NUREG-2256

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

INTEGRATED HUMAN EVENT ANALYSIS SYSTEM FOR EVENT AND CONDITION ASSESSMENT (IDHEAS-ECA)

[Comments]

Office of Nuclear Regulatory Research

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at the NRC's Public Electronic Reading Room at http://www.nrc.gov/reading-rm.html. Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and Title 10, "Energy," in the *Code of Federal Regulations* may also be purchased from one of these two sources.

1. **The Superintendent of Documents**
   U.S. Government Publishing Office
   Mail Stop SSOP
   Washington, DC 20402-0001
   Internet: http://bookstore.gpo.gov
   Telephone: 1-866-512-1800
   Fax: (202) 512-2104

2. **The National Technical Information Service**
   5301 Shawnee Road
   Alexandria, VA 22161-0002
   http://www.ntis.gov
   1-800-553-6847 or, locally, (703) 605-6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

U.S. Nuclear Regulatory Commission
Office of Administration
Publications Branch
Washington, DC 20555-0001
E-mail: distribution.resource@nrc.gov
Facsimile: (301) 415-2289

Some publications in the NUREG series that are posted at the NRC's Web site address http://www.nrc.gov/reading-rm/doc-collections/nuregs are updated periodically and may differ from the last printed version. Although references to material found on a Web site bear the date the material was accessed, the material available on the date cited may subsequently be removed from the site.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852-2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036-8002
http://www.ansi.org
(212) 642-4900

Legally binding regulatory requirements are stated only in laws; NRC regulations; licenses, including technical specifications; or orders, not in NUREG-series publications. The views expressed in contractor-prepared publications in this series are not necessarily those of the NRC.

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG-XXXX) or agency contractors (NUREG/CR-XXXX), (2) proceedings of conferences (NUREG/CP-XXXX), (3) reports resulting from international agreements (NUREG/IA-XXXX), (4) brochures (NUREG/BR-XXXX), and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of NRC's regulations (NUREG-0750).

NUREG-2256

INTEGRATED HUMAN EVENT ANALYSIS SYSTEM FOR EVENT AND CONDITION ASSESSMENT (IDHEAS-ECA)

[Comments]

Manuscript Completed: Month Year

Date Published: Month 20xx

Prepared by:
J. Xing
Y.J. Chang
J. DeJesus Segarra

Office of Nuclear Regulatory Research

ABSTRACT

This report describes a human reliability analysis (HRA) method developed by the U.S. Nuclear Regulatory Commission (NRC) staff. The method is known as the Integrated Human Event Analysis System for Event and Condition Assessment (IDHEAS-ECA). It is based on NUREG-2198, “The General Methodology of an Integrated Human Event Analysis System.” IDHEAS-ECA supports risk-informed decisionmaking by providing an HRA method to be used in probabilistic risk assessment (PRA) applications. The NRC staff uses PRA in the review of risk-informed license amendment requests and evaluations of notices of enforcement discretion, operational events (e.g., Management Directive 8.3, “NRC Incident Investigation Program,” and the accident sequence precursor program), and inspection findings (i.e., the significance determination process). IDHEAS-ECA was developed because, in recent years, the scope of application of HRA has expanded into situations beyond the scope of existing HRA methods.

IDHEAS-ECA is intended to apply to the same situations modeled by existing HRA methods (e.g., nuclear power plant internal events while at-power) and beyond (e.g., external events, low power and shutdown events, and events for which flexible and coping strategies (FLEX) equipment is used). The IDHEAS-ECA method provides step-by-step guidance for analyzing a human action and its context. It models a human action by using five macrocognitive functions: *detection*, *understanding*, *decisionmaking*, *action execution*, and *interteam coordination*. The failure of a human action is modeled with a set of cognitive failure modes and performance-influencing factors, which are then used to calculate the human error probability (HEP). The IDHEAS-ECA method includes a software package that facilitates the documentation of the analysis of a human action and its context and uses the results of the analysis as input to calculate the HEP.

The report also provides additional information in the appendices, which include (1) a worksheet for analyzing and modeling human actions and their context, (2) the integrated human error data needed to calculate HEPs, and (3) two examples that demonstrate the use of the IDHEAS-ECA method. This report replaces Research Information Letter 2020-02.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The Integrated Human Event Analysis System for Event and Condition Assessment (IDHEAS-ECA) is a human reliability analysis (HRA) method developed by the U.S. Nuclear Regulatory Commission (NRC) staff to support risk-informed decisionmaking. IDHEAS-ECA analyzes human events and estimates human error probabilities (HEPs) for use in probabilistic risk assessment (PRA) applications. The method is based on NUREG-2198, “The General Methodology of an Integrated Human Event Analysis System (IDHEAS-G)” [1]. IDHEAS-G and IDHEAS-ECA were developed because, in recent years, the scope of application of HRA has expanded into situations beyond the scope of existing HRA methods. Also, they were developed, in part, to respond to Staff Requirements Memorandum M061020 [2], in which the Commission directed the Advisory Committee on Reactor Safeguards as follows:

> …work with the [NRC] staff and external stakeholders to evaluate different Human Reliability models in an effort to propose either a single model for the agency to use or guidance on which model(s) should to [sic] be used in specific circumstances.

IDHEAS-ECA models human actions in a PRA (i.e., human failure events) using five macrocognitive functions: *detection*, *understanding*, *decisionmaking*, *action execution*, and *interteam coordination*. These macrocognitive functions are based on the cognitive basis for HRA, which was published as NUREG-2114 [3] and are described as follows:

- *Detection* (D) is noticing cues or gathering information in the work environment.
- *Understanding* (U) is the integration of pieces of information with a person’s mental model to make sense of the scenario or situation.
- *Decisionmaking* (DM) includes selecting strategies, planning, adapting plans, evaluating options, and making judgments on qualitative information or quantitative parameters.
- *Action execution* (E) is the implementation of the decision or plan to change some physical component or system.
- *Interteam coordination* (T) focuses on how various teams interact and collaborate on an action.

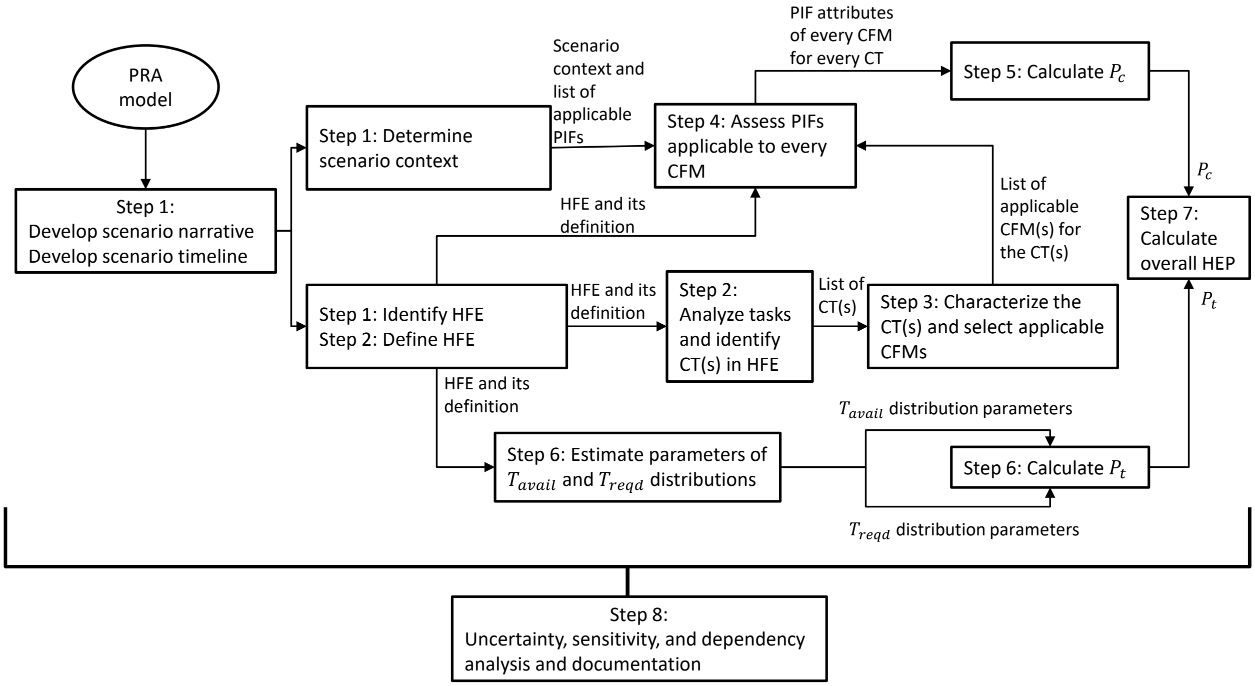
The first four macrocognitive functions (D, U, DM, and E) may be performed by an individual or a team, and *interteam coordination* is performed by multiple groups or teams. In general, a human failure event (HFE) occurs because of the failure of any macrocognitive function. In IDHEAS-ECA, the failure of a macrocognitive function is defined as the cognitive failure mode (CFM). The probability of an HFE (i.e., human error probability) is affected by the scenario context in which the action occurs. The context describes the conditions that challenge or facilitate human performance, and IDHEAS-ECA uses performance-influencing factors (PIFs) to model the context. Table ES-1 shows the 20 PIFs used in IDHEAS-ECA in four context categories.

