRA analyst is considering, for example, a new NPP design that uses a substantially different MCRA safe shutdown strategy, including re-constitution of the entire MCR operating crew at essentially a backup MCR, then

HRA guidance for MCRA would need to consider aspects specific to this application, which is beyond the guidance provided here.

The following is a summary of the treatment of Phase III HRA quantification for MCRA scenarios:

1. **General.** To the extent possible, existing HRA guidance and quantification tools from NUREG-1921 are recommended.
2. **Cognition.** Since there may be some NPPs that have some MCRA scenarios and procedures where decisions by the operator are required (i.e., the actions involve cognitive challenges), cognitive[10] modeling is still recommended and follows the quantification guidance in NUREG-1921. However, because the MCRA safe shutdown strategies and procedures for existing U.S. NPPs address potential fire-induced initiating events and spurious operations, and because there would be fewer trains of components available for safe shutdown under these anticipated conditions, typically, there is not as much of a demand on the operator to “diagnose” what safe shutdown option to implement. Thus, the HRA quantification in Phase III is usually dominated by the execution of operator actions called out in the MCRA procedures.
3. **Execution.** Regarding the execution aspects only, operator actions taken at the RSDP or local control panels in MCRA scenarios are similar to (or may be the same as) those local operator actions described in NUREG-1921. Consequently, HRA quantification guidance for the execution portion of these actions is similar to that given in NUREG-1921. (See also item #4 on C&C for impacts to execution.)
4. **C&C impacts on critical tasks.** In NUREG-1921 Supplement 1, several factors were identified as being different and important for HRA treatment of MCRA scenarios. Two of those important factors are C&C and communications. The reason these factors are important is because most U.S. NPPs have a MCRA safe shutdown strategy that involves a supervisor at the RSDP who uses the MCRA procedure and coordinates (as needed) the actions of multiple operators who are located at multiple local control panels. In addition, the supervisor typically uses radios (and maybe sound-powered phones) to individually communicate with each local operator. Most MCRA fire probabilistic risk assessments (FPRAs) model each critical safety function as an individual HFE (e.g., failure to start high pressure injection). However, since there may be actions conducted by one operator that may be required for success of the actions of a second operator, it is important to understand how all of the proceduralized operator actions are inter-related, especially if they are coordinated. For this reason, the C&C contribution may be non-negligible for MCRA scenarios. This section discusses how consideration of C&C is integrated into the Phase III quantification process. A useful approach is to identify these interfaces on a timeline showing all operators who implement actions modeled during MCRA, such as that shown in Supplement 1, Figure 7-9 (which, while for shutdown of dual units, is still relevant since these interfaces can exist in a single unit shutdown).

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[10] Note that, by using most HRA quantification tools that model "cognition" in the post-abandonment context, three of the C&C functions can be explicitly addressed: 1) maintaining a coherent understanding of the plant state, 2) making timely decisions, and 3) allocating resources. The remaining C&C functions, coordinating actions and managing communications, are addressed in items 4 and 5.

If the coordination of operator actions (e.g., one operator action is sequenced in a specific order after a previous action) is required, then the HRA must consider if a “sequencing coordination” failure is possible and assign an associated HEP. Existing HRA quantification tools may not be directly applicable for assigning an HEP for sequencing coordination failures in MCRA scenarios, so this report provides guidance suited to the MCRA context. The associated time required for communications associated with coordination (in general and specifically associated with sequencing failures) also should be addressed, as described in item #5 immediately below.

5. **Impact on time required.** As described above in item #4 for the critical tasks, development of the time required input should include all of the following:
    a. Critical communications and coordination[11] required to complete the HFE. Critical communications and coordination are items that would fail the HFE if the operators fail to perform them,
    b. Non-critical communications as part of the time required to complete the HFE, if it impacts the completion time, and
    c. Time required for recovery of initial operator failures (if recovery can be credited). There are two types of recovery that may be applicable to MCRA: 1) recovery within an HFE, and 2) recovery by adding an HFE (termed a recovery HFE) to the fire PRA model. Recovery within an HFE and recovery by adding an HFE, if possible, are addressed in Section 5.3.

5.2 Detailed Phase III (After the Decision to Abandon) HRA Quantification Guidance

The quantification for Phase III HFEs is conducted using the following steps:

1. **Review identification and definition and qualitative analysis of individual HFEs.** This step includes reviewing feasibility assessments, timeline development, and PSF identification per the guidance in NUREG-1921 Supplement 1 in order to:
    a. Understand the MCRA strategy, staffing, roles and responsibilities.
    b. Identify the steps in the procedure associated with the modeled HFEs.
    c. Review and update, as necessary, timing inputs and timelines.

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[11] The analyst should note that the timing analysis and development of timelines also addresses one of the C&C functions as defined in Supplement 1. Namely, the timelines address and represent the need to "[manage] communications between team members such that they are timely and effective."

2. **Qualitative analysis for C&C.** This consists of review and update of the HFE definition and timeline development as part of evaluating the impact of C&C, including:
   a. Identification of C&C critical tasks.
   b. Address timing impact related to C&C.
   c. Re-check feasibility with specific consideration of C&C.
3. **Quantify Phase III HFEs.** The guidance for the quantification of Phase III HFEs uses a mixture of existing NUREG-1921 guidance and new guidance from this report as summarized below:
   a. Quantification of cognitive errors. If detection, diagnosis, or decision-making (including the allocation of resources) is required, then an appropriate cognitive HRA method that takes situational awareness into account should be used, such as those discussed in NUREG-1921 Appendix B.[12]
   b. Quantification of execution errors. Execution errors are quantified following the guidance provided in NUREG-1921 [1] for actions at the RSDP or local actions, such as that given in Section B.7.5, Section B.8, and Appendix C.
   c. Quantification of sequencing errors. For C&C-related failures addressing coordination of multiple, sequenced operator actions (i.e., sequencing coordination), specific quantification guidance is provided in Section 5.2.3.3.
4. **Review the HEPs for the collective set of Phase III HFEs.**

   Following quantification, the final steps are to address dependency, recovery, and uncertainty; incorporate the HRA into the PRA; and document the HRA results. Dependency, recovery, and uncertainty are addressed in Section 6. Incorporating the results in the PRA and documentation are addressed in NUREG-1921 Supplement 1.

5.2.1 Step 1: Review Identification and Definition and Qualitative Analysis of Individual HFEs

The technical approach has been written presuming the HRA analyst has completed the HRA process steps described in NUREG-1921 Supplement 1, consisting of identification, definition, feasibility assessment, timeline development, and qualitative analysis including PSF identification. These steps also presume that relevant plant data and PRA data have been collected (such as from operator interviews involving walk/talk-throughs and simulator exercises).

5.2.1.1 Sub-Step 1.1: Understanding the MCRA Strategy

Understand the overall MCRA strategy, staffing, roles, and responsibilities.[13] For example, for the operating crew implementing the set of actions during MCRA, identify “who does what,” including:

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[12] Note that, traditionally, HRA methods that model cognition address three of the C&C functions: 1) maintaining a coherent understanding of the plant state, 2) making a timely decision, and 3) allocating resources.

[13] When reviewing MCRA procedures (or considering updates to such procedures), the analyst should note that the MCRA safe shutdown procedure should not assign any operator duties that are inconsistent with the NPP's "conduct of operations" procedure. For example, two NRC inspection reports [3,4] discuss green findings related to MCRA procedures that assigned various equipment manipulation duties at local control stations to the STA, requiring tens of minutes to complete.

- The key safety functions being accomplished by each operator
- Those key safety functions where multiple operators are required to accomplish the actions associated with an HFE

  Example: A single operator conducts all tasks needed to start electrical support systems, a second operator starts cooling water, and a third operator starts the front line systems during restoration of a function.
- Any personal protective equipment, tools, or other items needed for success

5.2.1.2 Sub-Step 1.2: Identify Actions Related to Transfer of Control from the MCR and Steps Associated with Critical Safety Functions

Identify those steps in the procedure associated with the HFEs that model both the transfer of control from the MCR and the actuation of critical safety functions. Specifically, identify the list of critical tasks, (i.e., those tasks whose failure will fail the transfer to the RSDP or the key safety functions needed to respond to the MCRA scenario):

- Transfer of control from the MCR to the RSDP or local control stations, e.g.,
  - Electrical isolation of the MCR
  - Startup of the RSDP such as to energize the panel and ensure that instrumentation is available
- Startup and operation of systems used to fulfill modeled critical safety functions, e.g.,
  - Decay heat removal front line and support systems
  - Injection front line and support systems
  - Reactivity control front line and support systems
  - Primary integrity and secondary integrity (if applicable)
  - Containment isolation and containment integrity
  - In case of loss of offsite power (LOOP), EDG and support systems

- Actions taken to mitigate potential spurious operations such as:
  - Spurious opening of primary or secondary relief valves
  - Spurious (uncontrollable) feeding of steam generators (SGs) (PWR) or injection to the primary (PWR and BWR)
  - Termination of spurious safety injection (SI)

5.2.1.3 Sub-Step 1.3: Review and Update Timing Inputs and Timeline

Review and update, as necessary, timing inputs and timelines, including cognition and execution times, travel time, and time for communications (as applicable).

Timing parameters are discussed in Section 2 of this report, Section 7.4 of NUREG-1921 Supplement 1, and in Appendix B of NUREG-1921.

Communications may be needed for critical tasks modeled in the HRA and also may be conducted as part of non-critical tasks. The impact of all communications (critical and non-critical) should be included in the timeline if it impacts the total time required to complete critical actions. Communications necessary for completion of critical tasks should be identified and accounted for as part of C&C. Step 2 (Section 5.2.2) provides examples of timing impacts related to C&C.

5.2.2 Step 2: Qualitative Analysis for C&C

This step identifies any tasks related to C&C that may lead to failure to properly sequence operator actions (or that may help with recovery), and also evaluates the impact on the timeline.

5.2.2.1 Sub-Step 2.1: Identify C&C Critical Tasks

The HRA analyst should review the MCRA procedure to identify operator actions that require C&C-related coordination and associated communications, specifically those whose failure to be properly sequenced would lead to failure of an SSC or a key safety function. This sub-step is new analysis (as part of this report), and it identifies C&C-related coordination of multiple operator actions involving communication via sound-powered phones, radios, or other type of remote communication. A description of C&C-related coordination and communication is provided in Appendix C.

An impact on the performance of critical operator actions should be considered if the supervisor must coordinate the operator actions such that they are sequenced in a specific order. This is considered to be a potential failure mode to C&C and, specifically, a failure in sequencing coordination. Also, the time required to accomplish these execution actions should account for coordination, especially the time required for the associated communication, even if a C&C coordination failure contribution is not ultimately assigned, as described below under Sub-Step 2.2.

Based on research conducted, C&C potentially impacts the model in the following ways:

- Negative impact. C&C may add a critical task (or tasks) and an associated additional failure mode to an HFE if coordination that involves proper sequencing of operator actions, along with associated communications, is needed for an operator to successfully accomplish an action. The time required to complete all actions should account for the time to complete critical coordination and associated communications.
- Potential negative impact. Communications associated with C&C may add to the time required to accomplish a critical action if non-critical communications occur. This sub-step identifies the potential impact and Sub-Step 2.2 captures that change in the timeline.
  - For example, an operator may have multiple tasks, and some of them may be non-critical for the fire scenario. The operator would complete these tasks and the associated communications following the procedure, and the non-critical tasks (including communication) would increase the time required for response. This type of modeling (i.e., establishing a realistic time required for response) is the same for all fire and non-fire scenarios, but it is especially relevant to MCRA since the MCRA procedure is typically written for multiple fire impacts.
- Positive impact. C&C may add the potential for recovery within an HFE of a critical task, if the supervisor at the RSDP is able to check indications related to actions taken at the local plant station. This can be modeled as a separate “recovery task” in the Technique for Human Error-Rate Prediction (THERP) HRA method.

Examples of actions that require communications include:

- The field operator is directed by procedure to report completion of a procedure step(s) to the supervisor responsible for C&C at the RSDP. In this example, the time required includes the time for communication with the supervisor responsible for C&C at the RSDP. The communication may not be critical for success of the action and, therefore, may not be explicitly included as a critical task in the HFE.
- An operator action requires execution at two different locations by two different operators: 1) start the pump in location A, and 2) control the flow from the RSDP. The time required should include the time for communication between the two operators. The communication is considered critical if, without this communication, the action would be failed.

5.2.2.2 Sub-Step 2.2: Address Timing Impact Related to C&C

Section 2 of this report and Section 7 of NUREG-1921 Supplement 1 provide detailed guidance on the development of timing inputs and timelines for MCRA scenarios. This guidance is expanded here to include the following guidance for HRA analysts related to coordination and associated communications:

- Determine the potential impact that coordination and associated communications can have on the time required for operator actions. For example, communications may be required to coordinate actions by different operators to ensure proper sequencing of those actions. Time delays associated with these communications should be factored into the time required for the actions.
- Account for the following potential C&C impacts on timing, including:

  - The specific way that the field operators implement the procedure steps (e.g., for a set of 10 actions, does the operator follow the steps explicitly, or is a prioritized approach such as changing the order of steps used?)
  - Extra time needed for information gathering tasks, such as health physics surveys, if they are needed for operator action implementation (e.g., operation of valves inside containment for PWRs)
  - Some margin for uncertainty (e.g., develop a range of timing estimates, if possible, rather than a point value)

- Determine the time associated with recovery actions. In many cases, timed walk-throughs or simulations of time-critical actions such as the MCRA procedure already include steps where another operator is either checking equipment or parameter status (e.g., flow through a valve that should have been opened). Successful completion of one step may be necessary before a subsequent step can be performed, such that attempting the second step could provide a means to identify that the earlier step had been missed. However, if these steps are not specifically timed, a starting assumption for this additional recovery time should be in the range of 1–3 minutes, but assignment of a recovery time should consider what indications of the initial failure are available (and where they are located), followed by the time needed to perform the recovery action(s). (Note that in some cases, even with consideration of additional time required for recovery, there may be a negligible contribution to the overall HEP. Alternatively, it is possible that the operator actions might become infeasible due to the additional time required.)
- Ensure that model logic for the HFEs captures the dependencies between operators and critical C&C tasks.
- Ensure that the time required accounts for C&C. Typically, for MCRA, validated timing data exists. Given that this data has been identified and collected, the HRA analyst should consider whether C&C-related communication and coordination steps are included in this timing. If these steps are not reflected in the timing, the analyst should conduct operator interviews to assess the timing impacts of C&C on the timeline and ensure that the overall MCRA scenario remains feasible.

5.2.2.3 Sub-Step 2.3: Re-Check Feasibility with Specific Consideration of C&C

If any Phase III HFEs appear to be infeasible based on the qualitative analysis (particularly the timeline), then review the existing data and analyses for potential conservatisms, and refine as appropriate.

1. Start by using the feasibility criteria listed in Supplement 1, Section 6, including a check of the plan for C&C. C&C considerations may already be included in the HRA, but they should be reviewed and confirmed.

2. Review the communications plan associated with MCRA, and ensure that it contains provisions or instructions for dealing with potential distractions and/or interruptions such as requests that are not directly associated with safe shutdown-related actions. These include internal requests (e.g., health physics to take a survey or chemistry to take a sample) and external requests (e.g., the arrival of the offsite fire department).
3. Re-assess feasibility, given the potential changes to the tasks and timeline.

5.2.3 Step 3: Quantification of Phase III HFEs

The HRA quantification approach for Phase III HFEs parallels that used for other fire scenarios and, to the extent possible, uses existing HRA methods. At a high level, HRA quantification must consider contributions related to:

- Decision-making (also referred to as "diagnosis," "situation awareness & response planning," "cognition," etc.)
- Execution (also called "response implementation")

In addition, it is important that HRA quantification methods address the operator performance issues of concern for the scenario and overall context. For Phase III operator actions, the operator performance issues are largely determined by the plant-specific strategy for MCRA safe shutdown and associated procedures.

5.2.3.1 Sub-Step 3.1: Quantification of Cognitive Errors

Generally, current practice in HRA considers contributions to HEPs for HFEs from both "cognition" and "execution." However, HRA experience to date for fire-related MCRA scenarios has indicated that the cognitive portion of the Phase III actions may not be a dominant contributor to the HEP. Nevertheless, this guidance recommends that "cognition" should still be evaluated due to the plant-specific variations in safe shutdown approaches after abandonment.

Specifically, the implementation of any procedure requires the operators to be thinking about the actions they are directed to take and detecting if the actions taken do not achieve the intended goal(s). As work by Roth, Mumaw, and Lewis [5] showed, for cognitively challenging scenarios, the variability between crews given the same procedures and scenarios can result in significant failure probabilities. While it is expected that there will be limited complexity in the post-abandonment procedures (e.g., actions that demand choices or having to diagnose particular fault conditions), the HRA analyst still must assess whether operators will accomplish the MCRA procedure steps as required. Since the specific steps and associated operator actions in MCRA procedures are plant-specific, the HRA assessment also will be dependent on plant type and plant-specific design.

For these reasons, analysts should address the modeling of failures in cognition in the Phase III MCRA HRA, following the guidance in NUREG-1921, as it is not always certain that such failures will be negligible. The design of the abandonment procedures and the associated training and practice will play roles in determining this contribution.

Some examples of Phase III actions that would involve modeling of cognition are:

- Deciding among injection systems to use when multiple systems are listed in the procedure
- Stop ESW if normal SW is operating
  - For example, the procedure guidance states the following: Consider stopping ESW if normal SW is operating and providing sufficient cooling to all systems. In this example, the crew must make a decision about what is sufficient and may choose to continue to run the ESW pumps even if the FPRA requires ESW to be stopped.
- Deciding among late containment venting options in a BWR
- Any action in which the operators must determine when a certain parameter has been met. For example:
  - Implementing RPV inventory/pressure control actions such as manual depressurization when 420 psig is reached or controlling SG level.
  - Because the RSDP often lacks interlocks that are present in the MCR, the operators may need to use extra caution before starting a piece of equipment. See Section 5.2.3.1.2 for additional discussion.
    - For example, typically, there is an interlock in the MCR that maintains an isolation valve of a low-pressure injection system closed when the reactor pressure is greater than a certain value. At the RSDP, this interlock may no longer be effective, and the operators would have to wait until the reactor pressure has sufficiently decreased before using that low-pressure injection system (i.e., opening the valve too early could lead to a LOCA).

5.2.3.1.1 Application of Existing HRA Methods That Address Cognition

The major issue in applying the NUREG-1921 quantification guidance to Phase III MCRA cognition is that these actions are taken outside the MCR at the RSDP or locally. Although the authors have not conducted an extensive review of how existing cognitive HRA methods map to the RSDP, it is possible to apply existing methods if the analyst does all of the following:

1. Recognize that most methods have been developed for in-MCR actions (and, therefore, may need to be applied more carefully and possibly differently than that for operator actions taken in the MCR),
2. Identify the important issues and factors in the differences between the RSDP and the MCR, and
3. Represent, as well as possible, the important issues and factors in applying the chosen HRA quantification tool.

The primary cognitive HRA methods highlighted in NUREG-1921 include HCR/ORE [6], CBDTM [6], and ATHEANA [7]. To repeat, it should be stressed that research has not been performed to evaluate how well these methods emulate the specific contexts and conditions for MCRA in order to address "cognition" as it is addressed in non-MCRA scenarios. However, since these HRA methods represent the state of practice in fundamental cognitive modeling, they are cited here as potential tools for the analyst. The overall assessment of the applicability of these methods to the cognition required in MCRA scenarios is as follows:

- HCR/ORE. Since the underlying data for the HCR/ORE method is based on in-MCR simulator exercises, it is not generally recommended for use in quantifying cognitive actions at the RSDP. It should be recognized, however, that if the Phase III action is based on a previously quantified HFE (from internal events or fire) that does use HCR/ORE, the MCRA value could be lower (since the HCR/ORE contribution will have been removed).
- CBDTM. The CBDTM provides a set of eight decision trees that address information adequacy and procedure use and, as such, are considered to be applicable as long as the analyst interprets the trees from the perspective of actions being taken at the RSDP or locally, as opposed to in the MCR. In particular, the first two branches of tree P_ca state “Indication available in CR” and “CR Indications accurate” and need to be interpreted as “Indication available at RSDP or locally” and “RSDP or local indications accurate” when applied to Phase III actions. Section 5.2.3.1.3 provides guidance and an example for Phase III MCRA interpretations of CBDTM.
- ATHEANA. ATHEANA provides a structured expert elicitation technique for evaluating HEPs, which is not restricted to any particular plant type or setting.

Similar assessments to those shown above would be needed if other cognitive HRA methods are considered for Phase III operator actions. In particular, analysts would have to consider the ability of these HRA methods to evaluate the important factors of cognition at the RSDP, as discussed in Section 5.2.3.1.2.

5.2.3.1.2. Important Factors for Operations at the RSDP Versus the MCR

In reviewing the MCRA procedure, the HRA analyst must understand that the strategy followed by each plant after MCRA is heavily controlled by the plant-specific installed features and controls. The existence (or not) of a RSDP, the extent of its functionality, and the need for actions at other locations will dictate the format of the procedure (e.g., use of MCRA procedure attachments dedicated to establishing certain functions).

The analyst will need to obtain diagrams or photos of the RSDP layout and controls, augmented by a walkdown to see its location and context in the plant to fully understand the RSDP capabilities and constraints.

NUREG-1921 provides a comprehensive description of issues associated with indications and cues for ex-control room actions including those taken at the RSDP. In addition, the following guidance is excerpted from Supplement 1 [2], Section 8.2.4 Cues and Indications:

> The intent here is to understand the difference between how the crew can access and integrate information from the RSDP compared to doing the same in the MCR. This is accomplished by asking the following two questions:
>
> 1. How is the range of indications different from what the operators are accustomed to seeing?
> 2. How do the available resources (e.g., STA and technical support center (TSC))[14] change the ability of the supervisor responsible for C&C at the RSDP to integrate the available information into a “big picture”?
>
> Another important task for the analyst is to conduct a comparison of the cues and indications presented at the RSDP with the information that the MCRA procedure or other procedures direct the operators to monitor. These additional procedures may be identified during operator interviews as being used at the direction of the SS. The availability of the TSC and the resources of the STA should be assessed for their ability to provide the “big picture” guidance that is usually available in the MCR but may not be available at the RSDP.

In addition, the potential effect of crews no longer having access to all of the information in the MCR (such as the full set of annunciators/indicators, plant process computer and associated alarms, plant drawings, and other documentation) needs to be evaluated.

Due to the different reactor types, vintages, and plant-specific design features in the U.S., each NPP can be considered to be unique with respect to ensuring that safe shutdown can be maintained outside the MCR. NUREG-1921 Supplement 1, Section A.3 discusses alternative and remote shutdown panel variations. Also, Tables A-1 and A-2 in NUREG-1921 Supplement 1 list various plant RSDP designs to illustrate the differences in panels utilized for alternative or dedicated shutdown capability, as well as the functionality of their critical systems.

NUREG-1921 Supplement 1, Table 8-1 provides guidance to the analyst on the consideration of detracting and compensating PSFs related to the capability of the RSDP and Table 8-2 discusses when certain PSFs, such as cues and indications, and human-machine interface (HMI), are consequential to MCRA and, therefore, should be considered in the cognitive modeling of Phase III actions.

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[14] When reviewing MCRA procedures (or considering updates to such procedures), the analyst should note that the MCRA safe shutdown procedure should not assign any operator duties that are inconsistent with the NPP's "conduct of operations" procedure. For example, two NRC inspection reports [3,4] discuss green findings related to MCRA procedures that assigned various equipment manipulation duties at local control stations to the STA, requiring tens of minutes to complete.

5.2.3.1.3 Generic CBDT Quantification Guidance for Phase III MCRA

NUREG-1921 Appendix B provides detailed guidance for the quantification of fire actions using the CBDTM and is considered to be directly applicable to MCRA Phase III quantification when cognition is required because MCRA Phase III actions are considered to be a sub-set of fire actions. The CBDTM assesses HEPs by evaluating eight separate decision trees that evaluate each of the cognitive failure mechanisms shown in Table 5-1. There are two high-level failure modes: failure of the operator-information interface and failure of the operator-procedure interface. Each high-level failure mode is composed of four failure mechanisms.

Table 5-1
CBDTM failure mechanisms

High-Level Failure Mode	Designator	Description	Unique consideration for MCRA?
Failures in the operator-information interface	P_ca	Data not available	**Y**
	P_cb	Data not attended to	**Y**
	P_cc	Data misread or miscommunicated	**Y**
	P_cd	Information misleading	N
Failures in the operator-procedure interface	P_ce	Relevant step in procedure missed	**Y**
	P_cf	Misinterpret instruction	N
	P_cg	Error in interpreting logic	N
	P_ch	Deliberate violation	N

For decision trees related to the operator-information interface, the key for quantification is to answer the CBDT trees a–d with respect to the indications identified as the cue for the action being modeled in the HFE. These decision trees are given in Appendix B of NUREG-1921, specifically, Figures B-13, B-15, B-17, and B-19. These indications will primarily be at the RSDP or local indications since Phase III actions take place after the operators leave the MCR. The analyst should note that, for the decision tree for failure mechanism "a", EPRI TR-100259 [6] explains that the asterisk on branch (g) denotes the following:

> In situations where the procedure or training specifies a course of action when the preferred information source is not available or the value of a parameter cannot be determined, the analyst must determine that the alternative specified will lead to the same action as the procedures would have directed, had the information been available. For situations where the crew must obtain information from ex-control room sources via a second-party report, the same analysis should be performed for the local plant operator, who may have different procedures (or none) and very different training than members from the control room crew.