IDHEAS-ECA also provides a process for implementing an HRA. Figure ES-1 shows an overview of the IDHEAS-ECA HRA process. For HRA applications in nuclear power plants, the HRA process typically starts with a PRA model. Then, the HRA process consists of eight steps, which are described below. The NRC staff developed a software package (i.e., the

IDHEAS-ECA software) to facilitate the documentation of the HRA process and calculate the HEP.

Table ES-1 PIFs in IDHEAS-ECA

Environment and situation	System	Personnel	Task
• Work location accessibility and habitability • Workplace visibility • Noise in workplace and communication pathways • Cold/heat/humidity • Resistance to physical movement	• System and I&C transparency to personnel • Human-system interfaces • Equipment and tools	• Staffing • Procedures, guidelines, and instructions • Training • Teamwork and organizational factors • Work processes	• Information availability and reliability • Scenario familiarity • Multitasking, interruption, and distraction • Task complexity • Mental fatigue • Time pressure and stress • Physical demands



CFM = cognitive failure mode
CT = critical task
HEP = human error probability
HFE = human failure event
PIF = performance-influencing factor

PRA = probabilistic risk assessment
P_c = error probability due to CFMs
P_t = error probability due to uncertainty in T_{avail} and T_{reqd}
T_{avail} = time available
T_{reqd} = time required

Figure ES-1 IDHEAS-ECA HRA Process

Step 1: Analyze the scenario. Analyzing an event includes developing the scenario narrative and timeline, determining the scenario context, and identifying the HFEs. The scenario narrative is a storytelling-style representation that specifies the initial conditions, initiating event, boundary conditions of the event, and the scenario progression and end state. The scenario timeline documents the system responses (to the initiating event) and HFEs in chronological order. Together the scenario narrative and timeline are the operational narrative. Determining the scenario context refers to the search for the conditions that challenge or facilitate human performance in the scenario and results in a list of applicable PIFs. The HFEs are usually identified in the PRA model and are the analysis units of an HRA.

Step 2: Analyze the HFE. This includes defining the HFE, analyzing the tasks within the human action, and identifying the critical tasks for HEP quantification. The definition of the HFE describes the failure of the human action, its link to the affected systems in the PRA model, and the timeline (i.e., time available and time required to perform the action). Analyzing the tasks within a human action shows how the HFE can occur and aids in the identification of critical tasks, which are those that are essential to the success of the human action. Failure of any critical task will result in the occurrence of the HFE.

Step 3: Model the failure of critical tasks in an HFE. This includes characterizing the critical task and selecting the applicable CFMs of the critical task. Characterization of a critical task means specifying the conditions relevant to the critical task that can challenge or facilitate human performance. Any critical task can be achieved through one to all five macrocognitive functions. The cognitive failure of a critical task is the result of failure of any macrocognitive function it demands. Thus, the CFMs are the classifications of the various ways that a critical task may fail.

Step 4: Assess the PIFs applicable to every CFM. This step uses the results of the scenario analysis (Step 1), HFE definition (Step 2), and task characterization (Step 3) to assess the PIFs, which results in a list of PIF attributes of every CFM for every critical task. The PIFs represent the context of the HFE and facilitate quantification of the HEP. A PIF attribute is an assessable characteristic of a PIF and describes a way the PIF challenges the macrocognitive functions of a critical task and thus increases the likelihood of error in the macrocognitive functions.

Step 5: Calculate P_c. P_c is the probability of failure due to the CFMs and is calculated as the probabilistic sum of the HEPs of all the CFMs of the critical tasks, which are based on the PIF attributes assessed in Step 4. P_c can be computed using the IDHEAS-ECA software or manually using the data in Appendix B.

Step 6: Calculate P_t. P_t is the probability of failure due to the uncertainty in time available and time required to perform the action. Estimates of the parameters of the probability distributions of time available and time required are obtained using the timeline in the HFE definition. Then, the IDHEAS-ECA software is used to calculate P_t.

Step 7: Calculate the overall HEP. The overall HEP is the probabilistic sum of P_c and P_t. That is, $Overall\ HEP = 1 - (1 - P_c)(1 - P_t)$.

Step 8: Analyze uncertainties in the HRA, perform sensitivity and dependency analyses, and document the results.

Appendix A to this report provides the worksheet to document the analysis and modeling of human actions and its context. Appendix B contains the human error data needed to calculate the HEPs. Appendix C presents an approach to calculate probability distribution parameters. Appendix D introduces the IDHEAS-ECA software. Appendix E and Appendix F present two examples that demonstrate the use of the IDHEAS-ECA method.

The eight-step process analyzes an individual HFE. If an HRA includes multiple HFEs in an event sequence (e.g., a sequence in a PRA minimal cutset), dependency analysis is needed to account for the impact of the occurrence of an HFE on a subsequent HFE. IDHEAS-ECA includes a dependency model. The guidance for using the dependency model is documented separately in Research Information Letter 2021-14 [4].

IDHEAS-ECA improves existing HRA methods by (1) providing a systematic process and guidelines to analyze and model human actions and the associated scenario context, (2) using a human error database to calculate HEPs, and (3) including an extensive set of PIFs to represent the context of scenarios under various operational conditions, such as using flexible and coping strategies (FLEX) equipment. IDHEAS-G (and, therefore, IDHEAS-ECA) provides a platform to incorporate and generalize human error data from various sources to inform HEPs. Data from the Scenario Authoring, Characterization, and Debriefing Application (i.e., SACADA) and operator simulator performance in other countries will be used to update the HEPs used in IDHEAS-ECA.

The NRC finds the IDHEAS-ECA HRA method acceptable for use to support risk-informed applications in which the PRA model used to support regulatory decisionmaking is intended to be consistent with Regulatory Guides 1.200 [5] and 1.247 [6]. IDHEAS-ECA is envisioned for use by the NRC staff for PRA applications, such as the review of risk-informed license amendment requests, and evaluations of notices of enforcement discretion, operational events (e.g., Management Directive 8.3, “NRC Incident Investigation Program” [7], The Accident Sequence Precursor Program, and inspection findings (i.e., IMC 0609, “The Significance Determination Process” [36]). IDHEAS-ECA is intended to apply to the same situations modeled by existing HRA methods (e.g., nuclear power plant internal events while at-power) and beyond (e.g., external events, low power and shutdown events, and events for which FLEX equipment is used). This report replaces Research Information Letter 2020-02.

ACKNOWLEDGMENTS

The authors of IDHEAS-ECA are thankful for the feedback provided by different reviewers and users inside and outside the U.S. Nuclear Regulatory Commission.

Specifically, the authors are grateful to John Stetkar for his in-depth review and comments on Research Information Letter 2020-02.

The authors acknowledge and appreciate the efforts of Michelle Kichline, Christopher Hunter, and Song-Hua Shen in performing a peer review. The results of the peer review were timely and improved this report.

The authors appreciate Qin Pan's assistance in preparing one of the examples (Appendix F) demonstrating the use of the IDHEAS-ECA human reliability analysis method.

Finally, the authors thank the external stakeholders who provided helpful comments on https://www.regulations.gov under the Docket ID NRC-2021-0089.

ABBREVIATIONS AND ACRONYMS

ADAMS	Agencywide Documents Access and Management System
AFW	auxiliary feedwater
ASP	accident sequence precursor (program)
BUGS	Bayesian inference Using Gibbs Sampling
CCP	centrifugal charging pump
cdf	cumulative distribution function
CFM	cognitive failure mode
CT	critical task
D	*detection* (one of the five macrocognitive functions)
DM	*decisionmaking* (one of the five macrocognitive functions)
E	*action execution* (one of the five macrocognitive functions)
ECCS	emergency core cooling system
EOC	error of commission
EOO	error of omission
EOP	emergency operating procedure
FLEX	flexible and coping strategies
HEP	human error probability
HFE	human failure event
HRA	human reliability analysis
HSI	human-system interface
IDHEAS	Integrated Human Event Analysis System
IDHEAS-DATA	Human Error Data Generalized with Integrated Human Event Analysis System
IDHEAS-ECA	Integrated Human Event Analysis System for Event and Condition Assessment
IDHEAS-G	General Methodology of an Integrated Human Event Analysis System
I&C	instrumentation and control
LOCA	loss-of-coolant accident
MCR	main control room
MFW	main feedwater
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
PIF	performance-influencing factor
PNNL	Pacific Northwest National Laboratory
PORV	power-operated relief valve

PRA	probabilistic risk assessment
psig	pounds per square inch gauge
PZR	pressurizer
RCP	reactor coolant pump
RCS	reactor coolant system
RHR	residual heat removal
RIL	research information letter
RO	reactor operator
RPV	reactor pressure vessel
RWST	refueling water storage tank
SACADA	Scenario Authoring, Characterization, and Debriefing Application
SAT	systematic approach to training
SDP	significance determination process
SG	steam generator
SI	safety injection
SLOCA	small loss-of-coolant accident
SPAR	standardized plant analysis risk
SSCs	structures, systems, and components
T	*interteam coordination* (one of the five macrocognitive functions)
U	*understanding* (one of the five macrocognitive functions)
P_c	error probability due to CFMs
P_t	error probability due to variability in T_{avail} and T_{reqd}
T_{avail}	time available
T_{reqd}	time required

1 INTRODUCTION TO IDHEAS-ECA

1.1 Intended Use

The human reliability analysis (HRA) method presented in this report is based on the General Methodology of an Integrated Human Event Analysis System (IDHEAS-G). Details about IDHEAS-G can be found in NUREG-2198 [1]. The method is intended to be used in HRA applications within a probabilistic risk assessment (PRA) for a nuclear power plant (NPP) or any safety assessments of an engineering system in which humans have a role. The method is referred to as the Integrated Human Event Analysis System for Event and Condition Assessment (IDHEAS-ECA). This report replaces Research Information Letter (RIL) 2020-02.

1.2 Scope of Application

The U.S. Nuclear Regulatory Commission (NRC) finds the IDHEAS-ECA HRA method acceptable for use to support risk-informed applications where the PRA model used to support regulatory decisionmaking is intended to be consistent with Regulatory Guides 1.200 [5] and 1.247 [6]. IDHEAS-ECA supports PRA and safety assessment applications by analyzing human events and estimating human error probabilities (HEPs). The application scope of IDHEAS-ECA is broad because the performance-influencing factor (PIF) structure (see Section 2.3), which models the context of a human failure event (HFE), is comprehensive. The method covers all the PIFs in PRA standards [8], [9], existing HRA methods, and the factors reported in the broad literature and nuclear-specific human events.

IDHEAS-ECA is cognition centered, technology neutral, and applicable to all the NRC's HRA applications; for example, PRA, integrated safety analysis, spent fuel handling, nuclear material users, and nuclear medicine. For PRA applications, the scope includes:

- Level 1 and Level 2 PRA
- Internal and external hazards
- At-power, low power and shutdown operations
- Conventional (analog) and digital control rooms
- Control room and field actions
- Actions with installed components and portable equipment
- Base (or baseline) PRA development
- License amendment request reviews
- Significance determination process (SDP) evaluations
- Notice of Enforcement Discretion evaluations
- Accident Sequence Precursor (ASP) program
- Pre-initiator, at-initiator, and post-initiator human failure events (operator actions)

Integrated safety analysis applications include fuel cycle facilities subject to the requirements of Subpart H, “Additional Requirements for Certain Licensees Authorized To Possess a Critical Mass of Special Nuclear Material,” to Title 10 of the *Code of Federal Regulations* Part 70, “Domestic Licensing of Special Nuclear Material.”

1.3 Intended Users

The intended users of IDHEAS-ECA include, but are not limited to, NRC staff working on risk-informed regulatory applications. Specifically, intended users are expected to be familiar with probability, statistics, and the system being analyzed and its interaction with humans.

1.4 Available Tools for Using IDHEAS-ECA

To facilitate using IDHEAS-ECA, the NRC staff developed the following:

a. a worksheet (see Appendix A) that allows the documentation of the IDHEAS-ECA process, which supports the calculation of the HEP estimates
b. a software tool that, based on user inputs consistent with the results documented in the worksheet, calculates the HEP estimates

1.5 Related Documents

The reports discussed in this section provide additional information for using IDHEAS-ECA.

The NRC report NUREG-2198 [1] documents the IDHEAS general methodology (IDHEAS-G) and detailed guidance for performing each analysis step. It is highly recommended that analysts use this report along with the guidance in IDHEAS-G. IDHEAS-ECA is developed from IDHEAS-G. Both have the same eight-step process, and the qualitative analysis is the same. Thus, the specific guidance on various steps in the IDHEAS-G appendices also applies to IDHEAS-ECA. Table 1-1 lists the specific guidance in the IDHEAS-G appendices and the corresponding steps in IDHEAS-ECA.

Table 1-1 IDHEAS-G Guidance and Corresponding, Applicable IDHEAS-ECA Steps

IDHEAS-G Guidance	Applicable IDHEAS-ECA Step
Appendix E, Scenario Analysis Appendix F, Identification and Definition of Important Human Actions	Step 1: Scenario Analysis • Develop scenario narrative • Develop scenario context • Identify and define HFE
Appendix G, Task Analysis	Step 2: Analyze an HFE and identify critical task(s) in the HFE
Appendix H, Identification of Cognitive Failure Modes	Step 3: Characterize the critical task(s) and select applicable cognitive failure modes (CFMs)
Appendix I, Assessment of Performance Influencing Factors	Step 4: Assess PIFs applicable to every CFM
Section 4.4.1, Overview of Human Error Probability Estimation in IDHEAS-G Section 4.4.3.2, IDHEAS-G Human Error Probability Quantification Model	Step 5: Calculate P_c

Table 1-1 IDHEAS-G Guidance and Corresponding, Applicable IDHEAS-ECA Steps

IDHEAS-G Guidance	Applicable IDHEAS-ECA Step
Section 4.4.1, Overview of Human Error Probability Estimation in IDHEAS-G Chapter 5, Time Uncertainty Analysis	Step 6: Calculate P_t • Estimate parameters of the T_{avail} and T_{reqd} distributions
Section 4.4.1, Overview of Human Error Probability Estimation in IDHEAS-G	Step 7: Calculate overall HEP
Appendix K, IDHEAS-G Treatment of Dependency Between Human Failure Events Appendix L, Uncertainty Analysis and Documentation	Step 8: Uncertainty, sensitivity, and dependency analysis and documentation

The NRC report "Generalizing Human Error Data for a Human Reliability Analysis Database (IDHEAS-DATA)" (to be published as NUREG-2257) explains the method and process to generalize various human error data into IDHEAS CFMs and PIF attributes and documents the data in a database referred to as IDHEAS-DATA. The report also demonstrates how to integrate generalized human error data to support HEP quantification in IDHEAS-ECA. The NRC report "Human Error Data Generalized in the Integrated Human Event Analysis System (IDHEAS-DATA)" (to be published as a RIL) presents the human error database IDHEAS-DATA. The base HEPs and PIF attribute weights used in IDHEAS-ECA (as presented in Appendix B) are integrated from the human error data in IDHEAS-DATA. The report helps to understand the data basis for calculating HEPs with IDHEAS-ECA. The NRC report "Verification and Documentation of Human Error Data Generalized in the Database IDHEAS-DATA" (to be published as a RIL) presents the verification of the data generalized in IDHEAS-DATA and documents the evaluation of the original data sources in the IDHEAS framework. The documentation of the original data sources also would help analysts to understand the CFMs in various tasks and PIF attributes in various operational contexts.

The NRC report RIL 2021-14 (IDHEAS-DEP) [4] presents guidance for using the IDHEAS dependency model along with IDHEAS-ECA to perform HRA dependency analysis. The guidance is also incorporated in the IDHEAS-ECA software. The IDHEAS-DEP report will be updated and published as NUREG-2258.

The NRC report "Integrated Human Event Analysis System Time Uncertainty Analysis Guidance (IDHEAS-TIME)" (to be published as NUREG-2259) presents guidance for using the IDHEAS time uncertainty model to calculate HEPs due to the time required to perform a human action being greater than the time available. NUREG-2259, in particular, would present the technical basis and guidance on how to estimate and adjust the time distributions under different contexts.

The NRC report "Integrated Human Event Analysis System Human Action Recovery Analysis Guidance (IDHEAS-REC)" (to be published as NUREG-2260) presents guidance on evaluating the potential recovery from human errors made in performing an action and quantifying the effect of human error recovery on the HEP of the human action. IDHEAS-ECA calculates HEPs using the HEP quantification model to which HRA analysts can assign a recovery factor. NUREG-2260 would provide guidance on how to determine the recovery factor.