Also, for MCRA Phase III actions, the HRA analyst must verify that indications are available locally and/or at the RSDP.

For decision trees related to the operator-procedure interface, the procedure guidance required for diagnosis must be identified and then CBDT trees e–h are answered with respect to the cognitive procedure. These decision trees are given in Appendix B of NUREG-1921, specifically: Figures B-21, B-23, B-24, and B-25.

Tables 5-2 through 5-5 provide guidance for the failure mechanisms that have unique considerations for MCRA (e.g., p_ca, p_cb, p_cc, and p_ce). These tables provide detailed guidance for each failure mechanism in CBDTM with respect to fire scenarios, as well as any specific guidance related to Phase III MCRA. These tables are expansions of those given in Appendix B of NUREG-1921 to provide fire-specific guidance in using the CBDTs, specifically Tables B-6 through B-13. The generic guidance for CBDTM may be helpful in developing parallel guidance for other HRA methods in applications for MCRA scenarios.

Table 5-2
Fire-specific and MCRA guidance on decision nodes for P_ca: data not available

Decision Node	Guidance as Stated in EPRI TR-100259 [6]	Guidance Specific for Fire HRA (NUREG-1921)	Additional MCRA Phase III Considerations
Indication available in CR	Is the required indication available in the control room?	The **Yes** branch is used when all indications for the specific action are available or if a minimum set of information for the specific action is available. The **No** branch is used when all indications for the specific action are failed. This is the case for total impact: no instrumentation is available, and the HEP should evaluate to 1.0. If branch g is selected for this decision tree, the HRA methodology will display a warning that this HFE should be quantified as two separate actions: one for the control room and one for local actions. If there are no additional indicators (either in the control room or locally) that can be credited for fire HRA, the HEP should be set to 1.0.	The **Yes** branch is used when all indications for the specific action are available outside the MCR. Indications could be at the RSDP or locally. (If the indications are not co-located with the controls, then CBDTM is not an appropriate method). The **No** branch is used when all required indications for the specific action are not available from outside the MCR. In these cases, the analyst must justify feasibility. For actions that are included in the MCRA procedure, the relevant indications will usually be located outside the MCR. However, the FPRA may credit actions included in the EOPs/AOP/standard operating procedures (SOPs) that are implemented in conjunction with the MCRA procedure. In these cases, the location of the indications needs to be determined.

Table 5-2 (continued)
Fire-specific and MCRA guidance on decision nodes for P_ca: data not available

Decision Node	Guidance as Stated in EPRI TR-100259 [6]	Guidance Specific for Fire HRA (NUREG-1921)	Additional MCRA Phase III Considerations
Indication accurate	Are the available indications accurate? If they are known to be inaccurate (e.g., due to degradation because of local extreme environment conditions or isolation of the instrumentation), select No.	The **Yes** branch is used when indications are known to be accurate and available during the fire. The **No** branch is used when the fire causes partial impact to the instrumentation, and the indications are, therefore, assumed to be inaccurate.	The **Yes** branch is used when indications outside the MCR are known to be accurate and available. The **No** branch is used when indications outside the MCR are providing an inaccurate reading. The inaccurate reading could be caused by the fire or other failures such as degradation due to local extreme environment conditions or isolation of the instrumentation. In general, the MCRA procedures have been written assuming all indications are available and accurate, but this should be validated since the fire PRA may generate scenarios where this procedure assumption is not valid.
Warning or alternative in procedure	If the normally displayed information is expected to be unreliable, is a warning or a note directing alternative information sources provided in the procedures?	The **Yes** branch is used when the procedure lists alternative instrumentation to perform the specific task or provides a warning of potentially incorrect readings during a fire. The **No** branch is used when the procedure provides no alternative instrumentation or warning during a fire. If the warnings and cues are in different procedures (e.g., EOP and AOP), ensure that the procedures where the warnings exist are implemented before the cue occurs.	No additional guidance for Phase III MCRA.

Table 5-2 (continued
Fire-specific and MCRA guidance on decision nodes for $P_{c}a$: data not available

Decision Node	Guidance as Stated in EPRI TR-100259 [6]	Guidance Specific for Fire HRA (NUREG-1921	Additional MCRA Phase III Considerations
Training on indications	Has the crew received training in interpreting or obtaining the required information under conditions similar to those prevailing in this scenario?	The **Yes** branch is used when the operating crew has received training in interpreting or obtaining the needed information in a fire situation. The **No** branch is used when the operating crew has not received training in interpreting or obtaining the needed information in a fire situation.	No additional guidance for Phase III MCRA.

Table 5-3
Fire-specific and MCRA guidance on decision nodes for $P_{c}b$: data not attended to

Decision Node	Guidance as Stated in EPRI TR-100259 [6]	Guidance Specific for Fire HRA (NUREG-1921	Additional MCRA Phase III Considerations
Low vs. high workload	Do the cues critical to the human interaction (HI) occur at a time of high workload or distraction? Workload or distraction leading to a lapse of attention (omission of an intended check) is the basic failure mechanism for $P_{c}b$, and it interacts with the next two factors.	If the EOPs are implemented in parallel to the fire procedures, the workload is assumed high. However, if the action is time independent and the base case HFE (for existing EOP HFEs) is considered to have a low workload, the fire scenario can also be considered to have a low workload. In this case, it is assumed that the fire will be mitigated long before the action is required.	High workload is selected when the cue occurs at a time of high workload for the procedure reader. For MCRA, high workload situations are those in which the procedure reader is either monitoring or coordinating actions between different operators. Low workload is selected when the cue occurs at a time of low workload for the procedure reader. This would pertain to situations where the only other ongoing task is the monitoring of parameters.

Table 5-3 (continued)
Fire-specific and MCRA guidance on decision nodes for P_cb: data not attended to

Decision Node	Guidance as Stated in EPRI TR-100259 [6]	Guidance Specific for Fire HRA (NUREG-1921)	Additional MCRA Phase III Considerations
Check vs. monitor	Is the operator required to perform a one-time check of a parameter or monitor it until some specified value is reached or approached? The relatively high probabilities of failure for the monitor branches are included to indicate a failure to monitor frequently enough to catch the required trigger value prior to its being exceeded rather than complete failure to check the parameter occasionally.	No additional guidance for fire.	No additional guidance for Phase III MCRA. Since there usually are no alarms at the RSDP or local plant stations, "monitor" will typically be the most appropriate selection.
Front vs. back panel	Is the indicator to be checked displayed on the front panels of the main control area, or does the operator have to leave the main control area to read the indications? If so, the operator is more likely to be distracted or to simply decide that other matters are more pressing and not go to look at the cue immediately. Any postponement in attending to the cue increases the probability that it will be forgotten.	No additional guidance for fire.	Front panel is selected when the procedure reader can verify the indication reading without leaving his/her assigned location. Back panel is selected when the procedure reader needs to contact a person in a different location or if the procedure reader needs to travel to a different location to read the indication.

Table 5-3 (continued)
Fire-specific and MCRA guidance on decision nodes for Pcb: data not attended to

Alarmed vs. not alarmed	Is the critical value of the cue signaled by an annunciator? If so, the operator is more likely to allow himself to check it, and the alarm acts as a preexisting recovery mechanism or added safety factor. For parameters that trigger action when a certain value is approached or exceeded (Type CP-2 and CP-3 HIs), these branches should be used only if the alarm setpoint is close to but anticipates the critical value of interest; where the alarm comes in long before the value of interest is reached, it will probably be silenced and thus not effective as a recovery mechanism.	If the critical value of the cue is signaled by an annunciator, it must also be unaffected during the fire in order to credit the alarm for recovery. If it is not known if the alarm is available during the fire, the alarm cannot be used as a recovery, and the lower branch is used.	Most RSDPs do not have alarms. However, if a specific NPP does have alarms at its RSDP, “alarmed” can be selected only if the procedure reader can detect that the alarm is occurring without leaving his/her location. There may be situations in which there is a local alarm but operators are not stationed nearby to notice it when it annunciates.

Table 5-4
Fire-specific and MCRA guidance on decision nodes for Pcc: data misread or miscommunicated

Decision Node	Guidance as Stated in EPRI TR-100259 [6]	Guidance Specific for Fire HRA (NUREG-1921)	Additional MCRA Phase III Considerations
Indicator easy to locate	Are the layout, demarcation, and labeling of the control boards such that it is easy to locate the required indicator? The answer is no if there are obvious human factors deficiencies in these areas and the plausible candidates for confusion with the correct indicator are sufficiently similar that the values displayed would not cause the operator to recheck the identity of the indicator after reading it.	No additional guidance for fire.	No additional guidance for Phase III MCRA. Note: However, indications at the RSDP and/ or local plant station are more likely to have human factors deficiencies than MCR indications because these panels have received less scrutiny with respect to human factors than those in the MCR.

Table 5-4 (continued)
Fire-specific and MCRA guidance on decision nodes for P_cc: data misread or miscommunicated

Good/ bad indicator	Does the required indicator have human engineering deficiencies that are conducive to errors in reading the display? If so, the lower branch is followed.	No additional guidance for fire.	No additional guidance for Phase III MCRA. See note above for “Indicator Easy to Locate.”
Formal communications	Is a formal or semi-formal communications protocol used in which the person transmitting a value always identifies the value with which the parameter is associated? (This limited formality is sufficient to allow the person receiving the information to detect any mistakes in understanding the request.)	If the fire requires the operators to wear SCBA, no credit is given for formal communication, and the No branch is used.	Formal communication can be credited even in situations where two operators must communicate via phone. The key for MCRA is that either a formal or semi-formal communications protocol is expected to be followed, based on training, including alternative means of communication for those cases where communications equipment problems may be an issue.

Table 5-5
Fire-specific and MCRA guidance on decision nodes for P_ce: relevant step in procedure missed

Decision Node	Guidance as Stated in EPRI TR-100259 [6]	Guidance Specific for Fire HRA (NUREG-1921)	Additional MCRA Phase III Considerations
Obvious vs. hidden	Is the relevant instruction a separate, stand-alone numbered step? In which case, the answer is Yes, or the upper branch is followed in the decision tree. Or is it “hidden” in some way that makes it easy to overlook, for example, one of several statements in a paragraph, in a note or a caution, or on the back of a page?	No additional guidance for fire.	No additional guidance for Phase III MCRA.
Single vs. multiple	At the time of the HI, is the procedure reader using more than one text procedure or concurrently following more than one column of a flowchart procedure? If so, answer with Yes, or follow the upper branch in the decision tree.	If the EOPs are implemented in parallel to the fire procedures, multiple procedures will be in effect.	Once outside the MCR, some plants implement the MCRA procedure along with the EOPs. This can be the case for BWRs where operators could be in multiple legs of the flowchart or for longer term actions such as containment venting and residual heat removal (RHR) suppression pool cooling when EOP guidance would still apply. Other plants suspend the EOPs once abandonment occurs. Multiple procedures would be selected for MCRA if the procedure reader is required to follow more than one procedure or attachment at the time of the cue.

Table 5-5 (continued)
Fire-specific and MCRA guidance on decision nodes for $P_c e$: relevant step in procedure missed

Decision Node	Guidance as Stated in EPRI TR-100259 [6]	Guidance Specific for Fire HRA (NUREG-1921)	Additional MCRA Phase III Considerations
Graphically distinct	Is the step governing the HI in some way more conspicuous than the surrounding steps? For example, steps that form the apex of branches in flowchart procedures, steps preceded by notes or cautions, and steps that formatted to emphasize logic terms are more eye-catching than simple action steps and are less likely to be overlooked simply because they look different from surrounding steps. However, this effect is diluted if there are several such steps in view at one time (as on a typical flowchart); for this reason, the only steps on flowcharts that should be credited as being graphically distinct are those at the junction of two branching flow paths. A procedure step is considered graphically distinct (as used in $P_c e$) if it is preceded by a “caution” note, set off in a box, or is the only step on the page.	No additional guidance for fire.	No additional guidance for Phase III MCRA.
Placekeeping aids	Are placekeeping aids, such as checking off or marking through completed steps and marking pending steps, used by all crews? The EOPs are written in a columnar “response/response not obtained” format. They may incorporate check-offs and may have provisions for placekeeping. Use of both of these aids would be noted during operator training on the simulator.	No additional guidance for fire.	No additional guidance for Phase III MCRA.

5.2.3.1.4 Example Modeling of Cognitive Contribution to Phase III Actions

NUREG-1921 Supplement 1, Section 5.8.3 provides an example of qualitative considerations associated with an action at the RSDP. An example of how such qualitative considerations for a cognitive contribution to an HFE would be addressed in quantification using the CBDTM is shown below. Note that the authors have not identified a specific HFE for this example, but this example assumes that relevant instrumentation and controls are available at the RSDP. Also, the example evaluations given below are based on expected conditions at RSDPs from the authors' experience. Since RSDPs vary from one NPP to another, the HRA analyst must evaluate their specific case, which can lead to different CBDTM assessments. Finally, the analyst should note that if, for example, some indications or controls were available only at local plant stations, rather than at the RSDP, then the decision trees in Figures 5-1 through 5-8 would be evaluated differently.

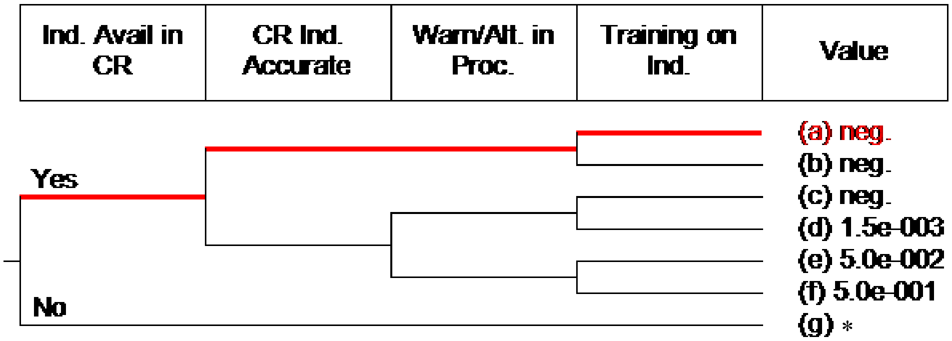
In this quantification example of the application of the CBDTM to the cognitive contribution from a Phase III action, evaluations of trees P_ca through P_ch are provided to illustrate how this method could be applied considering the specific action location setting of an RSDP.

P_ca: Availability of Information

Notes/Assumptions: The indications on the RSDP (e.g., reactor level, reactor pressure, suppression pool level, etc.) are functional even with the master transfer switch in the "normal" position. Taking the transfer switch to the "transfer" position will isolate the cables associated with these instruments to ensure that the instruments will be unaffected by a MCR or CSR fire.

Operator interviews indicated that key parameters are available at the RSDP.

Training on the indicators is provided during simulator exercises using an exact mockup of the RSDP.



* Note that in the guidance for P_ca, if the indications are not in the MCR, this tree is evaluated based on local indications.

Figure 5-1
Decision tree for P_ca: data not available

P_cb: Failure of Attention

Notes/Assumptions: Workload is considered high due to the variety of tasks to be performed by the operator leading C&C at the RSDP when the cues for action occur. Parameters would be monitored at the RSDP, and none of the monitored parameters have associated alarms.

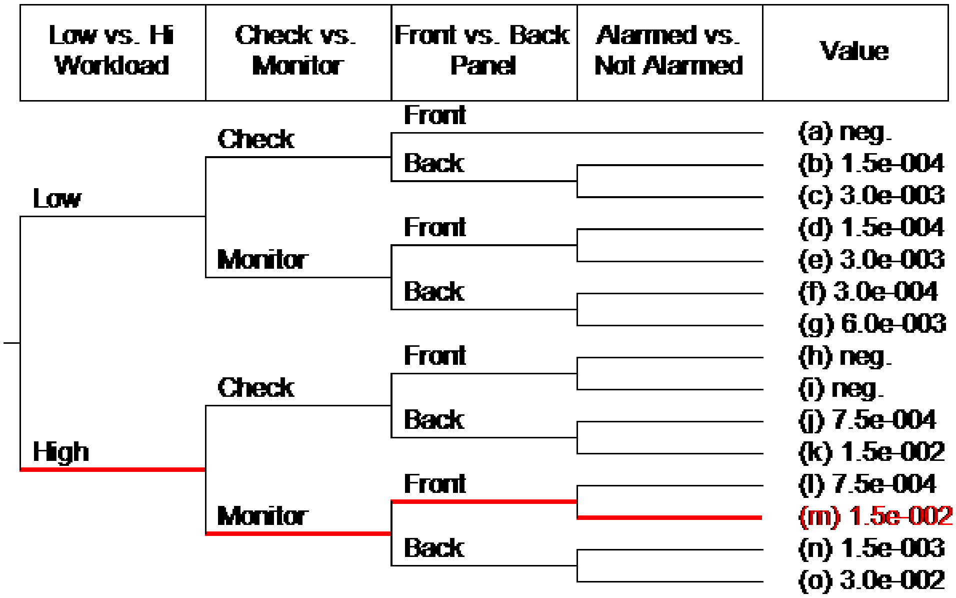


Figure 5-2
Decision tree for P_cb: data not attended to

P_cc: Misread/miscommunicate data

Notes/Assumptions: Indicators are clear and easy to locate at the RSDP. The indicators were considered "good" in that they provided clear information about the key parameters. The observed communications between the operations team at the RSDP was rather informal and did not use the action statement and confirmatory response structure.

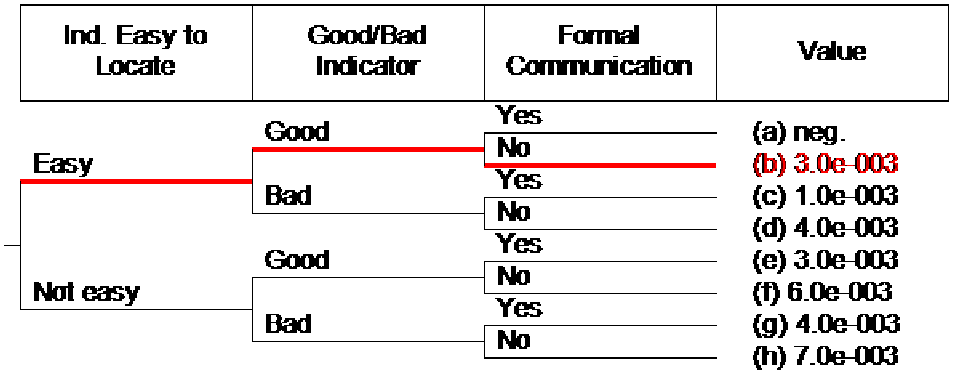


Figure 5-3
Decision tree for P_cc: data misread or miscommunicated

P_cd: Information misleading

Notes/Assumptions: The indications on the RSDP are functional, and circuit analysis has verified that they are unaffected by a MCR or CSR fire.

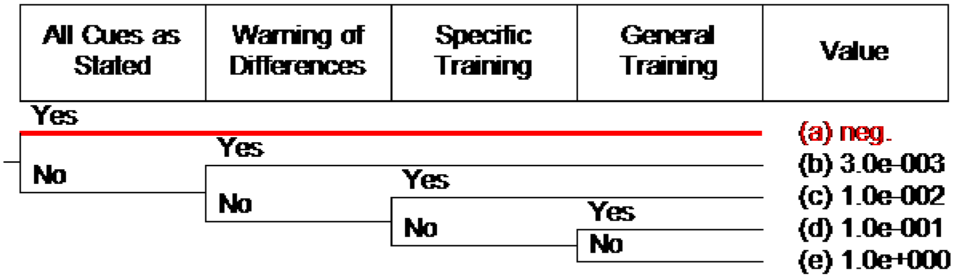


Figure 5-4
Decision tree for P_cd: information misleading

P_ce: Skip a step in the procedure

Notes/Assumptions: Steps required for taking the plant to a safe and stable condition are obvious in the procedure.

For this specific example, the EOPs are assumed to be still in effect upon implementation of the MCRA procedure. They will be used, if necessary, to supplement any safety function that cannot be fulfilled by following the MCRA procedure.

Steps are distinct from each other, and there are lines to be checked off when steps are completed.

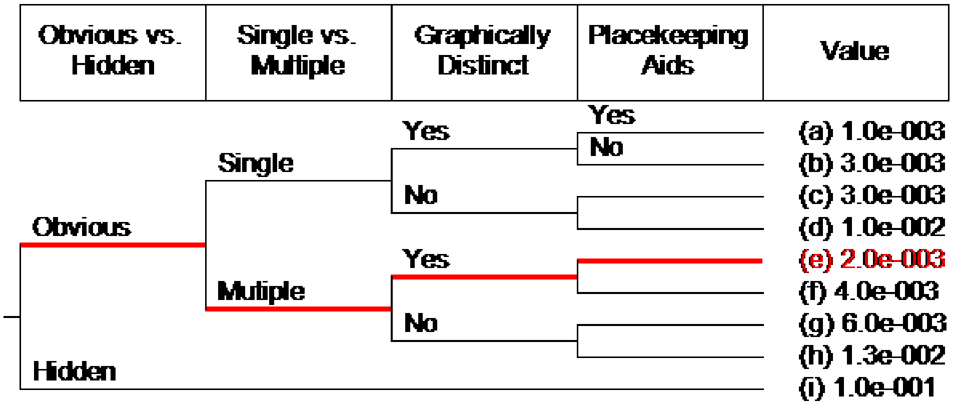


Figure 5-5
Decision tree for P_ce: relevant step in procedure missed

P_cf: Misinterpret Instructions

Notes/Assumptions: Wording of the MCRA procedure[15] follows the EOP standard language and formatting. All required information to perform the task is contained in the procedure.

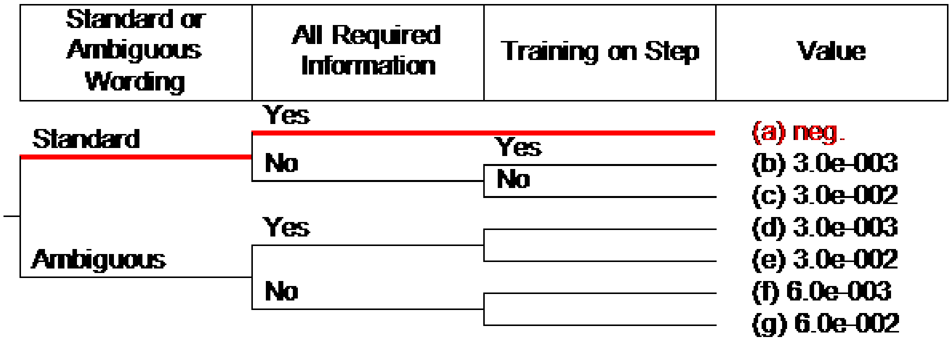


Figure 5-6
Decision tree for P_cf: misinterpret instruction

P_cg: Misinterpret decision logic

Notes/Assumptions: The path shown is based on a NOT statement in the procedure. This scenario is practiced in the simulator during semi-annual MCRA training on an exact mockup of the RSDP.

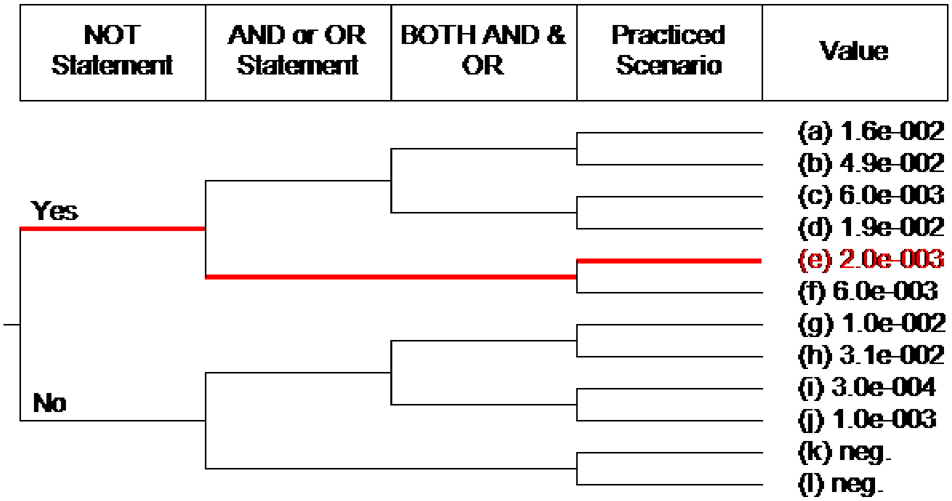


Figure 5-7
Decision tree for P_cg: error in interpreting logic

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[15] The analyst should make an explicit check on the MCRA procedure wording and format with respect to procedure writing requirements for EOPs. The MCRA procedure may not be required (per NRC regulations) to follow the EOP procedure writing guidance, depending on which type of procedure set the MCRA procedure is in. Different NPPs have made different choices on how to categorize the MCRA procedure.

$P_c h$: Deliberate violation

Notes/Assumptions: The operators, when interviewed, did not express hesitancy or lack of belief in the ability of the instruction to address the scenario goals. (This selection would be expected for Level 1 internal events and fire actions that were identified in an Appendix R program; however, the branch selection could be different for Level 2 or FLEX actions.)

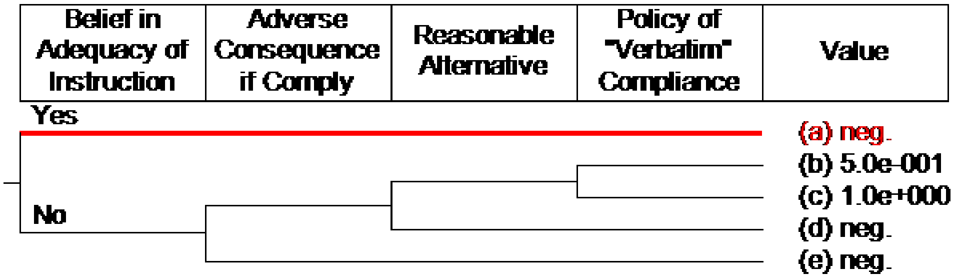

Figure 5-8
Decision tree for $P_c h$: deliberate violation

5.2.3.2 Sub-Step 3.2: Quantification of Execution Errors

The modeling of execution errors associated with MCRA scenarios is similar to (or may be the same as) those local operator actions described in NUREG-1921. Consequently, HRA quantification guidance for the execution portion of these actions should be similar to that given in NUREG-1921, such as provided in Section B.7.5.3 (for THERP) and Appendix C. The THERP approach to quantification is to identify each critical task, consider an error of omission and/or an error of commission, and then apply an overall stress factor.

5.2.3.3 Sub-Step 3.3: Quantification of C&C Sequencing Errors

This section describes the process for identifying coordination failures (which could include communication errors) associated with the incorrect sequencing of operations. Details describing the background on this approach, what the C&C error represents, and what it does not represent, are provided in Appendix C.

The first task is to identify the need for C&C functions in MCRA scenarios. This task may have been started (or completed) as part of the HRA qualitative analysis. The second step is to determine if it is necessary to include an HEP contribution from a C&C sequencing failure. The analyst should follow the flow chart depicted in Figure 5-9 to determine if a C&C sequencing failure should be included. There are three possible outcomes when using the flowchart: 1) there are no C&C sequencing failures that need to be modeled (i.e., C&C sequencing failures are screened out); 2) a C&C sequencing failure must be included, but there are compensating measures; and 3) a C&C sequencing failure must be included, and there are no compensating measures.

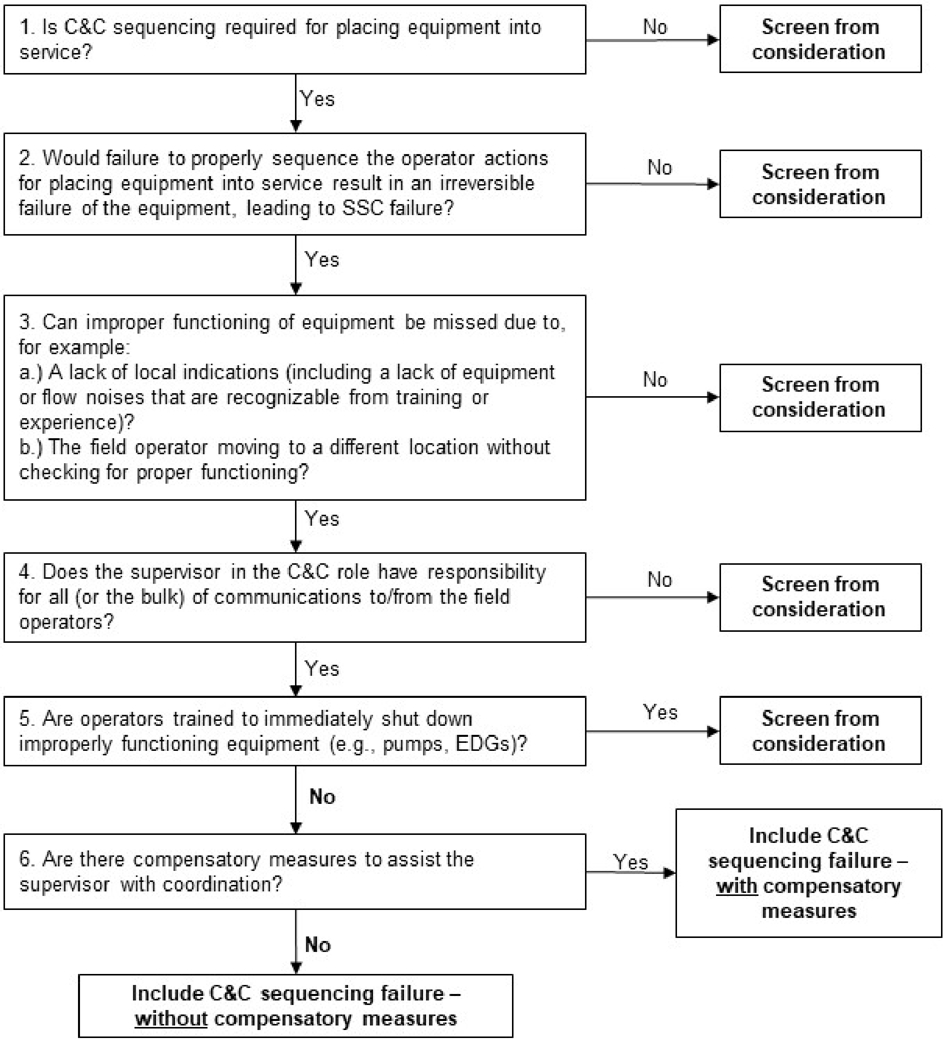

Figure 5-9
Screening test for the inclusion of a C&C sequencing failure

The following examples may be used to help the analyst in evaluating the criteria:

- Criteria 1: A successful pump operation that requires adequate suction head from supporting equipment/system is an instance in which C&C sequencing is required for placing equipment into service.
- Criteria 4: Examples of cases in which the supervisor in the C&C role may have responsibility for all (or the bulk) of communications to/from field operators are:
  - No one else is providing significant help to take or make calls to field operators implementing the MCRA safe shutdown strategy and calls from other plant staff (e.g., fire brigade, health physics).
  - C&C is **not** sufficiently focused on the communications associated with the equipment of concern and its supporting equipment/systems (due to lack of help from other staff in taking/making these communications).
  - Communications are "segregated" such that the supervisor and multiple field operators whose actions must be coordinated are **not** on a common channel; therefore, all parties

do **not** hear all communications (e.g., the operator controlling cooling water to a pump does not hear the command to start the front-line system pump and, therefore, cannot alert the supervisor that there is no cooling water in service).

- Criteria 6: Examples of cases where compensatory measures are not present are:
  - The MCRA procedure does **not** include a written step, Hold Point, or Warning (Caution) that prerequisite SSC alignment is needed prior to operation (e.g., if a MCRA procedure does **not** include a caution about putting supporting equipment/system into service before putting the primary equipment in question into service)
  - The MCRA procedure does NOT include place-keeping aids such that the supervisor can record when support systems are in service, allowing the start of front-line systems.

Different plants employ different training demonstrations of MCRA safe shutdown strategies, but it is uncertain how many implement **integrated** simulations or talk-/walk-throughs in which the SS performs the required C&C functions and either operators or trainers take on the roles of the field operators implementing the actions. Regardless of the training process and the lack of an actual MCRA event to demonstrate this, the authors believe that: (a) C&C sequencing failures could arise in MCRA scenarios from a variety of factors, depending on plant-specific MCRA strategies, procedures, training, and so forth, and (b) the best strategy to address them would be to conduct integrated training to identify any C&C sequencing vulnerabilities.

In addition, no existing HRA methods explicitly address C&C sequencing failures for the contexts and concerns for MCRA. Appendix C provides a brief discussion of a few methods (e.g., THERP [8], NUREG-2114 [9], NUREG-2199 [10], and NARA [11]) that were reviewed to identify failure modes that seemed relevant to C&C functions and, especially, sequencing failures. Each of the HRA methods reviewed provided a different possible failure mode that could lead to a C&C sequencing failure.

Based on its capability of addressing compensating factors, the authors recommend using the HEPs associated with NUREG-2199 and two crew failure scenarios, discussed further in Appendix C, Section C.3. Specifically:

- For C&C sequencing failures **with** compensating measures, assign an HEP of 1.9E-2 (mean value).
- For C&C sequencing failures **without** compensating measures, assign an HEP of 9.4E-2 (mean value).

5.2.4 Step 4: Review the HEPs for the Collective Set of Phase III HFEs

The HRA analyst should check for reasonableness, particularly the overall HEP of each HFE and the number of critical tasks. The consistency check required by the ASME/ANS PRA Standard [12] SR HR-G6 discusses the need to ensure that HEPs are reasonable when compared with other related HEPs based on the scenario context (e.g., higher workloads should be expected for operator actions in Phase III, given that these actions are taken either at the RSDP or field location, rather than in the MCR), plant history, procedures, operational practices, and experience.

The overall HEP should be neither unrealistically conservative nor optimistic. In the former cases, it is a well-known limitation of THERP that HFEs that require many individual tasks can result in excessively high HEPs. Grouping of tasks by functional, perceptual unit is allowed in THERP and is frequently used for MCRA scenarios to counter this limitation. In the latter case, an overall HEP of less than 1E-03 for a Phase III MCRA task (except for long term actions) is generally considered to be unrealistically optimistic. Also, the analyst should compare the HEPs for all MCRA HFEs in a scenario to see whether the HEP matches the complexity of the actions modeled.

Finally, the analyst should re-check for feasibility and check that the dependencies between actions are captured appropriately in the model logic. See Section 6.2 for more discussion on dependencies.

5.3 Recovery of Phase III HFEs

The actions performed in Phase III represent, for the most part, the execution of steps in the post-abandonment procedural guidance. The opportunities for recovery in this phase are of the following types:

- **Self-checking or peer checking** for actions, where the person taking the action (or a co-located peer) realizes that they took a wrong action (e.g., operated a wrong switch or valve) and corrects the action before it has significant consequences. This recovery is typically applied within the same HFE that models the original action.

  In most MCRA cases involving actions taken in plant areas, it is likely that there will be only one person present, so self-checking will be the predominant recovery opportunity at such locations. Also, self-checking would require local indications with appropriate feedback (e.g., flow indications at the same location as where a pump is started). The potential benefit of self-checking is limited; although training can reinforce the behavior of operators to perform self-checking. However, the guidance in THERP [8] (NUREG/CR-1278, Chapter 10), for example, would suggest no more than a credit of 0.5 reduction in the overall probability of failure from self-checking. It is recommended that this credit be permitted only where the training and work practices explicitly include self-checking as part of the tasks and when the analyst has confirmed that sufficient time for self-checking is available.

  Examples of when recovery from peer checking can be credited include:

  - Actions and checking at a local plant station: More than one operator is co-located in plant areas post-abandonment (such that each can check the actions of the other).
  - Actions and checking at the RSDP: The results of the action are indicated at the RSDP such that the supervisor responsible for C&C at the RSDP can observe the consequences of the action or its failure and relay the failure to the relevant operator.
  - Actions at a local plant station, but checking at the RSDP: There is explicit procedural guidance for the supervisor responsible for C&C at the RSDP to check the indication upon completion of the action that is not co-located.

An example of peer checking would involve a local valve opening that should cause system flow with indication at the RSDP. If no flow is indicated at the RSDP, the supervisor responsible for C&C at the RSDP could inform the local operator that the valve has not been successfully opened. Given that, in most cases, the supervisor at the RSDP will be using the abandonment procedure steps as the basis for confirming parameters (e.g., the start of flow or changes in status indicators), the corresponding likelihood of the recovery for such steps is 0.05 based on the discussion of special one-of-a-kind checking discussed in NUREG/CR-1278, Chapter 19 [8].

- **Recovery actions aimed at hardware failures and incorporated in the procedures** that are taken if a normal step fails to accomplish the expected action (e.g., if a piece of hardware fails to start when selected to run). This recovery may be applied within an HFE, or it may be a separate HFE.

  Many procedures contain instructions as to what actions are to be taken in the event that the operator actions in one step do not accomplish the intended outcome. These are often in the form of:

  a. Start Pump "X"
     i. If pump X does not start, then:
        1. Start pump Y
        2. ….

  Such sequences correspond to following the steps in any type of procedure and can, therefore, be modeled using the standard form of THERP.

- **Recovery if the abandonment procedure fails to accomplish its purpose**, where the supervisor responsible for C&C at the RSDP has to recognize the failure and decide on an alternative set of actions (see discussion below). This recovery is typically applied as a separate HFE.

Within the scope of this supplement, only the first two are considered explicitly in the guidance provided in this report. The likelihood of events leading to the need for the third type of recovery, following failure of the procedural actions to accomplish the safety mission, is considered to be low. However, it is recognized that, conceptually, it could be considered in some analyses of NPP designs. In such a case, the analyst would need to model the probability of failure of the supervisor responsible for C&C at the RSDP to recognize that the procedure is failing to accomplish its purpose and to make appropriate decisions about adopting an alternate strategy. This is consistent with the guidance in Supplement 1, Section 9.2, which acknowledges that recovery actions for the long term, such as use of the extensive damage mitigation guidelines (EDMG) and severe accident management guidelines (SAMG) procedures, could be considered. As observed there, "Recovery actions based on flexible and diverse mitigation strategies (FLEX) and SAMG procedures have been left to future evaluation and consideration."

5.4 References

1. EPRI/NRC-RES Fire Human Reliability Analysis Guidelines – Final Report. U.S. Nuclear Regulatory Commission, Rockville, MD, and the Electric Power Research Institute (EPRI), Palo Alto, CA: July 2012. NUREG-1921, EPRI 1023001.
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6

RECOVERY, DEPENDENCY, AND UNCERTAINTY

This section provides quantification guidance on recovery, dependency, and uncertainty for the quantification of MCRA scenarios. The fundamentals of each of these steps in the HRA process are not unique to fire HRA or MCRA HRA. NUREG-1921 Supplement 1 [1] Section 9 provides detailed guidance on what to consider qualitatively for these topics in modeling fires that lead to MCRA.

6.1 Recovery

Section 9.2 of NUREG-1921 Supplement 1 discusses the definition of recovery and the modeling of recovery actions. There are two types of recovery that may be applicable to MCRA: 1) recovery within an HFE, and 2) recovery by adding an HFE (termed a recovery HFE). Recovery HFEs may be added after the initial fire PRA model quantification in order to include an operator action to restore a function, reconfigure a system, or manually manipulate a component initially unavailable in the scenario. Crediting these types of actions is typically added to refine the model or reduce the conservatism that occurs during the initial development of MCRA scenarios, and it is implemented only if the recovery actions are feasible and plausible.

Quantification of recovery, both within an HFE and by adding a new HFE, are dependent on the phase where the action occurs:

- For Phase I HFEs, recovery credit is applied in the same manner as described in NUREG-1921 [2], with the quantification guidance for detailed HFEs provided in Appendices B and C.
- For Phase II HFEs, there is no additional recovery credit (such as if additional time was available).
- During Phase III, recovery credit within an HFE and by adding an HFE are discussed in Section 5.3 of this report (which is consistent with the qualitative guidance in NUREG-1921 Supplement 1 Section 9.2).

During MCRA, the “initial, planned plant response” is the alternate shutdown procedure (i.e., the MCRA procedure). Typically, this procedure was developed assuming one train of equipment was failed by the fire. Since many U.S. NPPs have only two electrical trains, this means the alternate shutdown procedure is using the one remaining train. Consequently, there are typically no proceduralized options for recovery using equipment on the alternate train. However, some of the MCRA scenarios may have longer time windows that could allow consideration of additional staff and additional recovery options that may be available for use during MCRA, such as actions to align non-safety systems or actions in the EDMG procedures. Although this report does not provide explicit guidance for such long-term cases, the quantification approach for newly identified recovery HFEs should follow the same approach as any other MCRA action. For example, any recovery action credited in a MCRA scenario should be accounted for in the MCRA timeline, feasibility needs to be ensured, C&C needs to be addressed, and dependence between actions in the scenario must be considered.

6.2 Dependency

Section 9.3 of NUREG-1921, Supplement 1 discusses factors to consider for dependency analysis and stresses the importance of the scenario timeline. Generally, only a few combinations of HFEs need to be considered because, in most cases, a single failure will lead to core damage. However, there is the potential for the PRA model to generate combinations of HFEs that were not previously considered in the MCRA scenario development; these would need to be reviewed in detail, and the associated timelines should be modified accordingly. Also, for some NPPs and associated MCRA safe shutdown strategies, additional recovery actions may have been added to the PRA since the MCRA timeline was developed (see Section 5.3). Consequently, the feasibility of these actions in combination with other actions will need to be addressed. For example, after failing to locally start an EDG, the plant may have a backup power source that is also manually started. The feasibility of the sequence of events and the potential for dependence must be evaluated.

The dependency assessments among HFEs should follow the guidance in Supplement 1 Section 9.3 and NUREG-1921 Section 6.2 [2]. For the HRA task, Phase III HFEs can be considered independent of the Phase II HFE; the logic in the fire PRA model should appropriately represent that Phase III actions are implemented only after the decision to abandon the MCR has been made. For Phase III HFEs, even if cognition is not included in the Phase III action, a dependency assessment is needed in case there are staffing limitations, timing constraints, or C&C issues. The aspects of C&C that relate to potential dependence consist of cues, procedures, staffing, and critical communications. Each aspect, except critical communications, is already included in the dependency tree depicted in Figure 9-1 of NUREG-1921 Supplement 1. For the evaluation of the dependency tree, critical communications and coordination should be treated in the same way as cues.

At the time of publication, there is no consistent technical view on some dependency issues, such as the minimum JHEP value.

6.3 Uncertainty

NUREG-1921 and NUREG-1921 Supplement 1 provide references and guidance regarding sources of uncertainty, including those for fire HRA/PRA. In particular, NUREG-1921 Supplement 1 addresses sources of uncertainty associated with the identification, definition, and qualitative analysis for fire HRA tasks for MCRA scenarios. This document focuses on the sources of uncertainty associated with the additional research presented in this report and in the quantification of uncertainty (i.e., parametric data uncertainty and sensitivity).

Sources of Uncertainty. The sources of uncertainty associated with the additional research presented in this report are primarily related to the modeling of the Phase II decision to abandon the MCR (described in Section 4). Sources of uncertainty related to communications and C&C were previously included in NUREG-1921 Supplement 1. Most importantly, the analyst must understand if the action(s) is a source of **key** uncertainty [4,5]. A key uncertainty is an uncertainty source that can have a significant effect on the risk metrics and affect the analyst's understanding of the most important contributors and the overall risk significance of the analysis [6]. Chapter 7 of NUREG-1855, Revision 1 [5], along with Sections 3 and 4 of EPRI 1016737 [7] provide detailed discussions on how to assess key sources of model uncertainty, including formulation of sensitivity studies for key uncertainties and interpretation of results.

Parametric Data Uncertainty. In the 2009 version of the ASME/ANS PRA Standard supporting requirement HR-G8 says to characterize the uncertainty in the estimates of the HEPs in a manner consistent with the quantification and PROVIDE mean values for use in the quantification of the PRA results [6]. The same requirements apply to all PRA capability categories. The quantification approaches described in this document are intended to produce mean HEP values (including HEPs associated with C&C sequencing failures in Phase III). The quantification approaches for Phase I and Phase III are based on existing HRA methods, and uncertainty distributions associated with these methods can be applied to MCRA HEPs.

The data associated with Phase II quantification is based on an expert elicitation, and each end state probability is considered to be a point estimate mean. No distributions associated with these HEPs were developed during the expert elicitation process. Since each of these HEPs is on the higher end of possible HEP estimates, one approach would be to use the EPRI HRA approach [8] of applying a Beta distribution. The resulting 5% and 95% HEPs are shown in Table 6-1.

Table 6-1
MCRA Phase II HEP uncertainty parameters

Phase II HEP	Distribution	Variance	5th Percentile	95th Percentile
1E+00	Beta	0.0	1E+0	1E+0
2E-01	Beta	2 E-2	3E-2	5E-1
1E-01	Beta	7 E-3	1E-2	3E-1
9E-02	Beta	6 E-3	1E-2	2E-1
8E-02	Beta	5 E-3	9E-3	2E-1
7E-02	Beta	4E-3	8E-3	2E-1
6E-02	Beta	3 E-3	7E-3	2E-1
5E-02	Beta	2 E-3	5E-3	1E-1
3E-02	Beta	7 E-4	3E-3	8E-2
2E-02	Beta	3 E-4	2E-3	6E-2

Alternatively, the analyst could use an approach consistent with the uncertainty modeling used with the SPAR-H HRA method [9]. The EPRI HRA approach referenced above is consistent with the following caveats presented in Section 2.7.1.2 of SPAR-H [9] on parametric uncertainty:

- "Some HRA approaches, such as THERP and accident sequence evaluation program (ASEP), made use of lognormal error factors, which often produced upper bounds for HEPs that were greater than one. Practitioners were aware of this unrealistic values and accepted it because of base assumptions regarding lognormal distributions of human performance and inabilities to move easily away from these normal and lognormal distributions as a basis for these human performance models (which can be overcome by using a Beta distribution as shown in Table 6-1 or any other distribution bounded between 0 and 1).
- The SPAR-H method does not use error factors, nor does it assume the use of a lognormal probability distribution. The SPAR-H method ultimately employs a Beta distribution, which is more flexible than normal and lognormal distributions in representing symmetric and non-symmetric distribution shapes."

Section 2.7 of SPAR-H then goes on to discuss specific human performance models for potential use in Bayesian update. This has not been explored in this guidance for MCRA HEPs, but it could be a topic of potential future research.

Sensitivity Cases. In addition to the parametric distributions described in Table 6-1, the impact of uncertainty in the Phase II HEP can be evaluated in bounding sensitivity studies. Two sensitivity cases are recommended. For Case 1, set the decision to abandon HEP to 1.0, and then characterize the impact on the overall results. For Case 2, set the HEP to 1E-3, and then characterize the impact on the overall results.

Table 9-1 of Supplement 1 lists potential sources of uncertainty to consider for MCRA**.** For MCRA scenarios, one of the key parameters is timing, and for HRA quantification the timing parameters are considered to be point estimates. To characterize the uncertainty associated with the timing parameters, the HRA analyst should consider sensitivity studies of various timing inputs as described in Section 2.3.2.

6.4 References

1. EPRI/NRC-RES Fire Human Reliability Analysis Guidelines—Qualitative Analysis for Main Control Room Abandonment Scenarios: Supplement 1. U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Washington, DC, and Electric Power Research Institute (EPRI), Palo Alto, CA: 2017. NUREG-1921 Supplement 1 and EPRI 3002009215.
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7. Treatment of Parameter and Model Uncertainty for Probabilistic Risk Assessments. EPRI, Palo Alto, CA: 2008. 1016737.
8. EPRI HRA Calculator Version 5.1. EPRI, Palo Alto, CA: 2014. 3002003149.
9. The SPAR-H Human Reliability Analysis Method. Idaho National Lab for the US NRC, Washington, DC: 2005. NUREG/CR-6883.

7
CONCLUDING REMARKS

NUREG-1921 Supplement 1 [1] provides the following (as stated in its conclusion section):

- Highlights of lessons learned and experience gained from the development of qualitative analysis guidance to support fire scenarios that may result in MCRA
- Description of good practices for MCRA modeling and HRA
- An outline of the type of interface that should be conducted with plant operations personnel during the MCRA HRA qualitative analysis process.

The focus of this report (Supplement 2) is to provide guidance on the quantification model used in the MCRA HRA. Therefore, the concluding remarks here will focus on key insights on MCRA from the quantification model development.

7.1 Key Lessons Learned About MCRA HRA Quantification

The NUREG-1921 [2] guidance for quantifying HFEs in a fire PRA is focused on actions that are directed from the MCR with both EOPs and FRPs being used. As discussed in Section 2.2 of Supplement 1 [1], there are some fundamental differences between the MCRA context and non-abandonment contexts. In HRA, the fundamental differences manifest themselves as changes to the quantification methods (e.g., a new quantification tool for Phase II) or the guidance for implementing an existing method (e.g., MCRA-specific quantification guidance for Phase III). The MCRA response can be broken down into three distinct phases, each with its own set of considerations and quantification methods. The key differences and their impacts to quantification are summarized below, by phase.

7.1.1 Key Lessons Learned – Phase I

Phase I actions are those actions that are taken prior to the decision to abandon. These actions are similar to other human actions modeled in fire PRA and follow the same EOP and FRPs, so no additional quantification guidance is provided in this report for Phase I; the methods in NUREG-1921 are adequate for modeling human actions during this phase.

7.1.2 Key Lessons Learned – Phase II

Phase II is the time period associated with the decision to abandon. There are two primary reasons why operators may abandon the MCR for fire-related events. Either the LOH criteria have been met, or the fire caused an LOC scenario and operators must leave the MCR in order to maintain control of the plant. For LOH scenarios, because the LOH criteria are based on physical parameters where it becomes untenable to remain in the MCR, there is no quantitative contribution associated with the cognitive decision to abandon the MCR.