1.6 Organization of This Report

This report is organized as follows:

- Chapter 1 is an introduction to IDHEAS-ECA.
- Chapter 2 introduces the basic concepts of IDHEAS-ECA. It is intended to give the HRA analysts an overview and to help them build the mental model of IDHEAS-ECA without diving into the details. The limitation of Chapter 2 is that some concepts introduced will become clear to the readers only after they read how the concepts are used in the IDHEAS-ECA process for conducting an HRA described in Chapter 3.
- Chapter 3 is the step-by-step guidance for the IDHEAS-ECA process. The guidance focuses on what needs to be done for each IDHEAS-ECA step and how to perform each step. The guidance does not describe the technical basis of the method. The technical basis is described in IDHEAS-G [1].
- Chapter 4 discusses the method and provides concluding remarks, including areas for future improvement.
- Chapter 5 lists the references used in this report.
- Appendix A contains the worksheet for analysts to document the results of their step-by-step analysis.
- Appendix B has 15 tables containing the base HEPs and PIF weights needed to calculate HEPs.
- Appendix C presents an approach to calculate probability distribution parameters.
- Appendix D introduces the IDHEAS-ECA software.
- Appendix E and Appendix F provide full examples demonstrating the IDHEAS-ECA process and documentation of the results.

2 IDHEAS-ECA BASICS

2.1 Overview of the Cognition Model for IDHEAS-ECA

IDHEAS-ECA uses the cognition model in IDHEAS-G, which consists of a cognitive basis structure (or macrocognition model) and a PIF structure. An HFE is analyzed for the given scenario context, which are the conditions that affect human performance. IDHEAS-ECA uses the five macrocognitive functions in the cognitive basis structure to model the failure of critical tasks in an HFE, and it uses the 20 PIFs in IDHEAS-G to model the context. Figure 2-1 outlines an overview of the cognitive basis for IDHEAS-ECA. This chapter will briefly describe the cognition model, Chapters 2 and 3 of NUREG-2198 [1] present the details.

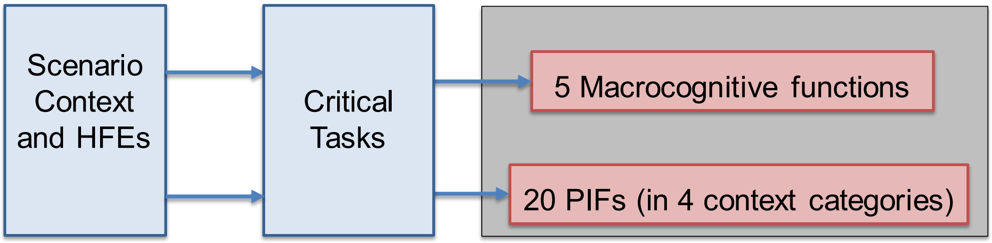


Figure 2-1 Overview of the Cognitive Basis for IDHEAS-ECA

2.2 Overview of the Macrocognition Model for IDHEAS-ECA

Figure 2-2 shows the IDHEAS-ECA hierarchy for modeling human actions in a scenario. The method identifies HFEs in the scenario and subsequently identifies critical tasks in an HFE. The failure of a critical task is modeled with the failure of the five macrocognitive functions in the IDHEAS-G cognitive basis structure. Several terms used in the IDHEAS-ECA hierarchy for modeling human actions in a scenario are defined below.

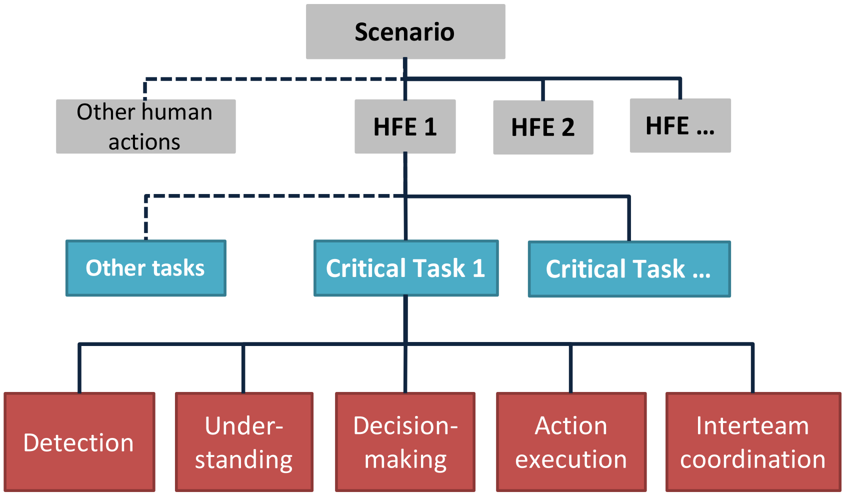


Figure 2-2 IDHEAS-ECA Hierarchy for Modeling a Human Event

Critical task—The human action defined in an HFE may be decomposed into a set of discrete tasks for modeling. A "critical task" is essential to the success of the human action; failure of any critical task in a human action will result in the occurrence of the HFE. The critical tasks are the ones for which the HEPs will be calculated.

Cognitive activities and Macrocognitive functions—Any critical task involves performing cognitive activities, which demand brain resources. IDHEAS-ECA models the cognitive demands of a critical task using five macrocognitive functions, which are the high-level brain functions that must be successfully accomplished to achieve the cognitive activities demanded by a critical task. IDHEAS-ECA uses the following macrocognitive functions:

- *Detection* (D) is noticing cues or gathering information in the work environment.
- *Understanding* (U) is the integration of pieces of information with a person's mental model to make sense of the scenario or situation.
- *Decisionmaking* (DM) includes selecting strategies, planning, adapting plans, evaluating options, and making judgments on qualitative information or quantitative parameters.
- *Action execution* (E) is the implementation of the decision or plan to change some physical component or system.
- *Interteam coordination* (T) focuses on how various teams interact and collaborate on a critical task.

The first four macrocognitive functions (D, U, DM, and E) may be performed by an individual or a team, and *interteam coordination* is performed by multiple groups or teams. The interteam coordination macrocognitive function addresses only interactions between teams of personnel (e.g., between the main control room (MCR) crew and local operators). It models interteam collaborative activities including cooperation, coordination, and communication. This function focuses on how the various distributed entities collaboratively carry out a mission. Interteam coordination does not address interactions among individuals within a team (e.g., among supervisors and operators of the MCR crew) to perform an action. Within-team interaction is a part of the *detection*, *understanding*, *decisionmaking*, and *action execution* macrocognitive functions. Each individual macrocognitive function may involve within-team collaboration through information sharing, supervision, and peer checking. For example, information sharing among members of a team can help individuals form the correct mental model for a cue or information to be detected, especially in unfamiliar scenarios or environments. Peer checking and supervision are also important for verifying the outcomes of *detection* so that errors can be noticed and corrected.

Cognitive failure modes—IDHEAS-ECA provides a set of five cognitive failure modes (CFMs) to model failure of a critical task. Each CFM represents the failure of a macrocognitive function demanded to accomplish the critical task. The five CFMs are defined as follows:

- CFM1 – failure of *detection*
- CFM2 – failure of *understanding*
- CFM3 – failure of *decisionmaking*
- CFM4 – failure of *action execution*
- CFM5 – failure of *interteam coordination*

Some HRA methods classify human failure as cognition failure, or action or execution failure. In that sense, the failure of *detection* (CFM1), failure of *understanding* (CFM2), and failure of *decisionmaking* (CFM3) in IDHEAS-ECA are equivalent to "cognition failure," and the failure of *action execution* (CFM4) is equivalent to "action execution failure" in other HRA methods. Existing HRA methods do not explicitly model the failure of *interteam coordination* (CFM5).

Probability of an HFE—The probability of an HFE, P (i.e., the overall HEP), has two parts, P_c *and* P_t and is calculated as $P = 1 - (1 - P_c)(1 - P_t)$. P_c is the HEP attributing to cognitive failures assuming that the time available for performing the human action of the HFE is adequate. P_c is calculated as the probabilistic sum of the HEPs of the CFMs of all the critical tasks in an HFE. P_t is the HEP attributing to the uncertainty in the time available and time required to perform an action. It is calculated as the convolution of the probability distributions of time available and time required.

2.3 Overview of the Performance Influencing Factor Structure for IDHEAS-ECA

The IDHEAS-ECA HRA process begins by analyzing a scenario and searching for the context that challenges or facilitates human performance. The method provides a PIF structure composed of the following: (1) PIF category, (2) PIFs, and (3) PIF attributes. The method uses 20 PIFs and the associated attributes to model the scenario context. Several terms related to the IDHEAS-ECA PIF structure are defined below.

Scenario context and PIF category—The context of a scenario are the conditions that challenge or facilitate human performance. Scenario context is documented in four categories: *environment and situation*, *system*, *personnel*, and *task*, which are described as follows:

(1) Environment and situation context—This consists of conditions in the personnel's work environment and the situation in which actions are performed. It includes the weather, radiation or chemicals in the workplace, and any extreme operating conditions.

(2) System context—Systems are the objects of the HFEs, through which the actions are achieved. Systems include operational systems, supporting systems, instrumentation and control (I&C), physical structures, human-system interface (HSI), and equipment and tools.

(3) Personnel context—Personnel are the people who perform the action and include individuals, teams, and organizations. The personnel context describes who the personnel are; their qualifications, skills, knowledge, abilities, and fitness to perform the action; how they work together; and the organizational measures that help personnel work effectively.

(4) Task context—The task context describes the cognitive and physical task demands for personnel and special conditions in the scenario that make tasks difficult to perform. An action may consist of one or more discrete tasks.

PIFs—Once the context of an event is identified, the context can be modeled with the PIFs. IDHEAS-ECA has 20 PIFs in the four context categories shown in Table 2-1. This list of PIFs covers all PIFs in the reviewed HRA methods and factors reported in the literature and nuclear-specific human event databases. Table 2-2, Table 2-3, Table 2-4, and Table 2-5, respectively, summarize all the PIFs in each of the context categories.

PIF attribute—A PIF attribute is an assessable characteristic of a PIF and describes a way the PIF increases the likelihood of error in the macrocognitive functions. A PIF is characterized with a set of attributes, each describing one aspect of the PIF that challenges the macrocognitive functions demanded by a critical task. For example, one of the attributes of the PIF *human-*

system interface is the salience of indicators. Therefore, HEP estimation of a CFM is based on the assessment of PIF attributes applicable to the CFM. The PIF attributes were identified from cognitive and behavioral studies, as well as human error data from various sources. PIF attributes have the capability to link to existing human error data for HEP quantification. Appendix B lists the attributes for all the PIFs.

Table 2-1 PIFs in IDHEAS-ECA

Environment and situation	System	Personnel	Task
• Work location accessibility and habitability • Workplace visibility • Noise in workplace and communication pathways • Cold/heat/humidity • Resistance to physical movement	• System and I&C transparency to personnel • Human-system interfaces • Equipment and tools	• Staffing • Procedures, guidelines, and instructions • Training • Teamwork and organizational factors • Work processes	• Information availability and reliability • Scenario familiarity • Multitasking, interruption, and distraction • Task complexity • Mental fatigue • Time pressure and stress • Physical demands

Table 2-2 Environment- and Situation-Related PIFs

PIF	Description
Work location accessibility and habitability	This PIF models the accessibility to and habitability of workplaces where critical tasks are performed. Workplaces that become inaccessible or uninhabitable negatively affect personnel performance of the critical tasks.
Workplace visibility	This PIF models the visibility in the workplace. Limited visibility may affect personnel performance of critical tasks.
Noise in workplace and communication pathways	This PIF models the ways noise affects communication of information required for critical tasks. Excessive noise can negatively affect the communication of information required to perform a critical task.
Cold/heat/humidity	This PIF models cold, heat, and humidity with respect to the performance of critical tasks. Extreme cold or heat and high humidity may affect personnel performance of critical tasks.
Resistance to physical movement	This PIF models the ways resistance to movement affects the performance of critical tasks. Required protective clothes, obstructions, and slippery surfaces may negatively affect movement needed to perform critical tasks.

Table 2-3 System-Related PIFs

PIF	Description
System and I&C transparency to personnel	This PIF models the impact of the design logic of systems and I&C on human performance. If the operation of the system or I&C is not transparent to personnel, or personnel are unclear about system interdependency, they can make errors because of not understanding the systems in unusual scenarios.
Human-system interface	This PIF models the impact of the HSI on human performance. Poorly designed HSIs can impede task performance in unusual event scenarios. Even a well-designed HSI may not support human performance in specific scenarios that designers or operational personnel did not anticipate. HSIs may also become unavailable or unreliable in hazardous scenarios.
Equipment and tools	This PIF models the availability and usability of equipment (including parts and portable equipment) and tools that are needed for the performance of critical tasks.

Table 2-4 Personnel-Related PIFs

PIF	Description
Staffing	This PIF models that there is adequate and qualified staff to perform the required critical tasks. This includes the number of personnel, their skill sets, job qualifications (including fitness for duty), and staffing structure (individual and team roles and responsibilities).
Procedures, guidelines, and instructions	This PIF models the availability and usefulness of operating procedures, guidance, and instructions. Following procedures should lead to the success of the critical task. However, there may be situations in which procedures give incorrect or inadequate guidance or may not apply to the scenario.
Training	This PIF models the training that personnel receive to perform critical tasks. Included in this consideration are personnel's work-related experience and whether they have been trained on the type of the event, the amount of time passed since training, and training on the specific systems involved in the event. However, training may not address all possible event scenarios.
Teamwork and organizational factors	This PIF models everything affecting team communication, coordination, and cooperation.
Work processes	This PIF models the aspects of doing work, supervision, management support, policies, and safety-conscious work environment at the organizational level.

Table 2-5 Task-Related PIFs

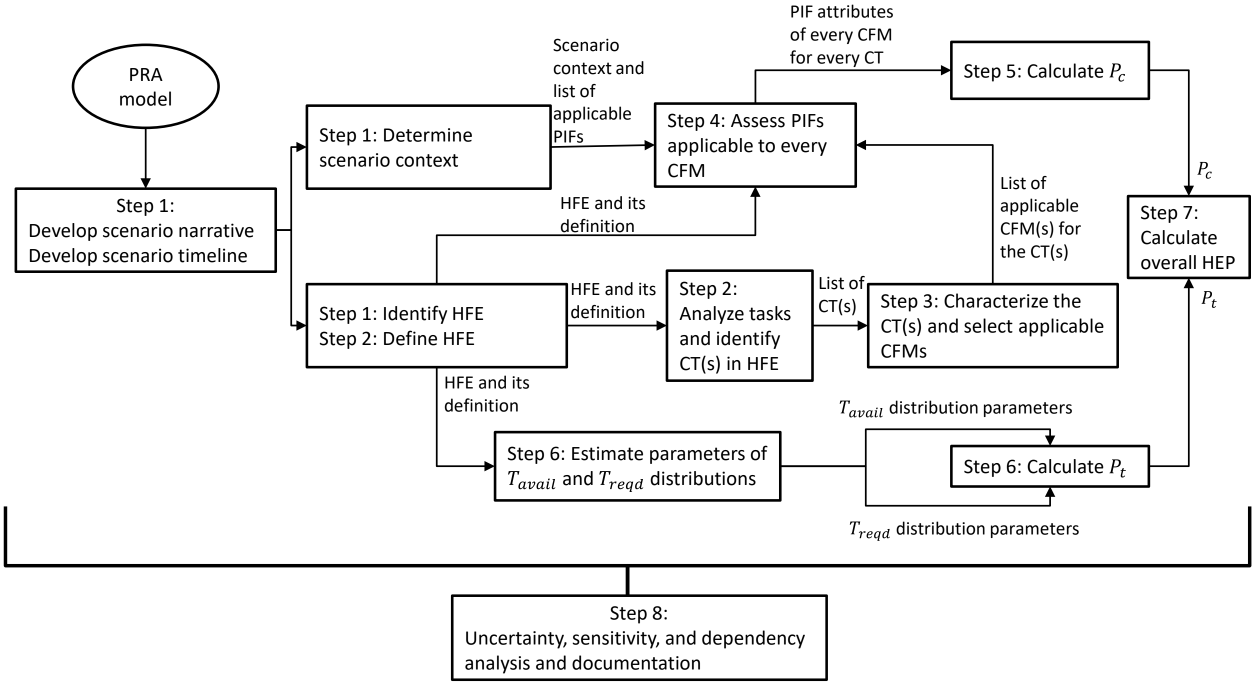
PIF	Description
Information availability and reliability	This PIF is one of the three base PIFs and models whether the information needed for personnel to perform critical tasks is available to be perceived. If the information is perceived, this PIF also models whether that information is reliable and perceived in a timely manner. Cues and instrumentation readings are of interest in the modeling of this PIF.
Scenario familiarity	This PIF is one of the three base PIFs and models the challenges to personnel in understanding the situation and making decisions. If the scenario is familiar, personnel are more likely to understand what is happening. In unfamiliar scenarios, personnel are more likely to perform situation-specific actions not identified in the procedures.
Multitasking, interruption, and distraction	This PIF models performing concurrent and intermingled critical tasks and things that interfere with personnel's performance of their critical tasks. Multitasking requires switching between critical tasks, and interruption and distraction keep personnel away from performing the tasks, which can make errors more likely.
Task complexity	This PIF is one of the three base PIFs and models the task demand for cognitive resources (e.g., working memory, attention, executive control). The task complexity has two parts: (1) the complexity in processing the information to achieve the macrocognitive functions of the critical task and (2) the complexity in developing and representing the outcomes to meet the task criteria. Complexity is characterized by the quantity, variety, and relation of the items to be processed or represented in a critical task.
Mental fatigue	This PIF models the personnel's vigilance and abilities to perform complex cognitive tasks. Mental fatigue can result from performing a task for an extended period of time, nonroutine tasks, and cognitively demanding tasks. Mental fatigue leads to loss of vigilance, difficulty in maintaining attention, reduced working memory capacity, and use of shortcuts in diagnosing problems or making decisions.
Time pressure and stress	This PIF models the personnel's sense of time urgency to complete a task. Because time pressure is based on personnel's perception and understanding of the situation, it may not reflect the actual situation. Other stresses and anxieties, such as concern for families in emergency conditions, fear of potential consequences of the event, and worrying about personal safety, can also increase the level of psychological stress and affect performance.
Physical demands	This PIF models required extraordinary physical efforts, such as twisting, reaching, dexterity, or strong force to complete a critical task.