Consequently, for Phase II, the HRA is concerned with LOC scenarios, specifically to quantify the HFE that the crew will fail to make the decision to abandon in sufficient time to execute the

MCRA safe shutdown strategy. With respect to impacts on quantification, the decision to abandon for LOC scenarios is substantively different from typical EOP actions in three ways:

1. **Cue response**: Typically, there is no individual indicator or explicitly defined parameter-based cue that is used to determine when the MCR must be (or would be) abandoned for LOC scenarios. The “cue” for abandonment is in reality a progression of indications about the fire including fire-induced failures and fire suppression. Operators are continuously evaluating information until it reaches a “tipping point” that is severe enough to satisfy the abandonment criteria. In all cases, some level of judgment is required in the decision to abandon following LOC, and operators must rely on their training to think critically and integrate their overall understanding of the plant state and plant response.
2. **Timing**: Supplement 1 provided an in-depth discussion about timing for MCRA. In addition, Section 2 of this report (Supplement 2) refines some of the timing definitions in Supplement 1 specific to Phase II and expands upon the timing guidance based on the quantification tools and methods recommended in this report. It should be recognized that the timing of MCRA Phase II actions is not as well defined as other actions in internal events or fire PRA, meaning that:
    a. The traditional concept of system time window (T_{SW}) based on thermal-hydraulics calculations does not fit for Phase II, because the time available for the decision to abandon is a derived value that depends on the time required for Phase III. Thermal hydraulics calculations typically apply from the time of a reactor trip until a damage state such as component damage, core damage, or a large early release has occurred. For MCRA scenarios, the same system time window is used for Phase II and Phase III. In addition, it may be difficult to determine timing parameters for Phase II (e.g., time required). Consequently, the analyst must allocate, rather than strictly calculate, time available for Phase II and Phase III.
    b. For LOC scenarios, the cue is not a single parameter. Instead, it is necessary to consider the collective set of cues. Determining the exact time at which the minimum set of cues becomes available can be difficult.
3. **Reluctance**: Based on discussions with operators and the expert elicitation, it was judged that there is a high level of reluctance associated with abandoning the MCR for LOC scenarios. This natural reluctance to abandon the familiar environment of the MCR is compounded by the fact that abandonment scenarios are rare. NPP operators are familiar with many "rare events" due to their frequent simulator training, but they may consider MCRA scenarios even less credible.[16] To date, no MCRA events have occurred in the United States, and realistic simulator training of MCRA decision-making is uncommon. The expert elicitation identified this underlying reluctance as the primary driver in quantification, and its effect is built into the baseline HEPs in the new decision tree for Phase II. This judgment was based on the range of RSDP capabilities, MCRA strategies, and training for the existing U.S. NPP fleet. However, the authors recognize that NPP utilities may make changes to their operator training programs, potentially allowing the collection of plant-specific simulator data on the decision to abandon for LOC scenarios. Such simulator exercises (and possibly additional research on what can reduce operator “reluctance” to abandon) may support different HRA quantification approaches. Appendix D documents the

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[16] In response to the Fukushima event, some U.S. NPPs are including simulator training on extended station blackout (SBO) events. Therefore, at these NPPs, SBO events may be considered more familiar to operators than MCRA fire events.

underlying research and assumptions regarding reluctance as it relates to making decisions with serious consequences.

NUREG-1921 stated that additional research was needed in order to address the cognitive challenges associated with the decision to abandon the MCR. These three aspects listed above for Phase II HRA were sufficiently different from typical cognitive actions that the HRA quantification guidance in this report and NUREG-1921 Supplement 1 should be used instead of NUREG-1921.

The entry criteria for the MCRA procedure often leaves discretion to the operator and may not prescribe a set of equipment or instrumentation failures that necessitate abandonment. The operator's overarching understanding and situational awareness (gained through both experience and training) may compensate for the lack of explicit criteria. Realistic training on the decision to abandon (versus classroom) is expected to be a strong compensatory measure or reliability factor for successfully making the decision to abandon.

7.1.3 Key Lessons Learned – Phase III

Phase III actions are those taken after the decision to abandon is made. These are typically local execution actions that are covered by the methods in NUREG-1921. However, the context of these actions differs from that for those operator actions taken outside the MCR in internal events and fire PRA. In particular, Phase III operator actions are even more localized, often require additional remote coordination, and are performed under a shifted C&C structure. Therefore, the quantification approach in this report for Phase III follows the existing methods with some additional considerations to account for the major differences in context.

Following MCRA, the C&C structure shifts from a co-located setting with multiple instruments, alarms, and communications circuits that are provided in the MCR to a distributed setting with limited instrumentation, alarms, and communications. As part of the development of this report, research beyond that given in Supplement 1 was conducted to define and address C&C-related failures. Key lessons learned from the research underlying Supplement 2 are:

- Despite research efforts for both Supplement 1 and Supplement 2, there is little relevant literature on C&C as part of human reliability:
  - Substantial C&C literature for military applications was found.
  - No C&C literature specific to the nuclear power industry context was found.
  - Some literature relevant to NPP operators is available for related topics such as teamwork.
- For a "new" context such as MCRA operations, it was helpful to compare and contrast what is known about C&C between MCR and MCRA operations.
- SMEs were helpful in identifying the most important issues for C&C in MCRA operations and the focus for HRA.
- Research for Supplement 2 identified a new failure mode applicable to Phase III operator actions that is caused by C&C sequencing failures.
- For the C&C sequencing failures, the SMEs did not develop quantitative estimates. Although this may have been due only to lack of resources, there were indications during the expert elicitation that, for this very unique and rare context, the SMEs were pushed to the limit of their experience and knowledge in developing qualitative insights (and it is possible that

even with additional resources they may not have been able to develop specific quantitative insights).

7.2 Future Activities and Research

Although Supplements 1 and 2 to NUREG-1921 represent a substantial amount of research related to MCRA scenarios in fire events, additional activities and future research would be beneficial in certain areas. In some cases, this additional work is related to fire HRA/PRA and MCRA scenarios (e.g., updates to MCRA HRA guidance if/when NPPs incorporate simulator training for the decision to abandon the MCR). In other cases, such research may involve extending or expanding the research documented in Supplements 1 and 2 to other NPP operations for the existing fleet of U.S. NPPs, other hazards, or new NPP designs. In particular, the author team recommends further research on operator decision-making when cues are uncertain or ambiguous in some way.

Regarding research on C&C, the following are examples of NPP operations and associated HRA/PRA applications that could benefit from additional NPP-specific C&C research:

- Implementation of security measures (e.g., B.5.b measures)
- Implementation of mitigating strategies (e.g., FLEX)
- Implementation of SAMGs or other guidance for post-core damage scenarios
- Implementation of accident response guidance in the case of site-wide events (e.g., seismic, flooding)

7.3 References

1. EPRI/NRC-RES Fire Human Reliability Analysis Guidelines—Qualitative Analysis for Main Control Room Abandonment Scenarios: Supplement 1. U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Washington, DC, and Electric Power Research Institute (EPRI), Palo Alto, CA: 2017. NUREG-1921 Supplement 1 and EPRI 3002009215.
2. EPRI/NRC-RES Fire Human Reliability Analysis Guidelines – Final Report. U.S. Nuclear Regulatory Commission, Rockville, MD, and EPRI, Palo Alto, CA: July 2012. NUREG-1921, EPRI 1023001.

A

USE OF EXPERTS AND EXPERT JUDGMENT IN THE DEVELOPMENT OF NUREG-1921, SUPPLEMENTS 1 AND 2

A.1 Introduction

This appendix summarizes how experts, expert judgment, and expert elicitation were used in the development of this report (i.e., Supplement 2 to NUREG-1921) as well as Supplement 1 [1] to NUREG-1921.

The purpose of this appendix is to describe how and why expert judgment was used in this project on MCRA HRA as background to the guidance described in the main body of this report. Also, the information provided in this appendix could be used as a starting point for future research or guidance development.

A.2 Background

The technical approach used to develop MCRA HRA guidance is essentially the same as that used to develop NUREG-1921 [2] and other HRA guidance. In particular, the approach is based on:

- Existing HRA guidance and methods
- The experience and expertise of the author team
- Assessment and understanding of relevant operational experience
- Review and assessment of relevant psychological literature, especially as it relates to the understanding of operational experience
- The experience and expertise of SMEs regarding U.S. NPP operations
- Integration and application of all information sources above by the author team

In the course of performing the work, the author team recognized that:

- Reaching full consensus within the author team on the appropriate treatment of key issues for the decision to abandon for LOC scenarios would likely exceed the amount of time available to complete project deliverables.
- Additional input from operations experts and NRC staff with NFPA 805 review experience would be beneficial.
- A more formal process for developing consensus would be useful and probably more efficient than author team debates.

For these reasons, an approach to incorporate expert judgment was decided upon. This approach is further discussed in the remainder of this appendix.

A.3 Use of Experts, Collection of Information, and Development of Understanding of Issues

This section summarizes how the experts were used in developing MCRA HRA guidance, including the development efforts for both Supplements 1 and 2, as well as NUREG-1921.

A.3.1 Use of Experts

This project made use of experts and expert information throughout the associated research. Also, different types of experts were used at different times and different ways.

The following types of experts, including members of the project team, were used in this project (with some experts representing more than one type of expertise):

- HRA/PRA method developers (especially for the ATHEANA quantification approach [3] that was used for expert elicitation)
- HRA/PRA practitioners (both NPP and non-NPP applications)
- Expert elicitation facilitators (including applications of the ATHEANA expert elicitation process)
- Fire HRA/PRA practitioners (especially for NFPA 805 [4])
- HRA/PRA reviewers (especially for NFPA 805)
- NFPA 805 audits or peer reviews (including plant walkdowns)
- Operators and operations experts (NPP and other)
- Analysts or operations experts with operational experience insights
- Former NPP personnel with operating procedure development or revision experience
- Operator trainers, especially with experience in aspects of MCRA (or related contexts)

Collectively, the joint EPRI/NRC-RES HRA team has expertise in all of these areas except the last two (e.g., operator trainers, specific operator or operator trainer experience in aspects of MCRA or related contexts). Throughout the project, the team pooled and compared their collective (and sometime different) experiences in order to advance an understanding of the MCRA context.

Experts outside of the project team were used several times during the project, such as:

- Initial interviews with HRA/PRA experts and operator/operator trainer(s) in order to better understand human performance concerns for MCRA
- Frequent interactions with NRC/Nuclear Reactor Regulation (NRR) staff who reviewed NFPA 805 submittals and/or performed NFPA 805 audits to identify HRA modeling and human performance concerns
- More targeted interviews of NRC staff who are former operators to identify human performance concerns for PWRs (both Westinghouse and Combustion Engineering) and BWRs, respectively
- Expert elicitation to develop HEPs for the decision to abandon on LOC and to identify key issues for HRA modeling to address with respect to C&C following abandonment of the MCR

The first three types of interactions with experts are documented in Supplement 1 [1]. For the most part, these interactions were informal, even if questions or topics were identified ahead of the interviews.

Supplement 2 included additional interactions with SMEs and an expert elicitation. More discussion on the expert elicitation, which involved a more formal process, is provided in Section A.4.

A.3.2 Experts Consulted in This Project

The SMEs that participated in the 1.5-day workshop are listed below. A short synopsis of their relevant expertise is included.

- **Harry Barrett** (U.S. NRC) received a BS degree in Marine Nuclear Science from SUNY Maritime College (Fort Schuyler) in 1975. Early in his career, he worked in the U. S. merchant marine as a Coast Guard licensed marine engineer and as a nuclear engineer at several shipyards refueling and testing naval reactors. He has extensive experience in the commercial nuclear industry in the areas of nuclear plant operations (Senior Reactor Operator), maintenance, engineering (PE), and project management. Prior to joining the NRC, he was responsible for the first National Fire Protection Association (NFPA) 805 Pilot Plant (Duke Energy's Oconee). Mr. Barrett came to the NRC in May 2007 as a fire protection engineer in NRR. Since that time, he has developed guidance and resolved technical issues related to risk-informed fire protection programs while performing numerous technical and regulatory reviews of NFPA 805 license amendment requests. He provided technical oversight of the first NFPA 805 pilot safety evaluation (Shearon Harris) and assisted at the triennial fire protection inspections at both NFPA 805 pilot plants and most non-pilot plant NFPA 805 inspections.
- **Erin Collins** is a Senior Engineer at JENSEN HUGHES with 32 years of experience in safety, reliability, and risk assessment, specializing in data analysis and human reliability analysis for nuclear, chemical, and aerospace applications. She was a key technical participant in the Fire HRA Task of the Fire PRAs for ANO-1, ANO-2, Kewaunee, Monticello, Nine Mile Point 1, and Prairie Island plants and provided review and input to the HRAs for the Browns Ferry, Ginna, and Palo Verde fire PRAs. She was also a primary analyst for the MCRA HRAs for the Diablo Canyon and V.C. Summer fire PRAs. Ms. Collins was a reviewer of the EPRI Seismic HRA methodology and is a key participant on the JENSEN HUGHES' Seismic HRAs for the Duke Energy fleet Seismic PRAs. Ms. Collins was the Principal Investigator for the EPRI Guidelines for PRA Data Analysis. She performed PRA equipment reliability database updates for ANO-1, Hatch, and Palisades, as well as the Federal Aviation Administration (FAA) regional air route traffic control centers (ARTCCs), the U.S. Army Chemical Weapons Destruction facilities, the Titan IV/Cassini RTG Safety Study for NASA and its contractors, and the U.S. Department of Energy's (DOE) License Application for the Yucca Mountain Project for nuclear plant waste disposal.
- **Jeff Julius** is a Director of Risk and Safety with JENSEN HUGHES. He has 37 years of experience in the operation, maintenance, and PRA of nuclear reactors. These analyses supported risk-informed decision-making such as plant licensing and startup, satisfied regulatory requirements including periodic safety reviews and transition of the plant's fire protection program to NFPA 805, evaluated potential plant modifications, and maintained safety while remaining online at power. He has researched and developed new risk assessment methods and PRA techniques in the areas of shutdown PRA and human reliability analyses. Mr. Julius has been the senior technical advisor or project manager for

several fire and flood PRAs and peer reviews. Additionally, Mr. Julius was a co-author on reports for Fire HRA (NUREG-1921 and NUREG-1921 Supplement 1).

- **Jim Kellum** (U.S. NRC) is a Senior Engineer in the Office of New Reactors with over 35 years of experience in the nuclear power industry. During his 11.5 years at the NRC, he has contributed to the Knowledge and Abilities (K/A) catalog developed for the AP-1000, ABWR, and NuScale designs. Mr. Kellum has extensive experience with main control room simulators, participating in the development of IP-41502 (simulator inspection), and has been a committee member of ANSI 3-5. He is also an Operator Licensing Examiner for the Westinghouse, Combustion Engineering, and AP-1000 designs. Prior to joining the NRC, Mr. Kellum spent 24 years in operations and training in the commercial nuclear power industry. Mr. Kellum held SRO licenses at Beaver Valley and Calvert Cliffs. Mr. Kellum's commercial nuclear experience also includes EOP development, SAMG development, simulator instructor, training supervisor, exam writer, and requalification supervisor. Mr. Kellum has a BS from the University of Toledo and spent 8.5 years in the nuclear Navy.

A.3.3 Collection of Information and Understanding of Issues

The collection of information and understanding of issues were particular objectives of the MCRA HRA research. In other words, these research activities overlapped the same activities that would be performed for a formal expert elicitation. In particular, Supplement 1 of NUREG-1921 includes the results of data collection (e.g., identification of relevant events, review of relevant literature, and interviews of experts) and the resulting understanding of human performance issues important to the MCRA context. (For examples, see Appendices A and B in Supplement 1).

Follow-on research for Supplement 2 expanded upon this understanding of human performance issues. In particular, work on Supplement 2 included additional information collection and development of a list of issues important to HFE quantification that were used in an expert elicitation. More information about the expert elicitation is provided in Section A.4.

A.4 Expert Elicitation for the MCRA HRA Project

As discussed in the main body of the report, an expert elicitation process was used to develop multiple aspects of the overall MCRA HRA quantification guidance. This section discusses the process that was followed to accomplish this. Sections A.4.1 and A.4.2 discuss the guidance for expert elicitations used for NPP HRAs and PRAs. Section A.4.3 discusses the specific scope of the expert elicitation performed for the MCRA quantification effort. Section A.4.4 presents the expert elicitation process used for the MCRA quantification effort and how it compares to the general guidance.

A.4.1 ATHEANA HRA Expert Elicitation

The ATHEANA HRA expert elicitation process [5] was developed to obtain HEPs from SMEs through a structured process that considers the plant conditions and relevant PSFs associated with each HFE's context in a holistic and integrated manner. While not all the tools of the ATHEANA process were applied, it was used to provide formalism to the selection of issues and failure modes to represent in MCRA scenarios and to assist in the development of HEPs for: 1) the HFE for the decision to abandon on LOC for MCRA scenarios, and 2) specific C&C failure modes that contribute to HFEs associated with operator failures after abandonment.

Because the elicitation did not include the development of uncertainty bounds, this specific application of the ATHEANA expert elicitation approach could be called "abbreviated" (although ATHEANA guidance and prior applications do not make such a distinction).

The ATHEANA HRA quantification approach (as documented in NUREG-1880 [3]) is similar to other, previously developed HRA quantification methods (e.g., SLIM-MAUD [6], SLIM [7]). However, unlike these previously developed HRA methods, the ATHEANA HRA expert elicitation approach is based on the expert elicitation approach cited in NUREG/CR-6372, Recommendations for Probabilistic Seismic Hazard Analysis Committee (SSHAC) [10], with some notable differences. For example, the ATHEANA expert elicitation is focused narrowly on the development of HEPs for HFEs, where each HFE represents a fairly narrow set of contexts. Also, the ATHEANA HRA expert elicitation approach identifies operational experts as critically important to predicting operator behavior. Consequently, an ATHEANA expert elicitation panel is typically composed of operators or operator trainers and HRA/PRA analysts. The job of the ATHEANA expert panel is to connect, or extend and extrapolate, the HFE context with the experts' operational knowledge and experience.

In addition to guidance on the overall ATHEANA quantification approach, NUREG-1880 provides instructions on how to conduct a facilitator-led, structured expert elicitation process, including:

- Guidance on "who should the experts be?" (see Section 3.8.2.1 in NUREG-1880)
- Description of the role of facilitator (see text box on page 3-67 on NUREG-1880)
- Guidance for the facilitator on conducting the overall expert elicitation and on special topics, such as how to control unintentional bias (see text box on page 3-68 of NUREG-1880)

- Guidance on all steps of the expert elicitation process, including how to develop distributions and develop a consensus HEP and distribution
- Technical background on the expert elicitation (or expert "information") approach used (see Appendix B in NUREG-1880)

The traditional application of ATHEANA would be for plant-specific applications with plant-specific experts. However, as noted earlier, most NPPs in the U.S. industry do not conduct training specifically on the decision to abandon (for either LOH or LOC scenarios). Also, training of the MCRA safe shutdown process rarely includes the direct involvement of field operators in order to simulate C&C functions from the RSDP. Consequently, the authors decided to use experts to develop generically applicable HEPs, rather than require expert elicitations for individual NPPs.

A.4.2 Other Expert Elicitation Guidance

The U.S. NRC does not have standardized guidance on expert elicitation. A Staff Requirements Memorandum (SRM) on expert elicitation was issued in 2011 [8], but it did not result in a consensus approach. However, a U.S. NRC white paper that provides insights and lessons learned on implementing expert elicitation [9] was developed. This section summarizes the contents of the white paper so that this guidance can be compared with the expert elicitation approach used in MCRA HRA research.

The white paper recognizes that SSHAC [10] provides a formal process for conducting expert elicitation and that different applications may require less formalism (or different levels of effort). An example of such an application is the ATHEANA HRA quantification method [3], which is based on the guidance given in SSHAC, but modified for the purposes of HRA/PRA.

Per the NRC White Paper [9], "…[an] expert elicitation should conform to the following principles, regardless of the scale, level of effort, and the method or procedures employed for the elicitation process:"

1. Representation of technical community
2. Independent intellectual ownership
3. Avoidance of conflicts of interest
4. Breadth of state of knowledge
5. Interaction and integration
6. Structured process
7. Transparency

In addition, the NRC White Paper [9] states that expert elicitations should be performed using "[a] structured and systematic process … that encompasses all the basic principles. This section describes a recommended systematic expert elicitation process that consists of ten steps across four phases:

> **Phase 1: Planning and preparation.** The purpose of this phase is to ensure the elicitation problem is sufficiently defined to address the regulatory application of interest; that the project team, expert panel and elicitation process are adequate to address the elicitation problem; and that the experts are provided with necessary information prior to the actual elicitation.
>
> **Phase 2. Pre-elicitation works** – The purpose of this phase is to ensure that compiling the dataset is performed with the involvement of the expert panel and all of the team members understand the project, the technical problems, the individual's role/responsibilities, and the theories of probabilities and uncertainties.
>
> **Phase 3. Elicitation** – The purpose of this phase is to elicit expert judgments through interactive workshops. The expert panel interacts to evaluate the data and models, make interpretations, form initial judgments, and integrate the judgments to represent the distribution of the views of the technical community.
>
> **Phase 4. Final documentation and sponsor review** – The purpose of this phase is to develop final documentation of the process and results, and have the technical staff of the sponsor organization to review the documentation for regulatory assurance.
>
> **All-Phases. Participatory peer review** – This is not a separate phase. Rather, the purpose of this activity is to ensure that the entire expert elicitation process is conducted with participatory peer review in all of the phases."

Table 3-1 in the NRC White Paper defines different levels of effort indicators for key steps in the explicit elicitation process. Also, the definitions of different levels of expert elicitation that were defined in SSHAC are shown in Table 3-2 of the NRC White Paper.

A.4.3 Scope of Expert Elicitation

The expert elicitation performed for the MCRA HRA project was based on the ATHEANA HRA quantification method. Two different types of HFEs or failure modes in MCRA scenarios were examined:

1. (HFE) operators fail to decide to abandon in LOC scenarios (i.e., Phase II)
2. (Either added failure mode for an existing HFE or a new HFE) C&C fails to sequence operator action A before operator action B.

For the first type of failure, the expert elicitation for the MCRA HRA project ultimately produced a decision tree with associated generic HEPs to be used in MCRA HRA quantification. However, the facilitator decided, while guiding the experts in their judgments, that uncertainties would not be developed for the elicited HEPs for two reasons: 1) the development of uncertainty values would be too challenging for the MCRA decision to abandon context, which has no operational or training experience, and 2) limited resources. Ultimately, while some additional work was done with the experts after the workshop, the time available for this work was the most important limitation. As a result, the range of HEPs produced was relatively narrow (i.e., a factor of 10), meaning that uncertainty ranges will overlap for HEPs represented on different branches in the decision tree.

For the second type of failure, the end results of the expert elicitation were: 1) a consensus agreement on the most important issues for C&C in Phase III, and 2) a consensus agreement that the only consequential C&C failures are those that result in sequencing failures such that irreversible damage of required equipment occurs. Further results were not attempted due to: 1) the judgment that experts would not be able to produce HEPs for such failures without operational or training experience, 2) the wide range of actions (and associated available times to perform those actions) would be difficult to address in an expert elicitation intended to develop generic HEPs (since the MCRA safe shutdown procedures are very plant-specific), and 3) limited resources.

Overall, the expert elicitation performed for the MCRA HRA project consisted of a one-and-a-half-day workshop and several follow-up conference calls and e-mails. The Phase II expert elicitation was completed in the first day of the workshop, while the Phase III expert elicitation was performed via the last half-day of the workshop and several follow-up communications. Due to the constraints of time, the final aggregated results of the Phase II elicitation were not provided to all of the experts for review and consideration.

A.4.4 Comparison of MCRA HRA Project Expert Elicitation to Other Expert Elicitation Guidance

There are a few differences between the expert elicitation performed for the MCRA HRA project and the formal expert elicitation processes described in the ATHEANA User's Guide [3] and the JACQUE-FIRE Phenomena Identification and Ranking Table (PIRT) exercise [11]. Most of these differences are related to two factors: 1) the research performed for the MCRA HRA project already addressed many of the activities that are part of an expert elicitation (discussed further below), and 2) the MCRA HRA research needs are more narrowly focused than other non-HRA expert elicitation efforts, such as a PIRT [11], where experts represent a much larger range of expertise and the questions are broader.

In addition, a number of project constraints, limitations, and other factors were considered in implementing expert elicitation for the MCRA HRA project. Examples of such considerations were:

- An aggressive delivery schedule in order to provide timely guidance for industry users and NRC reviewers
- Limited availability of suitable experts (due to, for example, the uniqueness of the context, loss of expertise through retirements, the need to represent the wide range of MCRA strategies across U.S. NPPs)
- The lack of data (e.g., no events of this kind have occurred)
- The lack of specific training experience for the decision to abandon

On the other hand, many of the research activities that were performed prior to the expert elicitation workshop justified certain efficiencies in the formal expert elicitation process. Examples of prior research activities are:

- Supplement 1 documents the search for relevant “data,” including near-miss operational experience and discussion of C&C deficiencies in contexts outside of MCRA scenarios.
- There were prior interactions with all of the experts at all stages of the research, specifically on the topic of MCRA scenarios.
- Two of the experts were also members of the research team.
- Both Supplement 1 and Supplement 2 document research that was performed to identify relevant issues for MCRA scenarios that were addressed in the expert elicitations.
- Two of the experts had prior expert elicitation experience.
- Three of the experts were also either experts in HRA/PRA or very familiar with HRA/PRA applications.
- The expert elicitation facilitator had prior expert elicitation experience, including prior experience as a facilitator and an ATHEANA co-author.

As a result of the above, omissions or simplifications from multiple existing guidance were considered to be justified, such as:

- Data examination was largely performed prior to the expert elicitation workshop, including:
  - Information and discussion provided in Supplement 1
  - Additional research performed to support Supplement 2
  - Research team assessment (both detailed and repeated) of the applicability of factors in existing HRA quantification methods (e.g., CBDTM) to the MCRA context
  - Prior discussions with each of the experts on the MCRA context
- Data examination in workshop discussions was less time consuming than might be otherwise because, for example:
  - Discussions with the experts in prior meetings or interviews had often already addressed experiences of specific experts (e.g., allowing the facilitator and other experts to recall these experiences quickly).
  - Documentation of the event review in Supplement 1 was already reviewed and understood by most of the experts.
- Identification of relevant technical issues was more efficiently performed because, for example:
  - Relevant technical issues were first identified in Supplement 1 (which was peer reviewed).
  - Relevant technical issues were refined by the author team in Supplement 2 research, including considerable effort to obtain a consensus list of key issues.
  - Members of the author team were involved in developing expert elicitation workshop prep materials.
  - The list of relevant technical issues was further refined through discussions during the expert elicitation workshop.

  - Ultimately, the list of relevant technical issues was finalized in a consensus agreement reached via the expert elicitation (which was possible to accomplish within the expert elicitation workshop because of all of the prior work and discussions).

NUREG-1880 [3] describes a process for eliciting each expert's HEP whereby: "…each expert is asked by the facilitator to independently provide his/her distribution including the three estimates [1st percentile, 99th percentile and most likely value, or mode] and the general shape for the HEP being evaluated. Once all the expert's values and approximate shapes are recorded and shown to the group, each expert is asked to describe the reasons why he or she chose the values and shape presented. An open discussion should be led by the facilitator allowing the experts to express their views and possibly affect other experts to want to change their estimates in light of this shared discussion."

Due to constraints on the time and availability of the experts, the following is important to note:

- Only the point estimate HEP values for each sequence were based on the expert elicitation; the uncertainty bounds of the decision to abandon scenario HEP distributions were not obtained through the MCRA HRA expert elicitation process.
- The elicitation process only developed the point estimate values only for the 5-minute and 25-minute timeframes; the values for the 15-minute timeframe were interpolated afterwards by the analysis team.
- The individual expert's HEPs were informally recorded by each expert first (rather than a formal prior documentation, such as use of worksheets as has been cited in some cases [9]) before sharing with the group). Then, each expert's informally recorded HEP was elicited by the facilitator, polling each expert for his/her HEPs as part of the group discussions. (The ATHEANA approach can be applied using either the informal or formal methods of documentation. In general, face-to-face interactions with informal documentation is preferred in applying ATHEANA since its specific objective of reaching a consensus opinion is based on the "evidence" provided to support each expert's opinion. In particular, experts may need the interaction with other experts to recall an experience that can be presented as "evidence," which, in turn, is the basis for achieving a consensus opinion—the objective of ATHEANA's expert elicitation. Appendix B in NUREG-1880 [3] provides some discussion on this topic.)

While NUREG-1880 specifically recommends holding group discussions since "There is a feeding on each other's ideas and challenges that is essential in pulling out a complete sharing of information," the NRC White Paper [9] cautions that "Each expert should also maintain independence from the other experts in the team in order to avoid (or mitigate) a groupthink bias risk."

Peer review comments on a draft of this document noted that the resulting spread of HEPs in the Phase II decision tree quantification approach represents a surprisingly narrow range, given the wide variation in the scenarios considered. Future research efforts should consider potential influences on this narrow range with additional information (perhaps decision-making in non-MCRA contexts).

A.5 References

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B

DEVELOPMENT OF THE TECHNICAL APPROACH FOR PHASE II, THE DECISION TO ABANDON FOR LOC SCENARIOS

This appendix discusses how the technical approach for assigning an HEP for the decision to abandon the MCR for an LOC scenario was developed, including a summary of the discussions with SMEs who informed the final quantification approach.

In general, development of the quantification approach for the decision to abandon for LOC scenarios involved the following steps:

1. Initial efforts to review existing methods for applicability
2. Development of a consensus list of key issues to address in quantification of the decision to abandon
3. Testing of CBDT against the key issues
4. Development of "strawman" decision trees for the decision to abandon
5. Adjustment of decision trees and assignment of HEPs using SMEs

The final decision tree and associated guidance are provided in Figure 4-5 and Table 4-2 in Section 4.

B.1 Initial Efforts to Develop a Quantification Tool for the Decision to Abandon

Initially, several HRA methods, including CBDTM [1], HCR/ORE [1], SPAR-H [2], IDHEAS at-power [3], NARA [4], and CREAM [5] were reviewed for insights and applicability to the decision to abandon. These methods were also reviewed for potential quantification gaps. For instance, the “cues” for LOC are not as explicit as other HRA cues. The softness of the LOC cue along with the general reluctance of operators to abandon the MCR were considered factors important to the quantification of the HEP for the decision to abandon for LOC scenarios.

B.2 Development of a Consensus List of Issues for the Decision to Abandon for LOC Scenarios

Following the initial reviews of existing HRA methods, the team developed a consensus list of issues important to the decision to abandon for LOC scenarios. NUREG-1921 Supplement 1 [6] was the key input to this list, especially Section 4 of Supplement 1 that described the process to determine fire PRA scenarios that may result in abandoning the MCR upon a LOC. Additionally, Supplement 1 described some of the PSFs and other qualitative considerations.

The team developed a list of issues that may be potentially important for the decision to abandon. This list is documented in Table B-1.

Table B-1
Items important to the quantification of the decision to abandon HFE for LOC scenarios

Issue	Differentiation Points	Compensatory/Synergistic Issues
Procedures	• **Meets criteria of "available:"** There is some level of qualitative or explicit criteria for LOC. Explicit criteria for identifying/confirming fire location and associated systems/components (consistent with fire PRA modeling) whose failure due to fire requires abandonment, or Procedure provides fire locations that, when identified and confirmed, indicate the likelihood of needing to abandon, but still leave it up to the operator making the decision. • **Judgment only:** There are no specific criteria, and the decision is purely at the discretion of the operator making the decision.	More detailed or realistic MCRA training may be able to partially compensate for lack of procedural content.
Training	• **Best case:** "Realistic" training in simulator with RSDP mockup or detailed talk-throughs • **Worst case:** Classroom only training at a minimum level	Training can help when procedural guidance is less explicit, but the reverse impact is unlikely to be true (i.e., better procedural guidance does not mean that operators need less training).
Time available (versus time required)	• **Best case:** Long (~20–25 mins) • **Worst case:** Short (~5 mins) • **Intermediate case:** Moderate (15 mins) The Phase II timing is based on the detailed timeline development discussed in Section 7 of NUREG-1921, Supplement 1 (also Section 2 of this report). For example, determination of the time available for Phase II depends on the Phase III time required and time available.	Traditionally, HRA would represent the impact of more explicit procedural guidance on the decision to abandon and more realistic training as a **faster** (and more reliable) action.

Table B-1 (continued)
Items important to the quantification of the decision to abandon HFE for LOC scenarios

Issue	Differentiation Points	Compensatory/Synergistic Issues
Reluctance	Reluctance includes consideration of: a) perceived reduction in capability to achieve safe shutdown conditions at the RSDP, as opposed to remaining in the MCR, b) operator comfort and familiarity with MCR, and c) acceptance that abandoning the MCR (a rare event) is indeed the only alternative remaining • **Best case:** Capable RSDP, explicit MCRA criteria and "realistic" training • **Worst case:** Very limited capability RSDP, no explicit MCRA criteria, and minimum classroom training • **Intermediate case:** Most major systems on RSDP, some MCRA criteria; some training	Factors that can influence reluctance include the capability of the RSDP, communications systems reliability, and explicit training using a simulator with an RSDP mockup.
Staffing & communications	• **Best case**: SS/SM aided in decision-making by STA or other crew who are monitoring abandonment criteria as would be done with critical safety function trees • **Worst case**: SS/SM discretion only • **Intermediate case:** SS/SM receives timely input from ex-MCR operator on the severity of the fire OR from other in-MCR crew on the status of MCR boards and key equipment	SS/SM assisted by extra crew members.

B.3 Efforts to Map Existing HRA Methods to the Issues List

Following the development of the issues list, the team returned to the review of existing HRA methods with the intention of identifying how the method can address each of the issues. This effort started with the review of the CBDTs.

Early on in the project, some of the CBDTs were re-interpreted specifically for the decision to abandon for LOC scenarios. It became clear, however, that the re-interpreted trees still contained elements that were not specific to the decision to abandon and it was also felt that using the same set of CBDTs could lead analysts to interpret them as they had conventionally done, rather than with the new guidance for the decision to abandon. This led to a subsequent review of the re-interpreted CBDTs to understand the following:

- Is the failure mode of the tree still applicable?
- Are the PSFs in the tree appropriate for the new context?
- Are there dominant failure modes or mechanisms missing from the set that should be accounted for?

This second review of the CBDTs yielded the following insights:

- The CBDTs were originally intended to be applied for one main cue (e.g., a procedure step, parameter, or set of parameters). For LOC, the “cue” is less obvious and encompasses the fire alarm, plus verification of fire, and verification of LOC.
- Both the actual abandonment procedural step and the transfer to the abandonment procedure were supposed to be covered with the definition of the HFE for the decision to abandon. This presented some confusion in the re-interpretation of the trees.

Table B-2 provides the results of the initial guidance for using the re-interpreted CBDTs and the discussion points related to review of these re-interpreted CBDTs by the team.

NOTE: The CBDTs are not reproduced here, but are included in NUREG-1921 Appendix B [7].

Table B-2
Comparison of initially re-Interpreted CBDTs

Tree Branch	Guidance for Evaluating CBDTs	Discussion
P_ca, Availability of information	The path selected for this decision tree is usually either [c] or [d], with the following rationales for each branch selection in the tree: Indication Available in Control Room - The primary cue of the fire alarm will be available in the MCR, and the unavailability of key instrumentation in the MCR due to fire will be noticed by the crew. Control Room Indication Accurate - One of the reasons for the decision to evacuate the MCR is the lack of reliable instrumentation due to the severe fire either in the MCR, CSR, or other similar location. Warning/Alternate in Procedure - The plant fire procedure identifies the possibility of potential indication differences and directs the operators to monitor unit/plant parameters and to notify the SM of any unusual or abnormal indications that occur. For fire areas in which indications could be impacted, the fire area guidance lists protected instruments by safe shutdown path. [The down branch should be selected if warnings are not provided in the procedure.] Training on Indication-The extent of training on the systems and instrumentation loss that would mandate MCR evacuation is not clear and is therefore not credited. [The down branch should be selected if interviews and observations determine that training is not provided or adequate for the instrumentation losses.] Another example discussion of the rationale for path [c] is the following: It is assumed that MCR indications are not reliable due to the fire. However, based on operator interviews, it was discussed that it is one of the responsibilities of the STA to identify and notify the operations crew on which indications are reliable. This is considered equivalent to Warning/Alternates in a procedure. It was stated that this is also covered in training.	This tree provided the basis for the new operator/information interface failure tree that represents the possibility that cues for abandonment in LOC events are not clear and available such that the operators do not decide that abandonment is necessary. For the LOC case, it was considered that the “CR Indications Accurate” branch would always be “no” for LOC because the large amount of “noise” in the cues is expected to obfuscate the decision to abandon versus a non-MCRA fire. This is the essence of an LOC fire, that indication failure modes cannot be predicted. The other two branches—asking about procedures and training —were directly incorporated into the new tree.

Table B-2 (continued)
Comparison of initially re-Interpreted CBDTs

Tree Branch	Guidance for Evaluating CBDTs	Discussion
P_cb, Data not attended to	The path selected for this decision tree is usually [j], with the following rationales for each branch selection in the tree: Low vs. High Workload - High workload is assumed due to fire conditions. Check vs. Monitor - The fire alarm would be checked to see what areas are impacted; this draws the crew's attention to the fire and the need to control the plant. Front vs. Back Panel – The alarm is located on the back panel. [The fire alarm location is plant-specific and needs to be identified during walkdowns or interviews.] Alarmed vs. Not Alarmed - The fire alarm is very loud, according to the operator interviews.	This tree was omitted as it was considered a negligible contributor; the combination of the fire alarm and the other instrumentation readings are unlikely to be missed, which is the intent of this tree.
Pcc, Misread/ miscommunicated data	The path selected for this decision tree is usually [a], with the following rationales for each selection in the tree: Indication Easy to Locate - Fire alarms and system functionality indications are expected to be easy to locate when the crew are confirming that the indicators are failed or do not respond. Good/Bad Indicator - The fire alarm provides the room location of the fire and a description. Formal Communication - Formal communication is used by the operators.	This tree was omitted because the indications are multiple and because this was a low-level contributor to the total HEP (e.g., the highest HEP is still in the 1E-3 range).

Table B-2 (continued)
Comparison of initially re-Interpreted CBDTs

Tree Branch	Guidance for Evaluating CBDTs	Discussion
P_cd, Information misleading	The path selected for this decision tree is usually [b], with the following rationales for each selection in the tree: All Cues as Stated - Secondary cues and indications not directly applicable to the operator action under consideration could be inaccurate as a result of fire impacts. Therefore, it is possible that not all cues present in the control room are as stated. Warning of Differences - The plant fire procedure identifies the possibility of potential indication differences and directs the operators to monitor unit/plant parameters and to notify the SM of any unusual or abnormal indications that occur. For fire areas in which indications could be impacted, the plant-specific fire area guidance may list protected instruments by a safe shutdown path. Consistent with P_ca, it is also expected that cues may be impacted by the fire, and warnings are provided by the STA during the fire event. Specific Training – N/A General Training – N/A	Because of the nature of the indications during LOC, it was difficult to see how this tree was substantively different than P_ca when applied to LOC scenarios. Therefore, this tree was absorbed into the new operator/information interface failure tree along with P_ca. Similar discussion to that given for P_ca as what are the cues (e.g., fire alarm, system failures) used to recognize a LOC scenario?
P_ce, Skip a step in the procedure	The path selected for this decision tree is usually [e], with the following rationales for each selection in the tree: Obvious vs. Hidden - The steps for this action are not hidden, but the direction from the fire procedure to the MCRA procedure is not clear and compelling. Single vs. Multiple - The operators would likely be in multiple procedures (e.g., fire procedures, EOPs, AOPs). Graphically Distinct - The steps are considered to be graphically distinct as there is a bolded caution statement concerning this action. Placekeeping Aids - There are placekeeping aids in the procedures.	This tree was omitted as it was considered a negligible contributor. While the crew will likely be in multiple procedures during the time, it is unlikely that the MCRA step would be simply “skipped” (e.g., 1E-3 or lower contribution).

Table B-2 (continued)
Comparison of initially re-Interpreted CBDTs

Tree Branch	Guidance for Evaluating CBDTs	Discussion
P_cf, Misinterpret instruction	The path selected for this decision tree is usually [f] or [g], with the following rationales for each selection in the tree: Standard or Ambiguous Wording - The step from the fire procedure to the MCRA procedure is ambiguous. All Required Information - The step does not contain all the information needed for making the abandonment decision. Training on Step – For [f] - The procedure step itself is ambiguous and does not contain all the information needed for making the abandonment decision, but training is provided. For [g] - Training is not provided; it is considered a judgment call on the part of the SM.	This tree was used as the basis of the new operator/procedure interface failure tree. The new tree was created to include both the clarity of the procedural path to transition to the MCRA procedure as well as the instruction within the MCRA procedure. The branches were altered to focus less on the "standardness" of the wording and more on the content and level of explicitness of the procedural step(s).
P_cg, Misinterpret decision logic	The path selected for this decision tree is usually [k], with the following rationales for each selection in the tree: NOT & AND or OR Statement -The procedure does not provide specific wording. Practiced Scenario -The scenario is practiced in training.	Similar to P_cf, for LOC, the important feature of the decision to abandon is if the step explicitly provides a decision logic or leaves the decision to judgment. The intent of this tree, along with P_cf was absorbed into the new operator/procedure interface failure tree.
P_ch, Deliberate violation	The path selected for this decision tree is usually [a], with the following rationale: Not Applicable. The decision to evacuate the MCR is left to the discretion of the SM; therefore, the question of whether the operator will follow the guidance is not relevant to this HFE (i.e., the procedure is simply providing the operator with a choice to perform the action or not).	This tree was traditionally included as a catch-all place holder for unusual scenarios where the operators were skeptical about the success of the procedural path and that the procedural path had negative consequences (e.g., irreversible plant damage). For LOC, this tree was replaced by a new reluctance tree, which specifies under what conditions operators are most likely to delay the decision to abandon beyond the time it would be useful.

Various tests of the revised trees were performed against a range of strategies and conditions defined in Table B-1. Based on these tests, the developers concluded that the trees could be consolidated by looking at: 1) operator-information interface, 2) operator-procedure interface, and 3) reluctance (new factor). In some cases, the revision of the trees was substantial enough that the developers were worried that users would not adequately consider the new guidance and, therefore, miss the significance of the revision in the quantification.

B.4 Development of New Decision Trees for the Decision to Abandon

From the insights and consideration of the “issues” table, three new trees were developed:

1. Failure to transfer to the MCRA procedure
2. Failure to understand that the MCRA criteria have been met
3. Reluctance/delay

These three decision trees are shown in Figures B-1 through B-3 (in Section B.5.2).

B.5 Use of Subject Matter Experts to Modify and Provide HEPs for the Decision to Abandon Quantification Tool

The next step in the process for developing a quantification tool for the decision to abandon for LOC scenarios was to perform an expert elicitation in order to: 1) verify (or modify) the three decision trees for applicability to the decision to abandon, and 2) develop HEPs for the end points on the decision tree(s).

The three trees and Table B-1 formed the skeleton for discussions with the SMEs. The results of this exercise are documented in Section B.5.3. As a result of the SME feedback, the trees were revised. A summary of the revisions included:

- The Failure to transfer to the MCRA procedure decision tree was removed from further consideration. This was determined not to be a significant contributor for failure.
- The Failure to understand that the MCRA criteria have been met decision tree remains. This tree will be further expanded to incorporate both reluctance and timing.
- The Reluctance/delay tree was eliminated. The reluctance will be built into the HEP estimates for the Failure to understand the MCRA criteria decision tree.

The re-structured decision trees were presented to the SMEs, who were asked to assign probabilities for a range of scenarios. A pairwise comparison between the different end states was also conducted. The final decision tree, probabilities, and guidance are provided in Figure 4-5 and Table 4-2 in Section 4.2.4.

The sub-sections below summarize aspects of the expert elicitation specific to the decision to abandon.

B.5.1 Discussion of Factors Important to Decision to Abandon on LOC

The following high level “issues” were discussed relative to the decision to abandon:

- Transfer to MCRA procedure
- Procedure guidance
- Cues and indications
- Training
- Timing
- Reluctance to leave the MCR
- Staffing and communications

At a high level, the thought process developing the draft decision trees asked the following questions:

- Can the operators get to the abandonment procedure?
- Do the operators have enough information to make the decision to abandon?
- Is there reluctance? If so, will the operators follow through with the decision to abandon in a timely manner?

Transfer to the MCRA procedure: Do the operators have sufficient pointers or guidance to review the entry criteria for MCRA in order to make the decision to abandon in time? A summary of the discussion about this topic included:

- The transfer to the MCRA procedure is less important than the other issues presented.
- Entry into the procedure is based on what the operators observe on the main control boards/annunciators.
- Operators will not leave the MCR unless there are significant control and instrumentation failures from the fire. This would likely include observation of multiple fire alarms and loss of significant control functions.
- Operators may be mentally running through the abandonment criteria as they track the severity and impacts of the fire. Operators are familiar with the specific locations that may require abandonment and are familiar with the entry criteria for abandonment.

After the discussion, the “Failure to transfer” decision tree was removed from further consideration since it is unlikely that the MCRA step would be simply “skipped”.

Specificity of procedure guidance: How much specificity in the entry criteria is helpful in making the decision to abandon? The relevant discussion included:

- More detail may help, but in reality, there are an infinite number of scenarios/failures that can occur. More detail helps with the decision, and training will compensate for gaps.
- Training and experience will help the operators recognize a potential LOC scenario. This may be more of a factor than the specificity of the criteria.
- Some procedures may be explicit: If a fire is in the switchgear room; trip the reactor, trip the turbine, close the main steam isolation valves (MSIVs), and abandon. Even with this specificity, crews may hesitate. There are criteria, but they know there is margin/leeway in them.

Changes to guidance: Qualitative and/or explicit guidance is helpful, but training and experience are more relevant in deciding whether to abandon the MCR.

Cues and indications: What types of information need to be captured from cues and indications for the operators to consider abandoning? The relevant discussion included:

- Operators are integrating the information as it comes in. Operators would need to observe cues related to the fire and observe system impact to consider abandoning, e.g.,
  - If a sprinkler alarm indicator comes in, you have a pretty good idea that it is a real fire.
  - Sometimes, you may see electrical impacts prior to the fire alarm.
  - Operators are more likely to trust the fire water flow alarm versus just a single smoke alarm.
- Based on what operators see, they may abandon immediately (e.g., loss of electrical distribution). For slower progressing fires, operators will likely want visual confirmation of severe fire (e.g., reports of operators not being able to see anything, heavy smoke, etc.) or observation of spurious equipment operations (e.g., power-operated relief valves (PORVs), atmospheric dump valves (ADVs), emergency core cooling system (ECCS) pumps).

Training: How does training specific to the decision to abandon assist the operators? The relevant discussion included:

- The simulator training for MCRA may exclude “the decision.” In other words, the operators are told by operator trainers that the conditions for abandonment have been met, but the operators being trained may not necessarily be presented with the **reasons** those conditions were met.
- Based on plant training philosophies, shift managers can make decisions based on knowledge and observation of what is occurring (e.g., this/that/the other thing goes away, and the SM makes the decision independent of procedures, just based on their understanding of the plant):
  - Reliability of the decision to abandon is not always a function of the available procedural guidance.
  - Training addresses the potential need to take “prudent actions,” allowing the operators to depart from the usual practice of verbatim compliance in special cases.
  - Even with good procedures and a very good RSDP, wrong decisions can be made—it comes down to judgment and understanding.

Timing: Will the decision be made in time, such that there is enough time for remote shutdown? The relevant discussion included:

- There is a sense of urgency needed when making the decision to abandon. The definition of urgency has two components:
    1. The fire progression is rapid/large/obvious; for example: electrical cabinets are on fire and the operators “see” the electrical distribution system going away.
    2. Time critical actions linked with fires in certain areas (e.g., need to start AFW) locally within 30 minutes).

Reluctance: What is the impact of reluctance? The relevant discussion included:

- The capability of the RSDP may play a role. If a plant’s RSDP is limited, there may be higher reluctance.
- At the same time, many operators will be familiar only with their plant’s strategy and will have some level of comfort in the strategy. (In other words, the operators will be reluctant to abandon the MCR regardless of the RSDP capability, and increasing the RSDP capability may not reduce reluctance significantly.)
- There will always be reluctance. The MCR is a familiar place with lots of capabilities and options.
- Plants with a self-induced station blackout (SISBO) strategy may be reluctant to leave the MCR prior to re-energizing (and aligning, if necessary) the equipment that was pre-emptively isolated and de-energized.
- There is a time pressure component to reluctance. Will they make the decision in time?
- Factors that may play into reluctance include: the capability of the RSDP, communications, the complexity of the plant, training using a simulator mockup, leaving a familiar place with lots of capability and options, scenario-specific conditions (e.g., SISBO, etc.).

Examples:

- Reluctance similar to BWRs injecting liquid poison
- Reluctance similar to injecting raw water into the reactor vessel during a severe accident progression

B.5.2 Discussion of Decision Trees

Tree 1: Failure to transfer to the abandonment procedure. Will operators be able to reach the procedure step to view the MCRA criteria in time? The tree included the following branch points:

- Clear procedure path to criteria? Is there a clear path in the procedures to the MCRA entry criteria?
- Status assessment supported by STA OR practiced scenario? Has the crew practiced this scenario or a scenario similar to this one in a simulator? Unless the training has covered the actual decision-making process, this will most likely be “No.” Also considered in this branch is “OR” STA is available “AND” trained on LOC abandonment criteria.

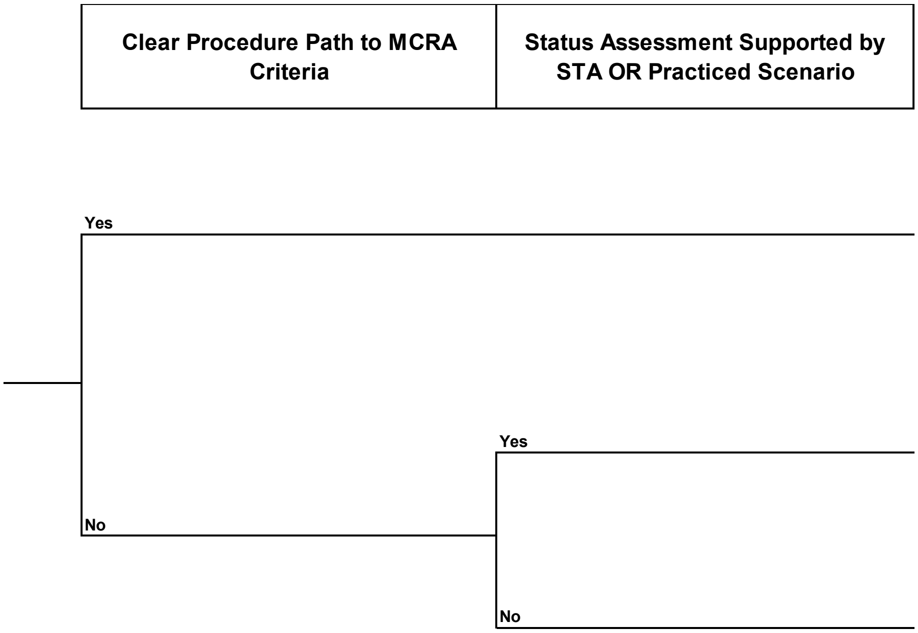

Figure B-1
Tree 1: Failure to transfer

The SMEs provided the following feedback:

- The fire has to be of a significant nature to review criteria.
  - If the fire is small, operators would not necessarily open the procedure even though there may be explicit transfer criteria. If a fire causes a reactor trip, you would still be in the procedure for post-trip actions/EOPs while verifying the severity of the fire.
- Typically, there are only a handful of plant locations that require abandonment. If a fire is in that area, they will be evaluating “when will it get so bad that I need to abandon?” Operators may open the procedure to review the criteria as the scenario progresses.