3 GUIDANCE FOR THE IDHEAS-ECA HUMAN RELIABILITY ANALYSIS PROCESS

The HRA process with IDHEAS-ECA has eight steps, which are briefly described below. The steps are described in more detail in the following subsections. Figure 3-1 presents an overview of the IDHEAS-ECA HRA process and the flow of information. Each box represents a to-do item of a step in the process. The arrows represent the input(s) and output(s) from each of the items. To perform a step, all the inputs (information) for the step need to be available.

- Step 1: Analyze the event scenario. Analyzing an event includes developing the scenario narrative, determining the scenario context, and identifying the HFEs to be modeled (if not given in the PRA model).
- Step 2: Analyze the HFE. This includes defining the HFE, including its timeline; analyzing the tasks in the HFE; and identifying critical tasks for HEP quantification.
- Step 3: Model the failure of the critical tasks in an HFE. This includes characterizing the critical task(s), identifying cognitive activities required to achieve the critical task(s), and subsequently identifying CFMs applicable to the critical task(s).
- Step 4: Assess the PIFs applicable to every CFM. This step uses the results of the scenario context (Step 1), HFE definition (Step 2), and task characterization (Step 3) to select the applicable PIF attributes for every CFM.
- Step 5: Calculate P_c of an HFE. P_c is the HEP attributing to CFMs and is calculated as the probabilistic sum of the probabilities of all the CFMs of the critical tasks. The probability of the CFMs and P_c can be computed using the IDHEAS-ECA software or calculated manually using the data in Appendix B.
- Step 6: Calculate P_t of an HFE. P_t is the HEP attributing to the uncertainty in time available and time required to perform the human action and can be computed with the IDHEAS-ECA software or any general-purpose computation software.
- Step 7: Calculate the overall HEP. The overall HEP is the probabilistic sum of P_c and P_t. That is, $Overall\ HEP = 1 - (1 - P_c)(1 - P_t)$.
- Step 8: Analyze uncertainties in the HRA, perform sensitivity and dependency analyses, and document the results.

Steps 1 through 4 in Figure 3-1 form the qualitative analysis in the HRA. The qualitative analysis provides the understanding of what happens in the scenario, what human actions are needed, what can go wrong, and what challenges human performance. These steps are the fundamentals of an HRA. All the guidance on these four steps in IDHEAS-G applies to the same steps in IDHEAS-ECA. Steps 5, 6, and 7 in Figure 3-1 form the quantitative analysis in the HRA or the HEP quantification. These steps can be performed with the IDHEAS-ECA software to assist the analysts in performing the calculations. Yet, it is essential that HRA analysts perform the qualitative analysis in Steps 1 through 4 and document the analysis in the IDHEAS-ECA Worksheet (in Appendix A). Only after completing the systematic qualitative analysis following the guidance from Step 1 to Step 4 may analysts enter the results into the IDHEAS-ECA software to calculate the HEP. Without a systematic analysis, the selections of applicable CFMs and PIF attributes may underrepresent the context challenges to human performance, which can underestimate the risk; misrepresent the context with the wrong CFMs and PIF attributes; or double count the impact of a certain context. Any of these introduces analyst-to-analyst variability in the HRA results.



CFM = cognitive failure mode
CT = critical task
HEP = human error probability
HFE = human failure event
PIF = performance-influencing factor
PRA = probabilistic risk assessment
P_c = error probability due to CFMs
P_t = error probability due to uncertainty in T_{avail} and T_{reqd}
T_{avail} = time available
T_{reqd} = time required

Figure 3-1 Overview of the IDHEAS-ECA HRA Process

The subsections first present a brief overview of the step (i.e., the what), followed by where the information obtained from that step is documented in Appendix A, and ending with guidance on how to perform the step.

3.1 Step 1 – Scenario Analysis

The purpose of this step is to understand human performance in the event and collect information for quantification. This step includes developing operational narratives, identifying HFEs, and assessing the scenario/event context that affects human performance and HFEs in the scenario. The information obtained and generated from the analysis of Step 1 can be documented in Appendix A.

A human performance model may be initially sketched to serve as a framework to develop the operational narrative (Section 3.1.1) and assess the scenario context (Section 3.1.3). A human performance model for an HRA scenario consists of the following elements:

1) The goal of the scenario — HRA focuses on safety; therefore, the goal of a scenario must relate to safety. For NPP events, the mission is to safely operate the plant or mitigate an unsafe condition in the plant. Specifically, the goal is to protect the fuel cladding, reactor coolant system (RCS), and containment.

2) The objectives and functions — The objectives represent the desired outcomes of the scenario in achieving the goal. Examples of the objectives in NPP operation are restoring electrical power, initiating feed and bleed, and evacuating personnel. To achieve the objectives, a set of functions must be performed. Systems, personnel, or a combination of both could perform the functions.

3) The systems — IDHEAS-ECA uses the term “systems” to broadly refer to structures, systems, and components (SSCs), as well as sensors, equipment, I&C, and HSIs. Systems are all the aspects that are necessary to achieve the objectives.

4) The personnel — Personnel include all the people who perform the tasks in an event. Personnel may work in various structures: (a) as individuals with roles, responsibilities, and tasks; (b) as teams working collaboratively for common goals; and (c) as an organization, which is a framework to outline authority and communication processes of individuals and teams. Generally, a team is a group of people who perform interdependent tasks to work toward accomplishing a common task objective. In NPPs, teams make up main control rooms (MCR) operation. The MCR crew is considered a team. On the other hand, operators in the control room and operators in the field are generally not considered as a single team because field operators may have task objectives independent of those for control room operators.

3.1.1 Develop the Operational Narrative

The operational narrative provides a detailed account of the scenario, which includes a scenario narrative and a scenario timeline. The scenario narrative is a storytelling-style representation that specifies the initial conditions, initiating event, boundary conditions of the event, and the scenario progression and end state. The initial conditions describe the beginning status of systems and personnel that have implications for the scenario progression, which are generally defined by the PRA. The initiating event originates from an internal or external hazard and causes abnormalities, which may require automatic system interventions, human interventions, or both, to achieve a safe end state. The boundary conditions describe the expected systems, site, and personnel status immediately after the initiating event and specify the scope and the assumptions applied to the HRA. The scenario progression describes the expected system and personnel responses and end state (or consequence). The scenario timeline documents the system responses and HFEs in chronological order and records the timing of system status changes and the cues for the HFEs. Figure 3-2 shows the composition of the operational narrative.

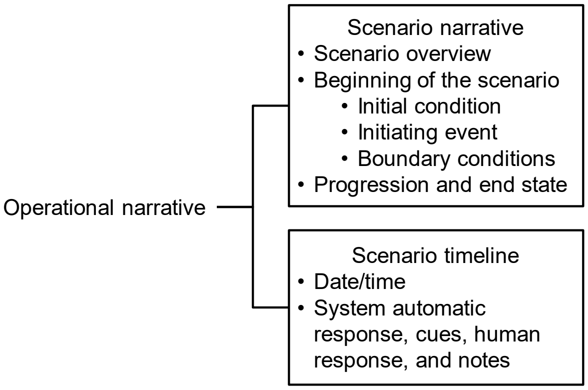


Figure 3-2 Composition of the Operational Narrative

For the purposes of IDHEAS-ECA, the operational narrative (scenario narrative and scenario timeline) should be developed by reviewing the PRA (i.e., the event tree where the HFE is being credited) and all the available documents related to the event. The operational narrative should be documented in Step 1.1 of Appendix A.

Guidance for Developing the Scenario Narrative

The scenario narrative should first provide an overview of the scenario and highlight the safety considerations of the scenario. At a high level, the scenario narrative covers the beginning of the scenario, the scenario progression, and the end state (or consequence).

Scenario Overview: The scenario overview documentation includes a title and a scenario summary. The title should be descriptive and provide a clue for the readers to predict the content. Therefore, the title should highlight the key safety considerations and consequence. The scenario summary should cover when, where, and how the event occurred; the safety considerations; how the safety considerations were mitigated; and the consequence.

Beginning of the Scenario: The beginning of the scenario includes the initial condition, initiating event, and boundary conditions.