- The tree is less important than the other factors discussed. Operators are not leaving unless there is a real fire impact (e.g., seeing functions that are lost). Once the impact is observed, operators will be thinking about abandonment automatically.
- Is local confirmation of a fire needed? If multiple fire alarms come in and the operators see plant impacts, they may not wait for confirmation of the fire (even if there is not a procedure step or if the procedure path is circuitous), particularly if the fire location is known.

Conclusions: The SMEs concluded that tree was not a driving factor in quantification. Tree 1 is removed from further consideration.

Tree 2: Failure to understand that the abandonment criteria have been met. Do the procedures help operators map between what they are seeing in the MCR and the definition of a LOC scenario? The tree included the following branch points:

- Abandonment criteria explicit in procedure? This included a best case (explicit criteria), intermediate (qualitative description, but with some decision-making), and worst case (no criteria/pure judgment).
- Information presented supports MCRA criteria? Do the operators have an immediate way of knowing whether the MCRA criteria are satisfied based on the information they have? Is it obvious or not (running vs. standby equipment)? For example, for standby systems (RHR, LPI), how do the operators know if they've failed until they try to actuate them?
- Simulator or talk-through training on decision and indications? Has the crew practiced this scenario or a scenario similar to this one in a simulator or via talk-through? Unless the training has covered the actual decision-making process, this will most likely be "No."
- Classroom training on decision? Is there classroom training on the decision to abandon on LOC?

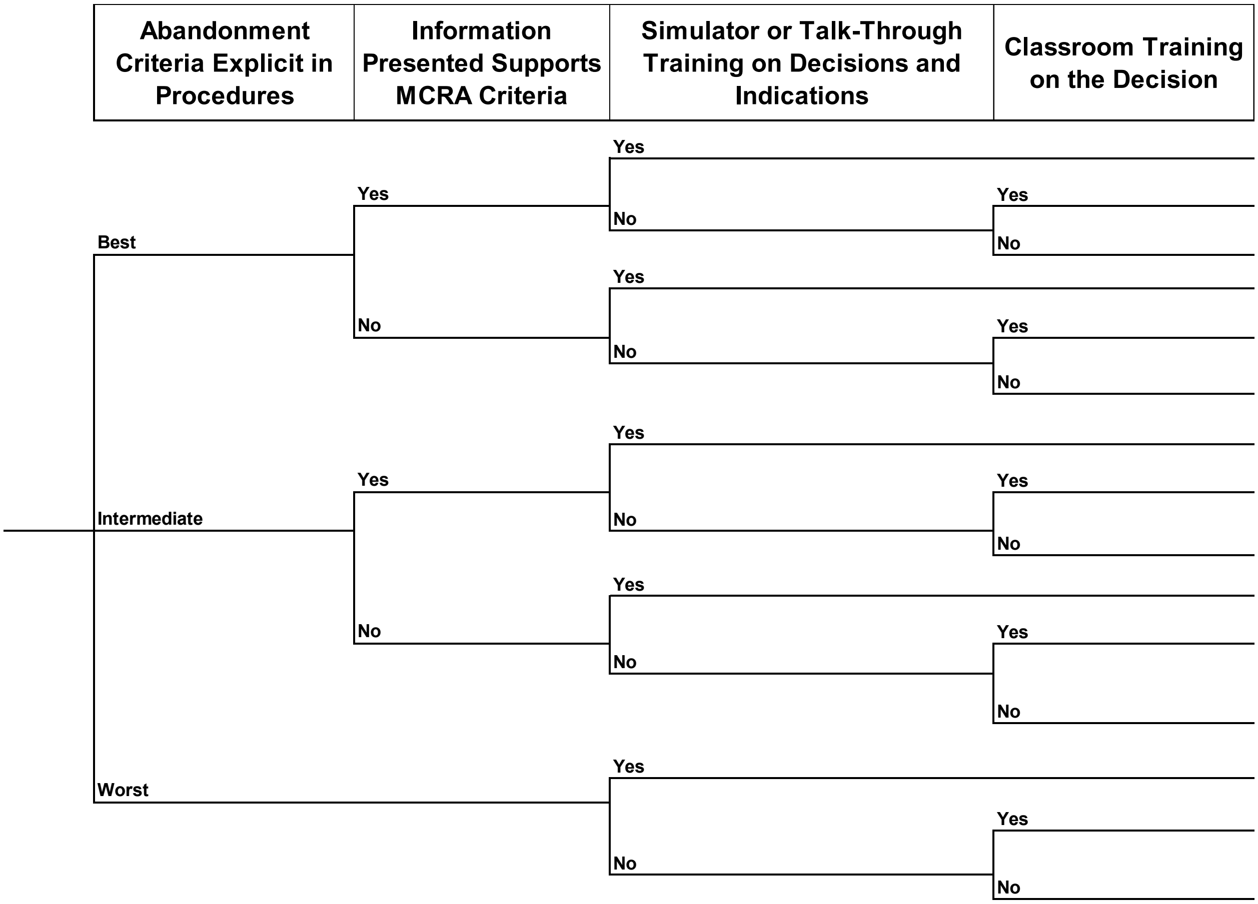

Figure B-2
Tree 2: Failure to understand abandonment criteria have been met

The SMEs provided the following feedback:

- There is an infinite number of potential scenarios, so while more detail in criteria is good, this may not be consequential because there will be consistent checking of systems as the fire progresses. Training and experience are more important than procedures in this case.
- In the abandonment criteria, there is a balance between the amount of guidance and the ability to think agilely, especially for less experienced operators that may be more reliant on procedures.
- More specificity may be needed for time-constrained scenarios.
- Is there a need to have three levels of differentiation between procedure criteria specificity? There will always be judgment involved, so more criteria are not necessarily better. The prescriptiveness of the criteria may not be the same for each plant, and a lot of that depends on the management philosophy (e.g., are the specific NPP's operators more procedurally reliant?).
- Operational experience is key. Senior Reactor Operators (SROs) should have an understanding of priorities. Less experienced SROs will be more reliant on procedures.

Conclusions: Condensed first branch point (explicitness of abandonment criteria) to criteria available or judgment.

Tree 3: Reluctance/delay tree. The branch points include:

- Level of reluctance. Is there trust in the strategy? This includes the procedures following abandonment and capability of the RSDP.
- Awareness of urgency. Have the operators had training on the need for decision-making before it is too late? Do they understand that, beyond a certain time, abandonment will no longer be a successful option?

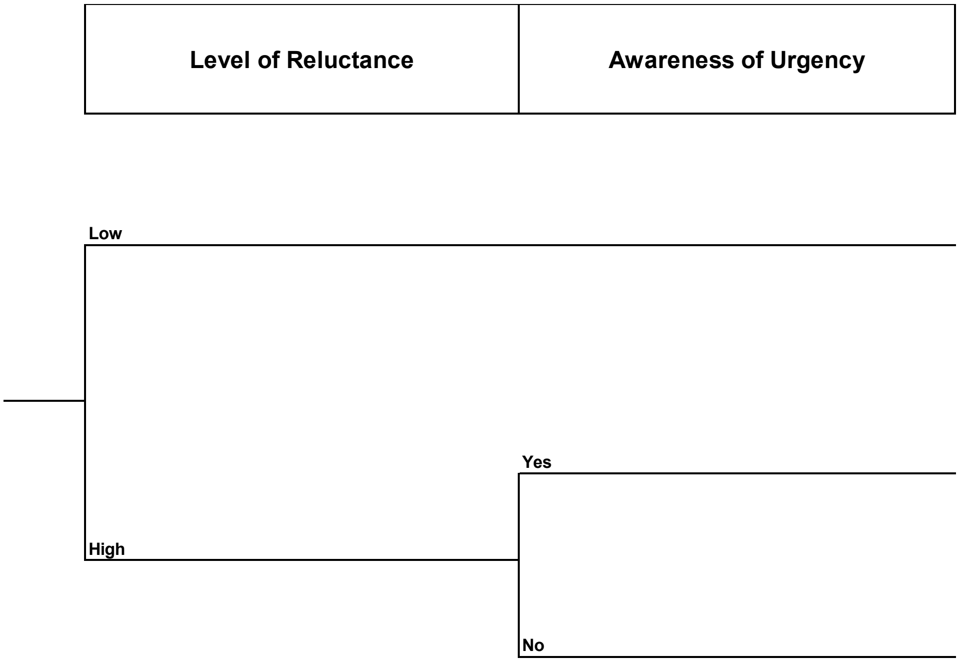

Figure B-3
Tree 3: Reluctance/delay tree

The SMEs provided the following feedback:

- There is always some reluctance that will surround the decision to leave the MCR.
- Like liquid injection following an ATWS, operators really do not want to do it, but they understand when it is necessary and will do it.
- The scenario really boils down to what is lost due to the fire. The operators are worried about random failures, and if you get one at the RSDP, it may be fatal to the strategy. There is also a reluctance due to a lack of familiarity with the panels; there may be training only once every two years.

- Is communication important to reluctance? This depends on the plant and how important the communication plan is to success. If there is no RSDP, communication becomes a big deal. If you have one panel and send operators to configure equipment but all of the control happens at the panel, then it is not as big of a deal.
    - This would also depend on the complexity of the plant (e.g., if only a few actions are required, such a strategy may not challenge your teamwork and C&C).
- SISBO situations would have an extra layer of reluctance.

Conclusions: Reluctance is a general influence in the decision to abandon. Merge the awareness of urgency with Tree 2.

B.5.3 Expert Elicitation Results

Once the decision tree was finalized as shown in Figure B-4, the next objective was to obtain probability estimates.[17] The following calibration points were provided to the experts:

- Not possible = 1.0
- Very likely to fail = 0.5
- Infrequently failed = 0.1 (9/10 are successful)
- Unlikely to fail = 0.01 (99/100 are successful)
- Very unlikely to fail = 0.001 (999/1000 are successful)

The experts were then asked about a range of different LOC scenario contexts. The worst case scenario was discussed first, followed by the best case. Pairwise comparisons surrounding the intermediate end states were conducted to determine the ranking and probabilities for the remaining end states.

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[17] Note that the decision tree has since been further refined, as shown in Section 4.

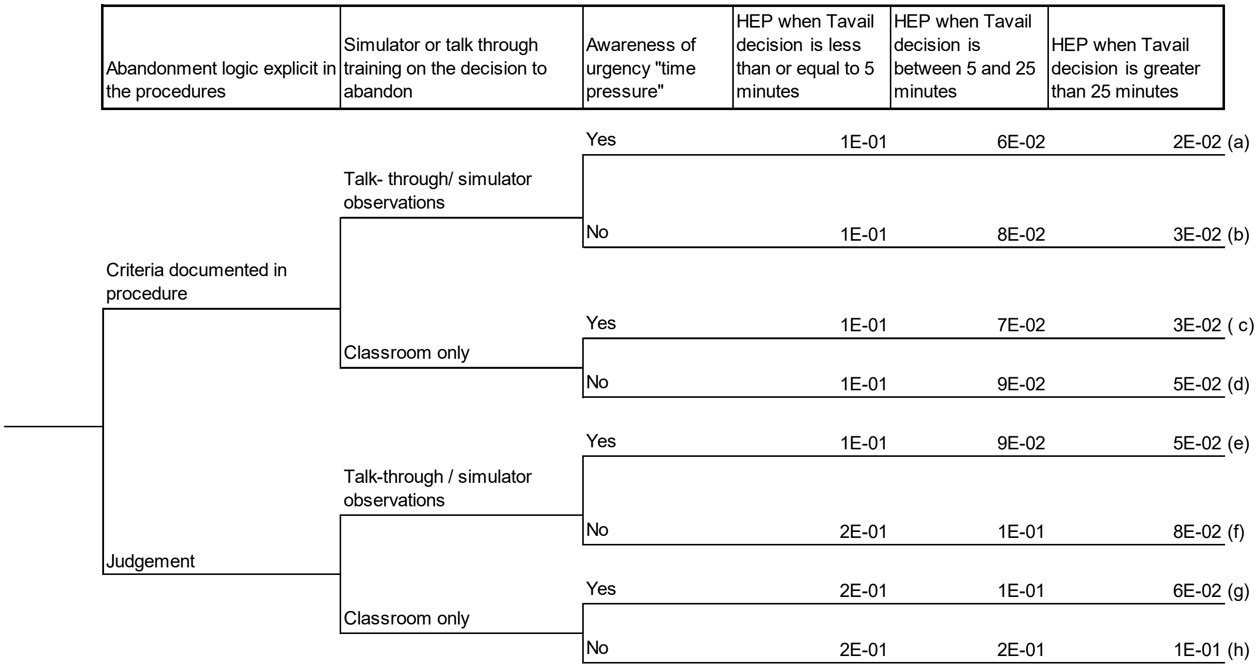

Figure B-4
Initial decision to abandon decision tree

Worst case (end state (h) with a short time regime)

The first scenario discussed was the least favorable case. The scenario included a short timeframe (5 minutes or less from the last cue), judgment only (no qualitative or quantitative criteria, but a consensus among the operators), classroom training, and no awareness of time urgency. For awareness of time urgency, this branch of the decision tree evaluates the operator's sense of time for accomplishing tasks after abandonment, such as restoration of AFW, not necessarily the time for the decision.

The SMEs provided their initial estimate based on the context of the scenario. The individual estimates[18] include:

SME1: 0.1

> Comment: The driver was lack of urgency and short timeframe.

SME2: 0.1

> Comment: For 5 minutes, the awareness of urgency is a driver, but experience is an offset. Out of the total number of crews, I thought how many would be less experienced and that was the failure driver.

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[18] For documentation purposes, the same order of SME estimates is used in this appendix. In the actual expert elicitation, the facilitator varied the order in which SMEs provided their initial estimates.

SME3: 0.1

> Comment: Started with 0.5, but agree on 0.1. 0.5 is pretty high, and we haven't talked about the rest of the process (e.g., post abandonment actions). Lack of time is the driver for the estimate.

SME4: 0.3

> Comment: Reluctance is the driver in this scenario, and operators will have difficulty processing information in this short timeframe. May try and take alternate actions (like trying to start a charging pump) instead of preparing to abandon the MCR.

Discussion followed the initial estimates. Overall, the SMEs felt that this is a consequential action and that reluctance would be a primary driver (so the distribution is not very broad). The reluctance is also based on leaving the control room to go to a remote location that likely does not have access to the same information present in the MCR. Some new plant designs may not have the same level of reluctance.

Time, awareness of urgency, and reluctance are drivers in this scenario. Experience can offset the lack of awareness, but a less experienced crew may not correctly interpret the signals to abandon in time. The short timeframe was also a concern; with minimal time, reluctance will drive, and operators may take alternate actions (such as trying to start another charging pump) and not be focused on abandoning in time.

The SMEs settled on a consensus value of 0.2 for end state (h) with a short time regime.

Worst case (end state (h) with a long time regime)

This scenario is identical to end state (h), with the exception of a longer time regime. The scenario included a long timeframe (~25 minutes from the last cue), judgment only (no qualitative or quantitative criteria, but a consensus among the operators), classroom training, and no awareness of time urgency. For awareness of time urgency, this branch of the decision tree evaluates the operator's sense of time for accomplishing tasks after abandonment, such as restoration of AFW, not necessarily the time for the decision.

The SMEs provided their initial estimate based on the context of the scenario. The individual estimates include:

SME1: 0.05

> Comment: Reduced reluctance by additional checking (one-half of original estimate).

SME2: 0.08

> Comment: Differentiated from short time frame, but not that much.

SME3: 0.1

SME4: 0.1

The SMEs agreed to a consensus value of 0.1.

Discussion summary: With additional time, there is reduced reluctance and time for additional checking.

Best case (end state (a) with a long time regime)

This scenario describes the optimal LOC case. Scenario characteristics include criteria for abandonment, simulator or talk-through training on the decision to abandon, an awareness of the time urgency, and a long timeframe.

The SMEs provided their initial estimate based on the context of the scenario. The individual estimates include:

SME1: 0.01

> Comment: Based estimate on weak crew; debated going lower, but general reluctance is still an override. After more than 25 minutes, the crew may think the fire is out or not so bad, and they may not abandon.

SME2: 0.001 -> revised to 0.01[19]

> Comment: 25 minutes is very long, and if you have clear criteria, then the action should be reliable. Revised estimate based on SME4's comment on general unreliability, the first estimate may be too optimistic.

SME3: 0.01 -> revised to 0.02

> Comment: Estimate based on reluctance, but training can offset. Moved estimate up to 0.02 based on agreement with SME4 on general unreliability.

SME4: 0.05

> Comment: Estimate based on general reluctance. It is surprising what people do and do not do, compared with what you expect them to know. The reference point is Davis-Besse—they knew and they didn't [about the significant reactor pressure vessel head degradation that would have been discovered earlier had the NRC inspection not been delayed by the plant from December 2001 to February 2002].

The SMEs agreed to a consensus value of 0.02 for end state a with long time regime.

Discussion: General reluctance is still the overriding factor in quantification. Training helps offset, but still, there is a tendency for incorrect actions to be taken (or not taken in time). On the other hand, 25 minutes is quite a long time, and if there are clear criteria, then the action should be reliable.

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[19] SMEs were allowed to revise their initial estimates if their estimate would be revised by "evidence" that is provided by another SME.

Best case (end state (a) with a short time regime)

This scenario is identical to end state (a), with the exception of the time regime. Scenario characteristics include criteria for abandonment, simulator or talk-through training on the decision to abandon, an awareness of the time urgency, and a short time frame. The SMEs provided their initial estimate based on the context of the scenario. The individual estimates include:

SME1: 0.1

> Comment: Operators will spend time checking parameters and may not abandon in time.

SME2: 0.1

SME3: 0.05

> Comment: Short time frame was a driver.

SME4: 0.15

> Comment: 3 out of 20 would still want to check indications and parameters to confirm given reluctance. The short time frame is a driver, and operators will be trying to take corrective actions; and this would be a distraction.

The SMEs agreed to a consensus value of 0.1 for end state a with a short time regime.

B.5.4 Calculation of Probabilities

Table B-3 lists the pairwise comparison raw data. Since all four experts agreed that end state (a) is the best and end state (h) is the worst, the pairwise comparison determines the ranking of end state (b) through end state (g). The numbers in the columns two through four of Table B-3 correspond to the number of experts who believe the first end state is either better, worse, or equivalent to the second end state.

Table B-3
Pairwise comparison of raw data

End state comparison	Better (e.g., first end state is better than second end state)	Worse (e.g., first end state is worse than second end state)	The end states are equivalent in terms of HEP
g-f		4 – but if the simulator scenario is the same, then it is close.	
g-e	4		
g-d			4
g-c	4		
g-b	4		
f-e	4		
f-d	1	1	2
f-c	4		
f-b	4		

Table B-3 (continued)
Pairwise comparison of raw data

End state comparison	Better (e.g., first end state is better than second end state)	Worse (e.g., first end state is worse than second end state)	The end states are equivalent in terms of HEP
e-d			4
e-c	3		1
e-b	3		1
d-c	4		
d-b	4		
c-b		4	

The pairwise comparison scores of end states b through g are summarized in Table B-4 in a matrix format. If an expert thought that the end state in a particular row was better than the end state in a particular column, the end state in the row gets 1 point. Similarly the end state gets half a point for a tie, and loses 1 point for being worse than the end state in a particular column.

From Table B-4, we can conclude the following (A > B means A is better than B):

1. a > c > b > d > h
2. g > f
3. e > f
4. d = e, d = g (**bolded entry in Table B-4)**
5. e > g (italicized entry in Table B-4)

Item 5 contradicts Item 4. Considering the structure of the decision tree and the PSFs associated with end state g and end state e, it is logical to reconcile the inconsistency by assuming
d = e >= g (A >= B means A is not worse than B).

To summarize, the ranking is determined to be a > c > b > d = e >= g > f > h

To assign a probability to each end state, the ranked end states are assumed to be a geometric series with a constant ratio of $(\frac{0.1}{0.02})^{1/6}$ for the "long time" case and $(\frac{0.2}{0.1})^{1/6}$ for the "short time" case.

Table B-4
Pairwise comparison score summary

	c	**d**	**e**	**f**	**g**
b	4*(-1)	4*1	3*1+0.5	4*1	4*1
c		4*1	3*1+0.5	4*1	4*1
d			**4*0.5**	1-1+2*0.5	**4*0.5**
e				4*1	4*1
f					4*(-1)

The constant ratio, to some extent, implies a multiplicative impact of the PSF “simulator or talk-through training”.

The probabilities for each end state are listed in Table B-5 for each case. The HEP estimates for the intermediate time case are determined from averaging the short and long time cases.

Table B-5
End state probabilities

End state	Long time case	Intermediate time case	Short time case
a	0.02	0.06	0.1
b	0.034	0.08	0.13
c	0.026	0.07	0.11
d	0.045	0.09	0.14
e	0.045	0.09	0.14
f	0.076	0.13	0.18
g	0.058	0.11	0.16
h	0.1	0.15	0.2

B.6 References

1. An Approach to the Analysis of Operator Actions in Probabilistic Risk Assessment. EPRI. Palo Alto, CA: 1992. TR-100259.
2. The SPAR-H Human Reliability Analysis Method. U.S. NRC, Washington, DC: 2005. NUREG/CR-6883.
3. An Integrated Human Event Analysis System (IDHEAS) for Nuclear Power Plant Internal Events At-Power Application: Volume 1. U.S. NRC, Washington, DC: March 2017. NUREG-2199.
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C

DEVELOPMENT OF THE TECHNICAL APPROACH FOR COMMAND AND CONTROL IN PHASE III MCRA

C.1 Overview

Phase III represents the time period after the decision to abandon the MCR. This phase includes the collective set of actions needed to isolate the MCR electrically, start up the RSDP or local control stations, and achieve a safe, stable end state.

The guidance for Phase III quantification developed in this report and discussed in Section 5 is based on existing U.S. NPPs, a range of RSDP capabilities, associated MCRA procedures and training, and the manner in which MCRA procedures are expected to be implemented. In particular, most U.S. NPPs have a MCRA safe shutdown strategy that involves a supervisor at the RSDP who uses the MCRA procedure and coordinates (as needed) the actions of multiple operators who are located at multiple local control panels. In addition, the supervisor individually communicates, using radios (and maybe sound-powered phones) with each local operator. For this reason, C&C issues were considered to be important and required particular attention.

If the HRA analyst is considering a new NPP design that uses a substantially different MCRA safe shutdown strategy, including re-constitution of the entire MCR operating crew at essentially a backup MCR, then HRA guidance for MCRA would be substantially different.

C.2 How the Phase III Technical Approach for C&C was Developed

During the development of NUREG-1921 Supplement 1 [1], guidance was provided on the identification and definition of HFEs associated with implementing an alternate shutdown. Supplement 1 also provided guidance for a qualitative HRA analysis and considerations for feasibility. The development in this report (NUREG-1921 Supplement 2) started with the identification of factors or considerations that may impact the HFE but may not be addressed in current HRA methods. These factors are listed in Table C-1 and include communications and C&C. These factors were then discussed with an expert panel. Feedback obtained during the discussion on C&C helped define those factors that would be addressed qualitatively and those that would be included in the quantification.

The technical issues associated with the HRA for Phase III MCRA operator actions come from experience in developing fire PRA and from concern regarding the issues of communications and C&C. Communications are considered and discussed as part of C&C.

C.2.1 Research Underlying C&C for Phase III

In NUREG-1921 Supplement 1 [1], several factors were identified as being different and important for HRA treatment of MCRA scenarios. Two of those important factors were C&C and communications. In response to these factors, NUREG-1921 Supplement 1 added the following tasks for the HRA:

- Identified new feasibility assessment criteria for both communications and C&C (i.e., Section 6 of Supplement 1)
- Provided preliminary guidance on how to incorporate timing associated with communications and C&C into timelines (i.e., Section 7.3.4 of Supplement 1 [1], extract copied below):

> The timeline of the Phase III portion can be highly complex and requires the analyst to understand the expected procedure response. The timing should include any time for communication among operators in multiple locations as well as account for time delays due to feedback required by or from other operators before subsequent procedure steps can be taken.

- Discussed both communications and C&C in the context of PSFs (i.e., Section 8 of Supplement 1)
- Provided preliminary research on C&C for both MCR and MCRA operations (i.e., Appendix B of Supplement 1)

Following the publication of Supplement 1, the author team continued their research on C&C for MCRA operations. This research ended with an expert elicitation of SMEs on NPP MCRA operations. The elicitation for Phase III was conducted in conjunction with Phase II. The SME team qualifications are described in Section A.3.2. Discussions with the SME team confirmed that the definition of C&C presented in Appendix C.2.1.1 applies to NPP plant operations, including MCRA. Insights from the SME elicitation are included in the sub-sections below, specifically the advances beyond that in NUREG-1921 Supplement 1 that are important for HRA quantification for MCRA scenarios in Phase III.

C.2.1.1 Definition of C&C

Since the treatment of C&C is a new topic for HRA, much discussion was conducted on where and how C&C fits into the HRA quantification process. As part of the discussions on Phase III, Table B-3 of Supplement 1 [1] helped identify those aspects of C&C and communications that potentially impact Phase III quantification. This led to the development of a table of factors to consider in developing a quantification approach for Phase III (as shown in Table C-1). The PSF table along with discussions of scenario best-case and worst-case contexts supported a discussion with SMEs to obtain feedback on those factors and situations that may require explicit treatment during quantification.

NUREG-1921 Supplement 1 determined that C&C has not been previously considered explicitly for NPP operations, because it was thought to have a negligible contribution to HRA/PRA scenarios. Consequently, Supplement 1 reviewed various cognitive models and military definitions and then defined the C&C functions applicable to NPPs as:

- Maintaining a coherent understanding of the plant state (e.g., situational awareness)
- Making timely decisions
- Allocating resources as needed
- Coordinating actions
- Managing communications between team members such that they are timely and effective

In turn, the above characteristics are used in Section C.2.1.2 to compare how C&C may change when moving from MCR operations to operations following MCRA.

Table C-1
Factors associated with MCRA Phase III HRA

Factor s	Considerations applicable to all plants and crews	Worst case plant/crew characteristics	Best case plant/crew characteristics	Potential treatment in quantification
Communications	Interactions with plant staff conducting MCRA tasks. If the communication is associated with starting a modeled SSC, it is considered to be included with coordination below.	Slowest, limited communications such as a single, shared circuit or a circuit with noise. Multiple simultaneous communications.	Training and procedures supplement good hardware.	A communications plan (and associated hardware) exists and is trained upon; the plan addresses receiving reports from watch standers (RSDP staff) as well as external staff. Procedure (plan) and training are sufficient to demonstrate feasibility, such that during quantification, communications (by itself) will be treated as negligible compared to other C&C sub-tasks and compared to THERP HEPs associated with critical tasks (so the impact of communications is not explicitly quantified).
	Interactions with plant staff other than those conducting MCRA tasks, such as the local fire department.			Impact related to communications should be captured in the time required.
Coordination	Requires communications between two or more individuals.	Three people—where a supervisor coordinates the activities of two other operators can become a bottleneck or misdirect startup tasks (sequencing errors).	Peer-to-peer coordination; with a separate person to track (or check) if completion is not reported or seen in local indications.	Communication and coordination failures that lead to sequencing errors may lead to irreversible SSC failure. The impact of coordination should be captured in the time required.

Table C-1 (continued)
Factors associated with MCRA Phase III HRA

Factors	Considerations applicable to all plants and crews	Worst case plant/crew characteristics	Best case plant/crew characteristics	Potential treatment in quantification
Situational awareness	Function of the indication and alarms available at the RSDP	Challenging when a component in the success path (safe shutdown (SSD) path) is failed, requiring recognition and recovery.	All information is available at the RSDP.	Subsumed by communications and coordination. When communications and coordination are successful, and RSDP indications are successful, then situational awareness is successful. Recovery cannot be credited if the SS/SM is not aware of the plant state/plant conditions (i.e., situational awareness) and available equipment (e.g., there are alternative options to the SSD train).
Timely decision making	The procedure is written to assume the worst case, with typically no decisions.	Procedures do not address failures in the SSD train.	Training on the procedures ensures a timely response.	Includes failure to establish situational awareness in time. If situational awareness is successful, then timely decision-making is facilitated. Timely decision making is more important if the analyst is crediting recovery.
Resources allocated	MCRA procedures are well scripted such that resources are allocated and available	Resources are diverted or unavailable (then modeled as not feasible).	MCRA procedures are well scripted such that resources are allocated and available.	The allocation of resources is more important if the analyst is crediting recovery.
Tools and equipment	Tools are not co-located with the equipment where they are needed.	Equipment needed at the RSDP is a mixture of items located in the MCR and items at the RSDP with little control over potential "pirating."	All necessary equipment (except keys that an operator is trained to take from MCR to RSDP) is located at RSDP and verified on a regular basis to be available (e.g., no "pirating").	Demonstrated during feasibility The impact related to RSDP capability is captured in the time required.

Table C-1 (continued)
Factors associated with MCRA Phase III HRA

Factors	Considerations applicable to all plants and crews	Worst case plant/crew characteristics	Best case plant/crew characteristics	Potential treatment in quantification
Recovery	Most operating NPPs in the United States consist of two trains of safety equipment, and the MCRA procedure might be based on a single train (with the other train being fire damaged).	Lack of procedures, lack of training on recovery, and staffing limitations may not address equipment unavailability or the failure of SSCs needed to achieve a safe, stable end state.	Procedures, training (e.g., trust but verify steps taken) and C&C protocols provide an opportunity for recovery.	Consider an application of recovery within an HFE. Limit the addition of recovery HFEs to those that are plausible and feasible.
Many critical tasks	Successful isolation of the MCR and startup of the RSDP, including the start of critical safety functions such as decay heat removal, and isolation of spurious operations involve many procedure steps and tasks.	N/A (modeling issue, not a plant issue)	N/A (modeling issue, not a plant issue)	Task grouping is likely needed because there are too many steps for THERP. Conduct a reasonableness check to ensure that the overall HEP is consistent with the number of critical tasks and the context associated with the MCRA scenario.

C.2.1.2 C&C Differences Between MCR and MCRA Operations

The guidance developed in this appendix focuses on addressing differences from previous HRA guidance, specifically those differences associated with the challenges and context during MCRA. The reason C&C was identified as potentially important to the reliability of MCRA HRA was because the MCRA strategies involve a collective set of actions, and these actions may be implemented in a variety of ways such that they may require more communication and coordination than during operations in the MCR.

Having defined C&C for NPP operations, NUREG-1921 Supplement 1 went on to characterize in what ways MCR operations and MCRA operations may be different. In particular, Table B-2 in Section B.2 of Supplement 1 summarizes the differences between MCR and MCRA operations.

One of the challenges in developing a list of differences between MCR and MCRA operations is that there are variations between U.S. NPPs regarding their RSDP capability and associated MCRA SSD.[20] In other words, distinguishing MCR versus MCRA differences is complicated by the fact that there are plant-to-plant differences in MCRA operations.

For Supplement 2, input from SMEs allowed the following to be established as consensus:

1. The definition of C&C presented in Appendix C.2.1.1 applies to NPP plant operations, including MCRA.
2. Once the decision to abandon the MCR has been made, there typically is not as much of a demand on the operator to “diagnose” what SSD option to implement. Thus, the HRA quantification in Phase III is usually dominated by the execution of operator actions called out in MCRA procedures. (However as discussed in Section 5, consideration of the opportunity for cognitive errors is still recommended for Phase III when EOPs are used).
3. Because of how the MCRA SSD strategy is implemented (including the content and format of MCRA procedures), C&C is different for MCRA operations because:
    a. For most U.S. NPPs, there are fewer controls and indications at the RSDP for the supervisor to use in developing an understanding of plant conditions or to confirm completion of operator actions.
    b. For most U.S. NPPs, there are no alarms at the RSDP, requiring operators to closely monitor parameters. Such monitoring may be more susceptible to distractions.
    c. Although the supervisor is in charge of the overall MCRA procedures, he/she cannot directly observe implementation of MCRA procedure steps since most operator actions are performed at local plant stations (and not at the RSDP).
    d. The allocation of operator resources is done mostly via the various MCRA procedure attachments (rather than by the supervisor) that are assigned to specific operators.

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[20] Section 2 and Appendix A of NUREG-1921 Supplement 1 discuss some of these variations between NPPs.

4. Communications within MCRA operations are different and impact the time required for operator actions to be completed. For example:
    a. Most communications are NOT face to face.
    b. There are different types of communications, including reports from operators who have completed MCRA actions as well as communications that are not associated with SSD (e.g., radiation surveys).
    c. Communications equipment (e.g., radios) and associated problems (e.g., garbled communications, crosstalk on the same radio channel) are more of a concern during MCRA.
5. C&C in MCRA operations may involve the coordination of operator actions that may be complicated by operators being at different locations and by associated communications issues.

C.2.1.3 Most Important Concerns for C&C in MCRA Scenarios

As part of the discussions with the SMEs regarding MCRA operations, this report established that the most important concern regarding C&C in MCRA scenarios is the need for **coordination**. In particular, the coordination of operator actions, as a C&C function:

- Is more critical in MCRA operations than for MCR operations
- May involve multiple operator teams (but this may not be much different than for MCR operations, depending on the plant and MCRA strategy)
- May involve proper sequencing of operator actions:
    - Implementation of the MCRA SSD strategy can involve a significant amount of sequencing, especially before starting a pump.
    - The MCRA procedure itself usually addresses this sequencing (e.g., typically, the procedure will include a wait (or hold) step if sequencing is needed).
    - Errors in sequencing may be due to confusion in using the MCRA procedure, communication problems, or a selection error.
    - The likelihood of detecting errors in sequencing is reduced in MCRA due to fewer indications at the RSDP.
- Depends on communications and an awareness of plant conditions for success
- Is strongly influenced by training for its success, ranging from:
    - Classroom only (i.e., more passive "receiving training")
    - Practicing coordination in the field (i.e., "active" and more realistic training is "best case")

C.2.1.4 Implications of C&C for HRA Quantification of Phase III Operator Actions

The HRA quantification implications resulting from the updated research on C&C for Phase III operator actions are presented below and include communications and coordination. The impact of C&C on timing is discussed in Section C.2.2.

The HRA analyst should understand the important ways that C&C is different for MCRA operations, as opposed to MCR operations, in order to support HRA quantification. Identification of these differences and their implications was not finalized during the completion of Supplement 1, but it is important to the modeling of C&C. Most aspects of C&C during the Phase III implementation of critical safety functions are incorporated into the MCRA procedures and timed walkthroughs as specific steps by: (1) local operators reporting to the operator leading C&C at the RSDP on the status of their tasks and the enabled critical safety functions, such as “Inform CRS of source of power,” or (2) the operator leading C&C at the RSDP directing actions to be taken by local operators, such as “At the direction of the CRS, energize safeguards bus using an EDG.” However, while plants may have similar MCRA procedures and similar remote shutdown capabilities, the timing as well as the C&C aspects may vary since they are based on how the specific plant conducts its operations. Thus, careful review of the procedures and timing (e.g., implementation plans, JPMs, etc.), operator interviews, and simulator exercises are important to understanding the C&C policies and procedures at each plant.

The important aspects of C&C for MCRA operations are summarized under each characteristic of C&C as applicable to NPP operations:

- Maintaining a coherent understanding of the plant state (e.g., situational awareness)

  For MCRA operations, this means to establish and maintain a coherent understanding of the plant state following the establishment of a command post at the RSDP. This aspect of C&C is often addressed via task delegation or verification steps in the MCRA procedures (as discussed above). For MCRA, however, understanding the plant conditions may be hindered by the limited number of controls, indications, and alarms at the RSDP, in contrast to that available in the MCR. For MCRA operations, this element of C&C is important for the coordination of actions (for other cases, including recovery actions, see below[21]).

- Making timely decisions

  There are two aspects to consider within this element of the definition of C&C: decision-making and timing. First, since there may be some NPPs that have some MCRA scenarios and procedures where decisions by the operator are required and the actions involve cognitive challenges, cognitive modeling is still recommended and follows the quantification guidance in NUREG-1921. However, because the MCRA SSD strategies and procedures for existing U.S. NPPs address potential fire-induced initiating events and spurious operations, and because there would be fewer trains of components available for safe shutdown under these anticipated conditions, there typically is not as much of a demand on the operator to “diagnose” what SSD option to implement. Thus, the HRA quantification in Phase III is usually dominated by the execution of operator actions called out in MCRA procedures. Second, timing for C&C is addressed in HRA through the development of

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[21] For current U.S. NPPs and how their MCRA SSD procedures are written, recovery of a failed operator action may not be explicitly addressed. However, if a task fails and recovery is possible, then situational awareness is important to recognize the context associated with the failure in order to develop the appropriate response. In this case, “recovery” refers to hardware failure recoveries or recovery of a situation where the abandonment procedure fails to accomplish its purpose.

timelines and the evaluation of feasibility by comparing the time required to accomplish an action within the time available. For MCRA it is important that the time required to accomplish the action includes time for communications (internal and external) and time for coordination. For example, if the communications plan uses runners, then the time required to complete the action is likely to be longer than when radios are used. See "coordinating actions" and "managing communications" below for more guidance.

- Allocating resources as needed

  For MCRA, the allocation of operator resources is done mostly via the various MCRA procedure attachments (rather than by the supervisor) that are assigned to specific operators. In addition, the MCRA SSD strategy is typically validated such that resources are available and are allocated by the MCRA procedure. If there are additional failures such that there are more actions to be accomplished than there are operators, then some of the actions would not be feasible unless the available workforce could be re-delegated to accomplish them.

- Coordinating actions

  Coordination consists of two or more operators. Coordination may be required for starting a system/train or restoring a function. Coordination may also be required for long term control of a parameter. Both types of coordination are considered during the conduct of each task. If failure of communications or coordination would fail SSCs, then these are considered to be critical tasks and should be modeled explicitly.

- Managing communications between team members such that they are timely and effective

  Because most communications during MCRA operations are not face to face, there is less clarity than for MCR operations. For Phase III operator actions, communications may be needed for critical tasks modeled in the HRA and may be conducted as part of non-critical tasks. The impact of all communications (critical and non-critical) should be identified and accounted for as part of C&C.

C.2.2 C&C Aspects of the Integrated Phase III Timeline

Section 2 and Section 5.2.2.2 of this document, and Section 7 of NUREG-1921 Supplement 1 provide detailed guidance on the development of timing inputs and timelines for MCRA scenarios. This guidance is augmented by the following guidance for HRA analysts related to communications and coordination. This guidance also includes insights from the discussions with the SMEs as part of the expert elicitation. To summarize, from this report and Supplement 1, the HRA analyst should:

1. Determine the potential impact, if any, that communications or coordination can have on the time required for response:
   a. Communications may be needed for critical tasks modeled in the HRA, such as for coordination for the proper sequencing of actions. The time required for operator actions may be minimally impacted by time delays associated with the communication needed to coordinate actions.
   b. Communications may also be conducted as part of non-critical tasks. Extra time may be needed for information gathering tasks, such as health physics surveys, if needed for operator action implementation (e.g., operation of valves inside containment for PWRs).
   c. The impact of all communications (critical and non-critical) should be included in the timeline if it impacts the total time required to complete critical actions.

   d. Supplement 1, Section 7 discussed the development of an MCRA timeline where the major functions are plotted on the same timeline to understand the timing of individual HFEs with respect to the same time origin (see Supplement 1, Figure 7-9 (which is related to a dual unit shutdown, but is applicable to a single unit MCRA, as well).

2. The time required for operator actions should also account for the following:
   a. Manipulation time for some SSCs (such as larger valves or valves with a differential pressure) may be longer than might be expected.
   b. Manipulation time may be different in MCRA scenarios than for MCR scenarios (e.g., some motor-operated valves (MOVs) and air-operated valves (AOVs) are almost never operated without power).
   c. The specific way field operators plan to implement procedure steps (e.g., for a set of 10 actions, does the operator follow the steps explicitly, or use a prioritized approach such as changing the order of steps?) may result in a different time required than expected.
   d. Time required estimates should include some margin for uncertainty (e.g., develop a range of timing estimates, if possible, rather than a point value).
   e. Extra time may be needed for information gathering tasks, such as health physics surveys, if this information is needed for operator action implementation (e.g., operation of valves inside containment for PWRs).

3. Estimate the time associated with recovery actions. In many cases, timed walk-throughs or simulations of time-critical actions, such as the MCRA procedure, already include steps where another operator is either checking equipment status, parameter status (e.g., flow through a valve that should have been opened), or the performance of a step as a requirement for their own next step. However, if these steps are not specifically timed, a starting assumption for this additional recovery time should be in the range of 1–3 minutes, but assignment of a recovery time should consider what indications of the initial failure are available (and where they are located), followed by the time needed to perform the recovery action(s). (Note that in some cases, even with consideration of the additional time required for recovery, there may be a negligible contribution to the overall HEP. Also, it is possible that the operator actions might become infeasible due to the additional time required.) Specifically, if the action subject to recovery failed initially, then the additional time required for recovery would leave insufficient time for a subsequent action (assuming that the actions are performed in series and represent a critical path to SSD).

C.3 Basis for HEPs Recommended for Phase III C&C Coordination Failures

This section describes the background on how the authors developed their recommendation for an HEP associated with a C&C sequencing failure in coordination. Section 5.2.3.3 provides the quantification guidance for considering a C&C sequencing failure in Phase III HFEs as well as a specific recommendation for assigning an HEP.

C.3.1 Focus of HRA Modeling for C&C Coordination Failures

Unlike that for Phase II, the authors had not developed a candidate C&C-related HRA quantification tool before meeting with SMEs. Instead, the SMEs were presented with a set of candidate issues and were asked to confirm the relevance of these issues for C&C following MCRA. As a result of discussions with SMEs, a consensus on the important concerns for MCRA operations and C&C, specifically, was developed and is documented in Appendix C.2.1.3. The SMEs recommended that HRA quantification focus on failures in C&C coordination, especially C&C failures to properly sequence two or more operator actions (e.g., the supervisor directs that operator action B be performed before operator action A, when the normal order is A then B) such that equipment key to the MCRA SSD strategy is irreversibly damaged. Section 5.2.3.3 also describes the process for identifying such C&C failures.

C.3.2 How Can C&C Coordination Problems Result in Sequencing Failures?

Appendix C.2.1.2 highlights the key differences between MCR and MCRA operations and why C&C is different when implementing MCRA procedures. Summarizing the key facts, C&C coordination:

- Is more critical in MCRA operations than for MCR operations involving EOPs and may involve proper sequencing of operator actions:
  - Implementation of the MCRA SSD strategy can involve a significant amount of sequencing, especially before starting a pump.
- Depends on the MCRA procedure that usually addresses this sequencing (e.g., typically, the procedure will include a Wait (or Hold) step or a written Caution if sequencing is needed):
  - Errors in sequencing may be due to confusion in using the MCRA procedure, communication problems, or a place-keeping error such as if written “Wait” or “Hold”, or Cautions are not provided.
- Depends on communications for success:
  - Most communications during MCRA are **not** face to face.
  - There are different types of communications, including reports from operators who have completed MCRA actions that are needed for subsequent component startup.
  - Communications equipment (e.g., radios) and associated problems (e.g., garbled communications, crosstalk on the same radio channel) are more of a concern during MCRA.

- Depends on an awareness of plant conditions for success:
  - For most U.S. NPPs, there are fewer controls and indications at the RSDP for the supervisor to use in developing an understanding of plant conditions or to confirm completion of operator actions.
  - For most U.S. NPPs, there are no alarms at the RSDP, requiring operators to closely monitor parameters. Such monitoring may be more susceptible to distractions.
  - Although the supervisor is in charge of the overall MCRA procedures, he/she cannot directly observe implementation of MCRA procedure steps since most operator actions are performed at local plant stations (and not at the RSDP).
  - The likelihood of detecting errors in sequencing is reduced in MCRA due to fewer indications at the RSDP
- Is strongly influenced by training for its success during MCRA, ranging from:
  - Classroom only (i.e., more passive "receiving training")
  - Practicing coordination in the field (i.e., "active" and more realistic training is "best case")
- May be easily detected and recovered or may lead to irreversible SSC failure if not recovered.

C.3.3 Causes of Coordination Failures in C&C from Literature

According to the literature surveyed by the author team, the major causes of coordination failures related to C&C are distractions and interruptions.[22]

An interruption (e.g., something [like a new cue] that stops something from happening) or a distraction (e.g., something that turns your attention away from something you want to concentrate on) is disruptive to performance and can induce errors in almost all cases. For example, in the 1940s, Fitts and Jones [2] reported that interruptions were the cause of pilot errors and flying accidents and made recommendations on reducing these disruptive effects. To this end, the FAA implemented a “sterile cockpit” rule in 1981 that required pilots to refrain from non-essential activities during critical phases of flight to limit distractions [3]. Similarly, healthcare research has shown the perils of distractions during urgent care settings [4].

With respect to HRA, interruptions or distractions can:

- Cause errors
- Take time to deal with (e.g., if there are no cues to guide the operator back to the interrupted step in the procedure (e.g., place markers), this can take 1-2 minutes.)
- Take time to recover

The authors determined, based on the literature review, that "interruption" (i.e., field operator calls regarding systems or equipment that do not require coordination) is the term that best fits the MCRA context.

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[22] Differentiating distractions from interruptions can be difficult. In this report a distraction is an external cue that draws your attention away from what you are supposed to be focused on. An interruption is when someone tells you about an external cue that takes your attention away from what you are supposed to be focused on.

C.3.4 Search for Similar Issues in Existing HRA Methods

Using the insights from above, the authors reviewed existing HRA methods that addressed distractions and interruptions. Overall, there were no methods that exactly matched the contexts and concerns that have been identified for C&C sequencing failures due to coordination in MCRA scenarios. However, there were elements in existing HRA methods that matched some of the MCRA C&C coordination concerns (e.g., interruptions/distractions, communications). The following are the results of this review:

- NUREG-2114 [5] describes the adverse impacts of high workload on vigilance tasks such as monitoring as well as its impact on distracting attention to salient cues such that the presentation of key information may be missed (pg. 39).
- NUREG-2199 (i.e., IDHEAS At-Power HRA method; pages 5-72 through 5-74) [6] considers “workload” as multi-tasking and a “distraction” as "a simultaneous demand for attention from other sources, which could result in the crew looking or stepping away from a procedure and picking back up in the wrong place OR could result in the crew misreading the procedure because of interference.” The associated crew failure mode (CFM) is "misread or skip step in procedure." The associated decision tree (see Figure 5-14 in Reference 6) is replicated in Figure C-1.
- The NARA (Nuclear Action Reliability Assessment) HRA method [7] addresses some of the relevant issues, such as:
  - A generic task type (GTT) for verbal communications of safety-critical data (GTT D1)
  - Error-producing conditions (EPCs) such as:
    - Time pressure (EPC 4)
    - Difficulties caused by poor shift handover practices and/or team coordination problems or friction between team members (EPC 13)
    - Information overload, particularly one caused by the simultaneous presentation of non-redundant information (EPC 10)
- THERP, Table 20-8 [8] provides estimated HEPs of errors in recalling oral instructions that are not written down, as a function of the number of items communicated and the number of items that need to be recalled.

The range of The HEPS that are associated with these methods are:

- NUREG-2199 [6] assigns HEPs through decision trees and lookup tables. Using the decision tree shown in Figure C-1 and the table for "AP-1 Misread or Skip Step in Procedure (page D-21 in Reference 6), the following relevant HEPs are assigned:
  - Crew failure scenario 1: Workload high, complex procedure, **no** compensating factors: 9.4E-2
  - Crew failure scenario 3: Workload high, complex procedure, with compensating factors (e.g., work practices, place-keeping aids): 1.9E-2
- NARA [7] (HEPs are to be considered maximums; an analyst can make changes by adjusting the “strength” of the EPC’s effect [influence of EPC]):
  - GTT D1: 6E-3
  - GTT D1 plus EPC 10: 3.6E-2
  - GTT D1 plus EPC 13: 2.4E-2
- THERP [8]:
  - Recall one item out of three items: 1E-2
  - Recall one item out of five items: 0.1

Note that the HEPs from these different HRA methods are generally consistent, ranging from 1E-2 to 0.1. Because the IDHEAS at-power method in NUREG-2199 explicitly addresses differences in compensating factors in contexts where interruptions and/or distractions may be important, the authors recommend using this HRA method at this time. In particular, the authors recommend assigning HEPs associated with the two "crew failure scenarios" (i.e., 1 and 3) shown in Figure C-1. Future research, for MCRA scenarios in fire events or other contexts, may identify other options.