Initial Condition — The initial condition describes the initial system and human conditions that have implications for the scenario progression and safety. The discussion should include information about the environment, system, personnel, and task contexts. Important aspects that should be identified include the following:

- SSCs with latent failures, that are unavailable (tagged out), or have historically unreliable performance (especially the ones that would affect the operator’s decisions and the scenario)
- the facility operating modes (e.g., at-power, low-power, and shutdown)
- special or temporary system alignment
- workers not in their normal locations
- operating team not in normal configuration (e.g., temporarily having one individual performing dual responsibilities for a missing team member)
- personnel substitution (e.g., temporary substitution of the individual familiar with the tasks by another individual who does not normally perform the tasks is likely to affect human performance)
- other ongoing activities performed at the same time of the initiating event that can affect the scenario

Initiating Event — An initiating event could be triggered by a system failure or a human error. The initiating event narrative should be described at a level of specificity such that knowledgeable readers conversant with the design of the facilities in general, but not familiar with the details of the specific facility, can generally understand the scenario (e.g., a small loss-of-coolant accident (LOCA) at a hot leg, a loss of offsite power event due to grid failure, and the loss of an essential electric bus causing reactor trip due to human error in maintenance).

Boundary Conditions — The boundary conditions specify the analysis scope and the assumptions applied to the analysis. This could include limiting the analysis scope to focus on the primary considerations and to make simplified assumptions such as deterministic assumptions about the status of systems (e.g., damage associated with the initiating event) and personnel (e.g., personnel availability).

Scenario Progression and End State: The scenario progression documents the scenario development following the given initial condition, initiating event, and boundary conditions. The scenario progression should be documented from the eyes of the human in the scenario. HRA analysts need to understand the mindset of the operators in different steps of the scenario (e.g., their view of the situation, task priorities, concerns, and locations). The scenario progression should describe the safety consideration and the responses of systems and humans to the safety consideration. At a high level, these responses can be summarized using an analogy to the following macrocognitive functions:

- cues for *detection*
- diagnostic Information for *understanding* and *decisionmaking*
- physical actions for *action execution*
- interteam interaction for *interteam coordination*

The cues are the information that attracts the attention of the human for *detection* and triggers a person's cognitive process. The diagnostic information required to make a diagnosis and define the situation awareness is part of *understanding*. *Decisionmaking* refers to making a decision based on the situation and diagnosis. *Action execution* refers to the tasks required to implement the decision. For each of the bullets above, the scenario progression from the environment, system, personnel, and task contexts should be described. Table 3-1 provides guidelines for the content of the scenario progression.

Table 3-1 Narrative Information Coverage of a Scenario Analysis

Safety consideration: - What are the consequences? - What are the system functions and human actions needed to prevent the consequences from happening given the initiating events and boundary conditions? - What is the consequence's safety significance?
Cues: - What are the cues? - How are the cues generated? - What are the means to detect the cues?
Diagnosis and decisionmaking: - What is the information needed for diagnosis? - How are the diagnosis and decisionmaking performed? What are the bases and constraints of diagnosis and decisionmaking? - What is the information that could mislead the human to a wrong diagnosis?
Physical actions: - What are the automatic system responses to prevent the consequence from happening or to mitigate the severity of the consequence? - What are the manual actions needed to mitigate the safety consideration? How are the actions performed? What are the constraints of performing the actions?

Table 3-1 Narrative Information Coverage of a Scenario Analysis

Interteam coordination: - What kinds of communication, coordination, and collaboration among different entities are required? - What are the considerations that could have significant effects on team responses?

The description of the scenario progression should include the end state of the system after the successes and failures of the responses of systems and humans to the safety consideration.

Guidance for Developing the Scenario Timeline

The scenario timeline describes the scenario in chronological order. The documentation of the scenario timeline should use a two-column structure with the first column showing the date and time, and the second column showing all other information. It is recommended to add symbols in front of each statement in the second column to distinguish the type of information.

Column 1 — Date and Time: For predictive (hypothetical) event analysis, the initiating event occurs at time zero. For retrospective (actual) event analysis, the initiating event starts at the local date and time that the actual event occurred. The actual local date and time have hidden information for assessing human performance. For example, if an event happens on a Sunday night, it could imply a reduced staffing level. If incidents occurred before the initiating event, the incidents should be indicated in the timeline. In this case, these events are placed before the initiating event as part of the background information.

Column 2 — All Other Information — System automatic responses, cues, human responses, and notes: The information in the second column is classified into four types to improve the understanding of the human-system interactions. Each information type is denoted by a bold letter as described below:

- System automatic responses **(S)**: The "**S**" indicates that the information is a system automatic response based on the set points or logic of the automatic component actuations or that a system failed to perform its designed function. An example is "**S:** safety injection injected coolant into the RCS at 1,600 pounds per square inch gauge (psig)."
- Information needed for human responses **(I)**: The "**I**" indicates the information generated from a system or other source that is available for the human to diagnose the situation or make decisions. Examples are the alarms that trigger operator notification about a system abnormality.
- Human responses **(H)**: The "**H**" indicates important human cognitive activities that include detecting the cue, making a diagnosis, entering or exiting procedures, making decisions important to the scenario, and performing actions. The actions could be either physical interference with a system to change the scenario progression or the actions that should be performed but are not performed that allow safety degradation of the scenario. Each human response should include the task and the individual who performs the task. For example, a reactor operator's (RO) action can be denoted as **H(RO)**. If every crew member could perform the action, the action can be denoted as **H(Crew)**.

- Notes **(N)**: The “**N**” indicates background, explanatory, context, or supplemental information to the system automatic responses **(S)**, human response (**H**), and information **(I**). For example, an **H(RO)** is “depressurize the reactor pressure vessel (RPV) to a certain pressure range at a rate less than 100 °F/hr.” The **(N)** could be “the task takes about two hours by periodically manually opening and closing a safety relief valve” to provide additional information about the RO’s action to depressurize the RPV.

Realizing that constructing a detailed timeline is resource intensive and may be impractical to include all human activities, the analysis should be done at the proper level of detail that is technically justifiable to capture human actions that are important to the scenario.

3.1.2 Identify the Human Failure Events

The purpose of this part of Step 1 is to identify HFEs as the analysis units of an HRA and define them at a high level. PRAs provide the HFEs that need to be analyzed from the assumed basic scenario. Additional HFEs may be identified from potential deviations of the basic scenario. HFEs include pre-initiator, initiator, and post-initiator actions. PRAs explicitly identify, model, and quantify many pre-initiator human actions. Examples are errors that do not restore equipment to their normal alignments after maintenance and testing activities, and miscalibration of instrumentation. Real events, such as those analyzed by the SDP and ASP Program, may involve actions that are not included in the base PRA models. If that is the case, additional HFEs may be identified, defined, and analyzed.

For the purposes of IDHEAS-ECA, the identified HFEs should be documented in Step 1.2 of Appendix A.

Guidance for the Identification of Human Failure Events

As mentioned above, the PRA should already identify the HFEs that need to be analyzed from the assumed baseline scenario. If a new HFE needs to be identified to analyze a real event, the identification is based on how the real event deviated from the scenario modeled in the PRA. HFEs can be identified by searching for human actions in which there is an interaction of humans with mission-critical systems as well as noncritical systems.

While an existing PRA contains nominal ("baseline") HFEs for the desired personnel response, HRA analysts should conduct a critical assessment of those models and determine whether deviations from the specific modeled scenarios may contain conditions that have an important effect on human performance and, hence, require the definition and evaluation of additional HFEs (with corresponding changes to the event trees or fault trees). Therefore, identification of HFEs also involves the identification of alternative (or "deviation") scenarios that require modifications to the PRA event trees and fault trees and definitions of new HFEs. Those new HFEs may address the same functions that apply to the nominal (or "baseline") HFEs, but in a different scenario context. In some cases, the HRA process may also identify new HFEs that were not considered when the initial PRA models were developed. This search for alternative scenarios and the identification of new HFEs is an integral part of the HRA process and the development of a PRA model that appropriately accounts for human performance.

Manipulations of noncritical systems may impact mission-critical system functions and personnel performing key actions with mission-critical systems. Generally, HFEs are modeled as errors of omission (EOOs). However, the search process should also identify errors of commission (EOCs) that impact mission-critical system functions. With respect to EOCs, the following is a summary of the discussion in Section F.4 of NUREG-2198 [1]; NUREG-1624, Revision 1 [10]; and NUREG-1921 [11] regarding the identification of EOCs:

- The action directly disables the system, subsystem or component needed to provide the system function required in the scenario.
- There is a rational justification to indicate that the EOC is well-intentioned. The common situations are: (1) existence of competing goals, and (2) personnel cannot fully evaluate the consequences of the decided action, or personnel do not understand the systems and consequences of the decided action.
- The unintended (slips type) human errors have EOO and EOC considerations that need to be analyzed separately. For example, switching off the wrong pump because the pump switches are in close vicinity. First, the intended pump was not switched off (an EOO), and second, an unintended pump was switched off (an EOC). Whether the EOC should be explicitly modeled depends on the EOC's impact on the scenario. The EOC should be modeled explicitly if it has a cascading effect on the scenario course. If the EOC affects only the worker's performance (e.g., increased workload), then the EOC does not need to be explicitly modeled.