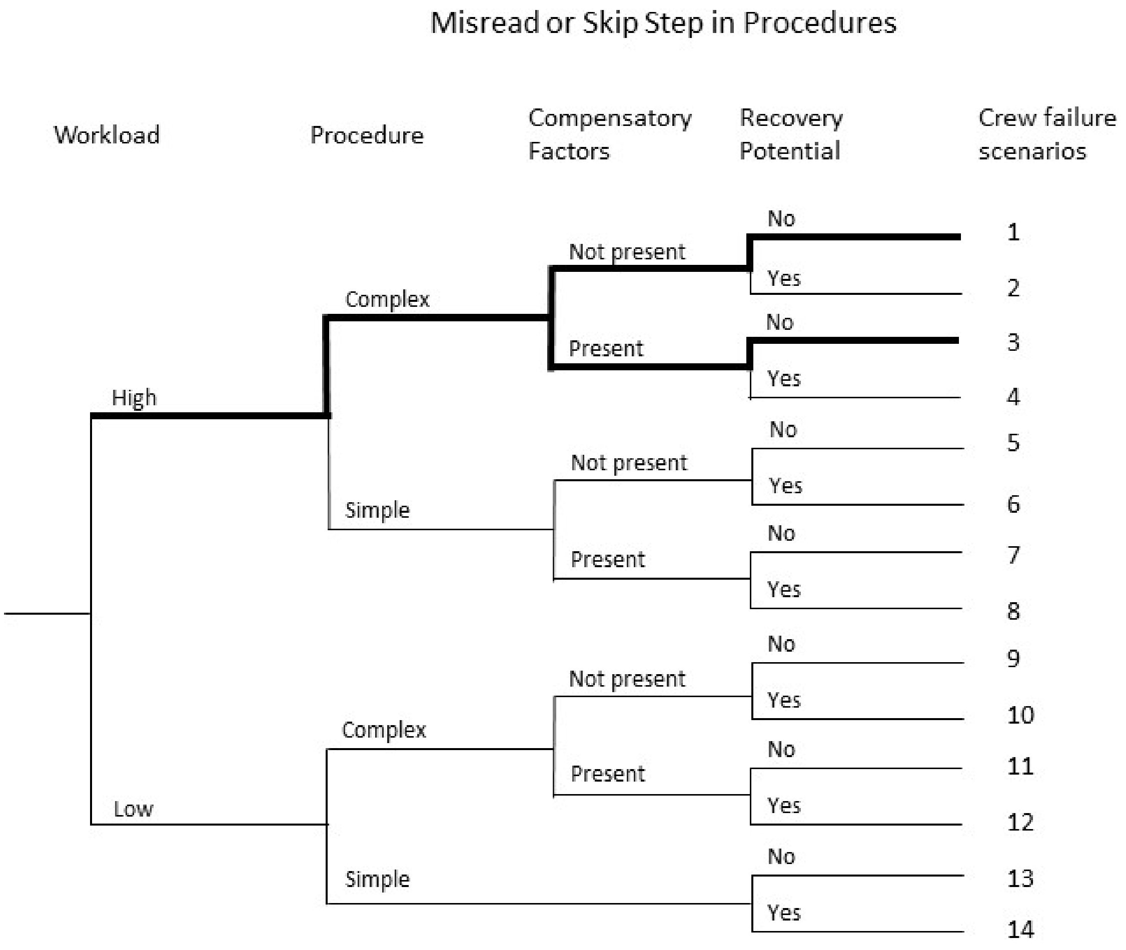

Figure C-1
IDHEAS at-power decision tree for "Misread or skip step in procedure"

C.4 References

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D

CONSIDERATIONS FOR POTENTIAL FUTURE QUANTIFICATION APPROACHES FOR THE DECISION TO ABANDON IN LOC SCENARIOS

At the time of this report, the authors were aware of wide variations across the U.S. NPPs regarding MCRA strategies, including: 1) the quality/capability of RSDPs, 2) clarity of cues and procedures, and 3) content and frequency of training. In addition, such strategies and their associated procedures and training were different enough from typical EOP actions that the existing HRA methods were not considered fully applicable to evaluate the HEP for the decision to abandon the MCRA on LOC. Particularly, this research (see Section 4 and Appendix B) identified “reluctance” as a significant driver as to whether operators will decide to abandon the MCR for LOC scenarios. As a result, the HRA quantification approach for Phase II (Section 4) was developed, representing a strong influence of “reluctance” in the recommended HEPs for this HFE.

However, the authors recognized that significant improvements to the state of practice for implementation of the decision to abandon the MCRA in LOC scenarios are possible. In fact, some of the elements in the HRA quantification approach in Section 4 represent recent changes at a few U.S. NPPs (e.g., identification of “cues” for abandonment in LOC scenarios, addition of explicit abandonment “cues”) in procedures for the decision to abandon. In the future, NPPs may identify additional ways to make the decision to abandon for LOC scenarios more reliable. Such future applications may also form part of the basis for potential, improved generic HRA quantification guidance.

Furthermore, the most important output of the HRA process is a better understanding of the most effective ways to increase the likelihood of operators successfully making the decision to abandon in LOC scenarios when they are risk significant. Also, because of the variations between NPPs in their MCRA strategies, it is likely that effective plant improvements to reduce reluctance (e.g., changes to procedures, training) are very likely to be plant-specific and may not be fully captured by the streamlined methodology in Section 4. Therefore, the objective of this appendix is to:

- Provide a discussion of the underlying research that was examined in this project regarding reluctance and decision making as a starting point for future research efforts in this area.
- Describe the underlying assumptions and scope such that an analyst can understand when the method in Section 4 of this report may not be applicable to a plant-specific circumstance because improvements have been made beyond the state of practice at the time of this report.

Finally, regarding interim plant-specific improvements, the authors recommend that the following be recognized:

- The concept of "reluctance" is not fully understood at this time, but it is likely to have both generic and plant-specific elements.
- The current state of knowledge regarding "reluctance" is important to address in the HRA qualitative analysis for MCRA LOC scenarios (then represented in HRA quantification).
- Caution should be used in comparing or extrapolating the state of knowledge and HRA practice with respect to other operator decisions that are represented in PRAs.

The remainder of this appendix is intended to summarize background information that the authors think will be relevant to future activities, whether they be efforts to make plant-specific improvements or develop additional HRA guidance. As such, the remainder of this appendix provides the following:

- The basis for the treatment of "reluctance" in this report
- A short history of HRA's treatment of a general category of decisions with serious consequences
- Other decisions with serious consequences in the PRA
- Examples of plant-specific improvements to MCRA strategies derived from actual HRA insights from plants
- Considerations for using or augmenting existing HRA methodologies

D.1 Basis for the Treatment of Reluctance in This Report

As expressed in Section 4.1, operator reluctance to abandon the MCR in LOC scenarios is considered to be an important factor for many NPPs. Specifically, reluctance can cause a delay in abandonment to the point where it may be too late to abandon and still safely shutdown the plant. Operator reluctance to abandon the MCR is embedded in the HEP assignments that were developed by an expert panel for this research (and as provided in Figure 4-5).

As documented in Table B-1, the authors have identified the following as potential reasons for not abandoning the MCR when the cues for abandonment are present:

- A perceived reduction in capability to achieve safe shutdown conditions with RSDP, as opposed to remaining in the MCR (since most MCRA safe shutdown strategies assume that there is only one train of safe shutdown equipment available)
- The operators' comfort and familiarity with MCR
- An inability to accept that abandoning the MCR (a rare event) is indeed the only alternative remaining
- A lack of experience with MCRA due to LOC

However, while the expert panel confirmed the key influences on the decision to abandon, the experts also indicated that reluctance may be more complex and may have some plant-specific elements. While the HRA quantification guidance given in Figure 4-5 identifies several factors that change HEP assignments (e.g., how explicit abandonment criteria are provided in procedures, type of training, amount of time available), these are considered generic, not plant-specific, factors that are expected to influence reluctance.

In developing HRA guidance for MCRA scenarios, the authors recognized the need to represent reluctance to abandon the MCR for LOC scenarios. Initial efforts to address reluctance included consideration of the IDHEAS at-power, internal events method (NUREG-2199) [1] and the associated cognitive basis [2]. This method considers where operators may experience a conflict between their perceived success strategy and the prescribed strategy. In this case, there must be both a negative consequence associated with the prescribed strategy (e.g., loss of capability) AND an alternate path that operators believe to be viable. An improper balance of priorities may lead the operators to choose a response option that is less optimal (with regard to plant integrity or safety).

Specifically, the IDHEAS at-power, internal events method has two decision trees that are relevant to MCRA that can provide a quantitative approach to evaluating the use of judgment and potential reluctance. (It should be noted that the preliminary decision trees for the decision to abandon that are discussed in Appendix B are based on these NUREG-2199 trees). These two crew failure modes (CFMs) are related, but different [1]:

1. **Choose inappropriate strategy CFM**: This CFM applies to **the deliberate choice to take one strategy over another**. For example, in PWR SAMGs in which the feeding of a hot, dry SG may result in a tube rupture with a potential for consequent releases. Therefore, restoring secondary cooling may be at the expense of sacrificing a release barrier. The operators may be reluctant to restore SG feed even though it would be a better strategy in the long term.
2. **Delay Implementation CFM**: This CFM applies to **purposefully delaying an action given a strategy has already been chosen**. For example, Westinghouse functional restoration procedure FR H-1 includes steps to try to restore feedwater until the cue for initiation of feed and bleed is reached. To apply the delay response, the operators know which the correct strategy is (implementing feed and bleed), but choose to delay the action (in this case because they may be trying to restore feedwater).

The “choose inappropriate strategy” decision tree captures reluctance in making the decision to abandon in the case that operators believe there is another potential success path (i.e., trying to control the plant from the MCR). This CFM is more likely to be relevant when the procedures call for a more judgment-based decision rather than a criteria-based decision. The tree considers 1) if there is a preference for the appropriate strategy based on training and experience, 2) if there is an advantage to the appropriate strategy that is known by the operators (does one strategy have known downsides or if there is a mismatch between the procedures and plant practices?), and 3) if there is recovery potential.

The “delay implementation” decision tree captures the reluctance to execute the decision once operators understand they are in an abandonment scenario, which is sometimes called reluctance. This decision tree considers 1) if there is a reason to delay—this requires both a reluctance to perform the action (in this case, abandonment of the MCR) AND a perceived viable alternative (i.e., an expectation that recovery is imminent or more information will show that abandonment is not needed), 2) if the operator has a correct assessment of the time margin and understands how long he can delay the action before it is no longer successful, and 3) if there are additional cues/alarms that prompt the need for imminent action (this is a recovery of sorts, and is not expected to be present for MCRA scenarios for current designs).

One critical element to the reluctance or uncertainty experienced by the operators is a lack of understanding or a misunderstanding or under-appreciation of the time available. An operator’s ability to develop an accurate mental model of the situation (i.e., have good situational awareness) increases with experience [3, 4]. However, there are other elements that might interfere with an operator’s situational awareness of the current conditions. Although the operator may be familiar with the abandonment conditions necessary to precipitate MCRA from classroom training, the lack of real experience in the setting might cause delays in the operator’s response time as he or she more carefully considers all of the ramifications of the decision [5].

Additionally, the organizational culture might impact the operator’s willingness to act on irreversible decisions. However, as discussed in References 6 and 7, organizational culture (and more precisely, safety culture) can be difficult to measure and lacks predictability.

It is possible that the effects of these factors may be reduced by developing relevant simulator training and/or creating an environment in which reluctance to act is reduced by providing experience in recognizing a LOC scenario. For instance, if the control room crew knew that they would be leaving the MCR to re-station themselves in a remote shutdown location that held all the same functionality of the MCR (including more than one train of available safety-related equipment), it is possible that much of their uncertainty could be eased.

D.2 A Short History of HRA’s Treatment of Decisions with Serious Consequences

During this research, the authors recognized that the decision to abandon the MCR has similarities with a more general class of decisions with serious consequences, and future HRA development is recommended to consider more explicitly other foundational HRA work discussed here. This classification of decisions can have several important features, such as:

- Decisions made with uncertainties (e.g., plant state unknown)
- Decisions between conflicting goals or priorities
- Decisions with potential negative consequences

Some of the early thinking on complex decision-making was documented by Dougherty in 1988 [8]. Dougherty discusses the difficulties in making various decisions, including those in the Three Mile Island 2 event [9] and the Davis Besse loss-of-feedwater event [10], which were of particular interest to the HRA community at the time. However, Dougherty uses the term “burden” (especially, “diagnostic burden”) or “hesitancy” to address this type of decision-making (which he recognizes is more likely in “off-normal” conditions). The following terms and phrases are used to describe the concept of burden:

- “…conflict between different goals that create hesitancy, a kind of cognitive lockup”
- “Hesitancy …due to uncertainty in conditions present or …uncertainty as to which goals to pursue when one or more appear to conflict”
- “…burdened not only with a decision…but [also] has to negotiate a trade-off between the restoration of the desired option and its alternative”
- “ ..decision burdened by conflict, competing resources, and confusion”

Dougherty also recognizes that “…the quality of procedures, the adequacy of the instrumentation and controls, and the adequacy of training…” can influence the reliability of decision-making with burden.

In the late 1990s and early 2000s, there were several efforts throughout Western Europe and the United States to better address cognition and operator decision-making in complex events, such as that in the Three Mile Island 2 and Chernobyl events. Most of these efforts resulted in new second generation HRA methods, such as EdF's MERMOS [11], Eric Hollnagel's CREAM [12], and NRC's ATHEANA [13, 14]. Because of interactions between the various authors of these methods (e.g., via international agreement working groups, professional communication among colleagues), there is some overlap of underlying thinking derived from the same cognitive and behavioral science literature. However, the specifics of the resulting methods were different.

Among those issues addressed in these second generation methods were concepts related to "reluctance" and "hesitancy." For example, ATHEANA provides guidance on searching for and identifying deviations in scenarios that could be challenging for operators and the associated unsafe actions and HFEs. Within the search schemes provided by ATHEANA, challenging decision-making contexts are identified, such as "trade-offs" (where operators must make impromptu judgments between alternatives), "dilemmas" (where ambiguity in the plan or situation can raise significant doubt about the appropriate next steps), and "double-binds" (for which conditions exist where operators are faced with two or more choices, all of which have undesirable elements). In the early 2000s, ATHEANA was used by the NRC in three PRAs supporting revision of the pressurized thermal shock (PTS) rule, particularly looking at the potential conflict between operator's more typical concerns for underlying cooling the RCS versus the PTS concern of overcooling the reactor vessel. In addition, ATHEANA provided an associated approach for retrospective analysis of operational events and example analyses.

Future research should consider these second generation methods and their applications to other consequential decisions.

D.3 Other Decisions with Serious Consequences in the PRA

The discussion above mentioned that there are other operator decisions with serious, adverse consequences that could be likened to the decision to abandon the MCR in LOC scenarios. This section discusses such similar decisions in more detail.

Feed and bleed is one important example of a consequential operator decision that is currently modeled in HRA/PRAs, and, historically, this action has had some element of "reluctance." In recent years, the HFE associated with feed and bleed has been modeled without substantial reluctance because:

- The procedural direction is clear and tied to specific parameter values (e.g., more than one steam generator level reading) whose implications are understood by operators through their training.
- Strict procedure adherence is expected and trained upon frequently, with little to no room for judgment in the case to begin feed and bleed.
- Beyond the training on the specific actions, operators fully understand the importance of cooling the core and understand that this action is the last line of defense.

It is important to note that much of the discussion provided regarding “reluctance” is consistent with the response to the 1985 loss of all feedwater event at Davis Besse, in which the operators delayed the decision to use the feed-and-bleed strategy (until, fortuitously, feedwater was restored). However, since no subsequent loss of feedwater events have occurred in the United States, it is not known if operators would be less reluctant to use the feed-and-bleed strategy since that event. Certainly, U.S. operators have logged many hours of simulator training in which the feed and bleed strategy was demonstrated. But, an actual loss of feedwater event (versus a simulated event) may result in different operator responses, which still needs to be reflected in the application of HRA modeling for such events. While there is evidence that simulator training generally improves human performance, the differences between simulator and actual performance is a source of uncertainty in HRA that may need to be explored in future work.

Other examples of at-power, internal events scenarios involving operator decisions with significant adverse consequences are:

- Automatic depressurization system (ADS) - Almost every BWR in the world includes an action to inhibit automatic actuation of this system and has ingrained its implementation in its procedures and training, despite it being a “one-and-done” safety feature. However procedures also include caveats as to when to reconsider such actions (e.g., if there is no high-pressure cooling). Reluctance is natural if the operators believe HPCI or RCIC can be brought back on line.
- Standby liquid control system (SLCS) - Possibly the only way to mitigate a BWR ATWS, which will significantly impact the functionality of the existing core vessel and internal vessel structures due to chemical impurities (i.e., major impact to the plant’s short and long term viability, if not a loss of the asset altogether).
- Use of unpurified water (e.g., fire water, city water, or raw water) - Similar to feed and bleed, although the potential consequences could be less severe than the above examples.

In addition, HRA/PRA guidance for scenarios beyond the traditional at-power, internal events are beginning to consider other consequential decisions, such as:

- EPRI 3002013018 [15] provides guidance on quantifying the decision to declare an extended loss of AC power (ELAP) condition using the EPRI HRA methodology, augmented by IDHEAS [1]. Declaration of ELAP has many parallels to the decision to abandon the MCR in a LOC and, as such, the approach provided in that report applies the same underlying research as those provided in this effort (including a benchmark against the LOC decision tree from Section 4). For example, both decisions may:

  - Involve judgment and discretion of the decision maker
  - Are based on the gradual understanding of the plant state based on a variety of pieces of information (local and in the MCR), rather than the value of one parameter or small set of parameters
  - Are not necessarily trained upon with the same frequency and depth as other EOP actions
  - Commit operators to one success strategy (last procedural line of defense)
- NRC's Office of Nuclear Regulatory Research (RES) is publishing the results of an expert elicitation for addressing HFEs associated with FLEX strategies [16].
- In the site-wide, all hazards Level 3 PRA study being performed by NRC-RES, the plant-specific Level 2 HRA [17] justified crediting the use of EDMGs without their being explicitly called out in the SAMGs and developed an HRA quantification approach for Level 2 HRA HFEs using both the ATHEANA HRA method and the Fire HRA Guidelines (i.e., NUREG-1921) as the general basis for its HRA approach. The decisions associated with the Level 2 HFEs parallel other decisions with serious consequences in several ways, as both decisions may:
  - Involve judgment and discretion by the decision maker because, for example:
    - The SAMGs provide multiple options or alternatives, rather than a single strategy.
    - Many of the alternatives have serious consequences (beyond core damage).
    - The SAMGs do not provide explicit, step-by-step implementation guidance.
  - Require an understanding of the plant conditions over time.
  - Require an integration of information from indications (in MCR and local), with some of these indications being inaccurate or failed (i.e., there is some uncertainty associated with indicated plant conditions).
  - Are very infrequently trained upon, with most training coming in classroom rather than simulator settings.
  - Require operators to select a single strategy.

The examples above show that, currently in PRA models, there are operator actions that require decision-making that could lead to substantial consequences to the plant. Existing HRA methods have been used to both qualitatively and quantitatively assess these actions and, in the case of feed and bleed, the HRA insights have resulted in plant procedure and training changes that are expected to reduce reluctance.

D.4 Examples of Recent Changes in MCRA Strategies Resulting from HRA Interactions with the Plant Operations and Training

Based on the understanding that operator confidence in the ability to safely control the plant from outside the MCR contributes significantly to the estimated likelihood of abandonment when necessary, some plants have made either physical changes to the plant or amendments to procedures and training.

Some operating NPPs are already working to address the reluctance to abandon through the review and refinement of procedures and training by:

- Acknowledging that the initial guidance for the decision to abandon the MCR during LOC scenarios was vague and not well trained upon.
- Utilizing the fire PRA to identify the most likely scenarios that lead to MCRA.
- Factoring the key equipment or functional losses from those scenarios into their procedural guidance and simulator training program for the decision to abandon.

Examples of such cases where significant plant improvements have been made with the potential to substantively reduce reluctance are:

- A plant that has built an entirely new building and associated equipment, including a small control room with both digital and analog controls that has the capability to control both primary and secondary safety functions to address fires in the relay and CSRs (which have virtually no separation).
- New generation plants with a separate, full-scope (duplicate) control room.

When crediting these changes to reduce the impact of hesitancy, care should be taken that these changes reflect a substantive change in understanding and crew behavior regarding the decision to abandon, including time urgency. This can be demonstrated through operator interviews and/or simulator observations.

For example, at one plant, abandonment on LOC was a significant risk driver in some scenarios. Using insights from the fire PRA, operations agreed to modify the abandonment procedures and training to simplify the entry criteria. Ultimately, however, verification and validation of procedure and training effectiveness through timed simulator exercises that evaluate operator response are necessary to provide justification that reluctance has been reduced.

Finally, other plants have found other ways to reduce risk based on the HRA insights. For example, one plant implemented a design change to utilize an additional feedwater pump to mitigate CSR fires. The new pump has been designed to specifically mitigate MCRA, but it does not require the MCR to be abandoned to establish flow at the local control station. As a result, the decision to initiate this new function is either symptom-based (no main feedwater/emergency feedwater and low steam generator level), which would direct the operators to initiate it in the MCR, or just before the decision to abandon. This modification both reduced the frequency of scenarios that require MCRA and limits the number of operator actions required in case of fire-related MCRA.

D.5 Considerations for Using or Augmenting Existing Methodologies

If a plant can demonstrate that substantial improvements have been made to the plant design and/or operations with respect to MCRA (beyond those considered in the development of the decision tree in Section 4) such that “reluctance” has been significantly reduced, then it may be appropriate for an analyst to consider an alternate HRA quantification approach for the decision to abandon on LOC. To use an existing methodology, analysts would need to explicitly explain how that methodology can represent the remaining influence of reluctance on operator actions. In general, the more similar the characteristics of the decision to abandon the MCR on LOC are to the characteristics of actions underlying existing methods, the more applicable the existing methods become as a tool for quantifying the HEP for the decision to abandon the MCR on LOC. For many existing HRA methods, such as the EPRI HRA methodology for modeling cognition [18, 19], some of the key characteristics/assumptions of the methodology include:

- Procedures match the situation context and provide clear criteria.
- Operators trust and follow their procedures, and there is a clear procedural path.
- Quality and frequency of training is consistent with actions in the EOP/AOP network
- Applicability to rule-based behavior, such as when procedures are used (i.e., little judgement or decision making is involved).
- Plant information-operator interface failures typically consider evaluation of a well-defined cue (i.e., a primary parameter or set of parameters against a fixed criteria, e.g., a trend or limit).

For plant-specific cases, an experienced HRA analyst can identify impediments to an operational strategy working, how to make it workable (through plant changes), and how to represent the resulting expected operator response with existing HRA methods. However, to use an alternative approach to that presented in Section 4 of this report, the burden is on the analyst to justify that the alternative method is applicable to their particular case and the action characteristics sufficiently match the underlying characteristics defined above. Some considerations include:

- Cue clarity
  - Cues and indications are clear and can be interpreted as a LOC scenario
    - Fire has been detected in a location relevant to the abandonment criteria
    - The MCR is no longer reliable as a source of system/component information and control
- Procedural direction, e.g.,
  - Explicit statement in procedures of the severe fire-caused conditions (such as extensive MCR instrumentation failure or equipment failure consistent with fire PRA modeling) that require abandonment.
  - Clear and compelling transfer from the initial procedure (EOP or fire, for example) to the MCRA procedure.
- Crew preparedness via reviewing and exercising plans and procedures, upgrading equipment, and conducting training and drill programs to maintain proficiency.
- Crew is assigned to monitor MCRA criteria and MCR indications in order to achieve quick transfer to procedural steps for MCRA, such as confirming the fire location in the CSR (or plant-specific locations including the relay room or computer room).
- Operators believe in their abandonment criteria.
- Training quality and frequency consistent with risk significance of the action:
  - “Realistic” training on the decision to abandon on LOC for a given scenario. For example, realistic training could be in the simulator with a set of failures that the operators could interpret and recognize that they would have to leave. The failure set should reflect timing and spatial effects that would be consistent with a fire that results in abandonment (i.e., PRA assumptions that everything fails immediately may not be “realistic”).

  - Training should emphasize the conditions that have to be met to abandon as well as how the operators would know those conditions were met (e.g., signal vs. noise).
  - Evaluation of training (e.g., simulator studies or talk-throughs) should occur separately from initial training. For example, a simulator run directly after the classroom training or simulations where the decision to abandon has already been made would not constitute “realistic” training.
- RSDP capability is consistent with the parameters that need to be controlled and monitored for MCRA, and the operators are familiar with the RSDP such that the operators believe abandonment will lead to probable success.
- Operator interviews reflect confidence in the action in that given scenario.

Also, an alternative method should be considered after the user has conducted a qualitative analysis, including a detailed assessment of the time required and time available for the decision to abandon as discussed in Section 2.2 and a thorough evaluation of the cues for the decision to abandon as described in Section 4.2.1. In addition, as represented in the quantification tool in Section 4, if timing is identified to be an important influence on the decision to abandon, then the analyst should use HRA quantification tools that appropriately represent this influence.

Examples of two alternative approaches are offered here for consideration. First, EPRI 3002016004 [20] describes a plant-specific application involving an alternative approach that was performed before this research and report were completed. This alternative approach is based on the EPRI HRA methodology [18, 19], specifically the CBDTM and HCR/ORE time-reliability correlation method. Regarding CBDTM, new guidance specific to the MCRA decision to abandon is provided for the tree branch selections. There are questions regarding the application of HCR/ORE to the case of MCR abandonment since the method was developed for procedure driven actions that are well standardized and well trained with clear cues and indications. The second alternative is to use the IDHEAS “Delay Implementation” tree to capture the time-reliability component in lieu of using HCR/ORE (as was done in [15] to address the decision to declare ELAP) in combination with CBDTM.

Finally, when applying an alternate method to that described in Section 4, a reasonableness check should be performed. This could include a comparison against the bounding Phase II values using the approach in Section 4, to ensure that the values are neither excessively high nor low.

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10. SUPPLEMENTARY NOTES
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11. ABSTRACT (200 words or less)

Fire probabilistic risk assessments analyze a wide variety offire-induced scenarios, one ofwhich is fire damage that renders the main control room (MCR) either uninhabitable or ineffective. In this scenario, operators cannot safely shutdown from the MCR, and the command and control (C&C) ofthe plant is transferred to remote or alternate shutdown panels. This is commonly referred to as main control room abandonment (MCRA).

While EPRI/NRC-RES Fire Human Reliability Analysis Guidelines (NUREG-1921) provided methods and guidance to estimate human error probabilities for fire PRAs, the subject ofMCRA was reserved for future research. Supplement 1 of NUREG-1921 addressed qualitative considerations for fire scenarios resulting in MCRA.

This report provides guidance for quantifying the probabilities ofhuman failure events for fire PRA scenarios resulting in MCRA, building upon both NUREG-1921 and Supplement 1. The HRA process for MCRA scenarios remains unchanged from NUREG-1921, but it has been supplemented by additional contextual factors unique to MCRA scenarios.

Guidance is provided based on the specific time phases ofthe MCRA timeline: 1) the time before abandonment, 2) the time for the decision to abandon, and 3) the time after the decision to abandon has been made.

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