3.1.3 Identify the Scenario/Event Context

Identification of scenario context refers to the search for the conditions that challenge or facilitate human performance in the scenario. The process of searching for scenario context should focus on the conditions that can affect the macrocognitive functions and lead to undesirable consequences. Context affects human performance by impacting systems and personnel or mitigating the adverse effects of other conditions.

Identification of scenario context tends to initially focus on safety considerations of the scenario that are directly relevant to the particular scope and success criteria of the HFE being analyzed. That information is certainly very important. However, it does not necessarily capture all of the potentially important influences on human performance. HRA analysts should also search for those potentially important influences and document them in the narrative. For example, personnel may be distracted by failures or damage to nonsafety systems that are important for overall plant investment protection or are perceived to affect the stability of overall plant conditions but are not modeled explicitly in the PRA. In some scenarios that involve severe plant damage (e.g., fires, floods, seismic events), operators may also need to attend to treatment and relocation of personnel who are physically injured. These concerns introduce conflicting strategic and time priorities for decisionmakers and constraints on the assignment of limited personnel resources. Analysts should account for these types of diversions and distractions. It is essential that the integrated scenario narrative describe the entire context of the plant damage, and not focus only on systems and equipment that are modeled explicitly in the PRA, and the distinct human actions that are needed to cope with only those failures.

In principle, the scenario narrative should describe everything that is happening in the plant, because that is the actual context within which personnel must respond. Of course, that ideal can rarely be achieved in a practical analysis. However, the narrative should describe all conditions that may have a potentially important effect on human performance, even if those conditions are not included explicitly in the PRA models. That description helps in identifying and evaluating the states of relevant PIFs that account for distractions, interruptions, multitasking, conflicting priorities, time pressure, stress, and other factors. It also helps in understanding which conditions were considered by HRA analysts and finding the reasons for possible omissions.

Scenario context is documented in four categories: *environment and situation*, *system*, *personnel*, and *task*. The four context categories are not intended to represent an exhaustive classification system. Rather, they are intended to guide the search. Scenario context serves as the high-level guidance for defining and analyzing HFEs and provides a basis for estimating the HEPs in the scenario. In HEP estimation, the context is represented by the PIF attributes.

The NRC staff developed several probing questions and considerations to identify the context that can affect the macrocognitive functions in each of the context categories. The probing questions and considerations are provided below. HRA analysts may develop additional questions and considerations to probe the possible conditions that impact on human performance.

For the purposes of IDHEAS-ECA, the scenario context (identified using the probing questions and their answers) and the list of applicable PIFs should be documented in Step 1.3 of Appendix A. Table 2-2 through Table 2-5 list all the potentially applicable PIFs for each of the context categories, respectively.

Guidance for Assessing the Environment and Situation Context

The environment and situation context specifies the performance-challenging conditions in the personnel's work environment and the situation in which the HFEs are performed. It includes weather, radiation or chemical materials in the workplace, and any extreme operating conditions. Hazards such as steam, fire, toxic gas, seismic events, or flooding can introduce environmental conditions that impede personnel performance.

Questions for probing the environment and situation context that could affect human reliability are as follows:

- Where do personnel perform the actions? Are there environmental considerations adverse to the action reliability?
- Are there things affecting accessibility or habitability of the workplace, including travel paths?
- Does the workplace have good visibility needed for human actions?
- Is the noise in the workplace and the communication pathways expected to affect the reliability of completing the actions?
- Is the work environment very cold, hot, or humid?
- Is there resistance to personal or vehicle physical movement, such as strong wind or still or moving water?

Below are some considerations for the environment and situation context:

- Noise, smoke, and precipitation can affect information detection.

- Harsh environmental conditions, such as extreme heat or cold, may lead to early termination of situation assessment because personnel are unwilling to seek additional data to reconcile conflicts in the information.
- Harsh environmental conditions can adversely affect decisionmaking (e.g., reducing decisionmakers' ability and effort in evaluating available strategies, thoroughly deliberating decisions, or mentally simulating action plans).
- Environmental conditions on travel paths and at worksites can restrict personnel's motor movement, reduce their motor skills, or limit the time that they can steadily perform motor activities. Examples of these conditions are wearing heavy protective clothes, high water on travel paths, high winds, extreme heat or cold, earthquake aftershocks, and chemical or other toxic contamination.
- Environmental conditions such as noise or smoke can impede interteam collaboration.

Guidance for Assessing the System Context

The system context specifies the conditions affecting the systems needed to perform design functions that can subsequently lead to human failures. Identification of system context should focus on conditions that create conflicting priorities, confusion, and distractions to human performance.

Questions for probing the system context include the following:

- What are the consequence and the causes (e.g., core damage caused by a LOCA)?
- Which system automatic responses are expected to be actuated (e.g., reactor trip and safety injection actuation)?
- Which SSCs are needed to mitigate the event? What are the constraints on implementing their use?
- Which system and human responses are required to bring the system to a safe state or to mitigate the event? What are the set points for the automatic system responses?

Below are some considerations for the system context:

- Systems may become unavailable or behave abnormally due to accidents, incidents, hazards, maintenance, repairs, aging, or concurrent activities to protect workers or major equipment. For example, computer systems may become temporarily unavailable because of network congestion; some sensors of NPP systems may become unreliable as the result of an electric fault; or operational system components or equipment may be disabled because of problems in related systems (such as other reactor units in multi-unit NPPs).
- Electrical faults may reset systems or components to an undesirable status.
- The designed operational range of the SSC could be exceeded, and functions needed to support the component or instrument operation may be inadequate.
- Structures may have degraded environmental conditions or be inaccessible because of hazards or construction activities.

- Automated systems could be intentionally turned off based on the crew's a well-intentioned, but incorrect, belief.

Guidance for Assessing the Personnel Context

The personnel context specifies the conditions that challenge or facilitate humans (e.g., individuals, teams, or organizations) in performing the tasks. The context affects personnel's task performance in detecting information, understanding the situation, making decisions, executing planned actions, and interteam coordination.

Questions for probing the personnel context include the following:

- What is the command-and-control structure?
- What are the key concepts of operation (e.g., staffing, training, validation)?
- Are there perceived potential fitness-for-duty (fatigue, substance abuse, or illness) issues?
- What are the manpower and skill sets needed in the scenario?
- What are the potential considerations that could adversely affect teamwork and communication?

Below are some considerations for the personnel context:

- Availability of personnel—Consider the amount and types of personnel available to respond to the event relative to the personnel needed. Personnel may become unavailable for reasons such as multiple simultaneous events, environmental effects, or duties unrelated to the event.
- Operational limitations of personnel—Personnel may not perform work as expected for reasons such as physical limitations, not being prepared or trained for the type of events, or conformation to special safety or regulatory requirements.
- Organizations may not have adequate infrastructure to support teamwork for reasons such as safety culture, authorization restrictions, conflict of interest or goals, or lines of communications.
- Availability of personnel support—Personnel may lack necessary support such as training, tools, procedures or protocols, expertise due to reasons such as hazards, "surprise" of the event, beyond-design-basis accidents, lack of experience using the supporting items, and needs for sharing the limited supporting items.
- Environmental conditions (such as fire, smoke, flood, earthquake, noise, illumination, temperature extremes, and high radiation) that directly impact human performance may change during the evolution of the scenario.

Guidance for Assessing the Task Context

The task context specifies special conditions for tasks that need to be performed, how these tasks are expected to be performed, the demands of the tasks, and the success criteria of the tasks. The conditions may change which human tasks are required, the task requirements, or the task difficulty. Task difficulty refers to the demand for personnel cognitive resources and collaboration. The characterization of the human-system interactions and the conduct of operations specify how tasks should be performed. Some aspects such as burden and pace of the tasks may be better understood from the perspective of the conduct of operations and operational experience.

Questions for probing the task context include the following:

- What are the constraints on implementing the tasks?
- What is the potential task interference (e.g., sharing the same resource with the other concurrent tasks) and task dependency (e.g., tasks have to be performed in sequential order, such as obtaining external permission to perform the task)?
- Cues for *detection*: This refers to cues that would lead an operator to notice the safety consideration.
    - What are the cues that point to the system problem?
    - How are the cues generated?
    - How are the cues detected (by whom, where, and timing)?
    - What training is related to the cues in the scenario?
    - What are the key factors affecting cue detection?
- Diagnosis and situation awareness for *understanding*: This refers to the information and mechanisms that enable the operator to understand the situation and diagnose the problem.
    - What information is needed for the situation diagnosis? How is each individual piece of information generated and obtained (by whom, where, and timing)?
    - What is the basis (e.g., which procedure) for making the diagnosis and situation awareness and by whom and where is it implemented?
    - What is the operator training related to the diagnosis?
    - What are the key factors affecting the diagnosis?
- *Decisionmaking*: This uses the information based on the understanding of the situation to make decisions about how to respond to the situation.
    - What are the criteria or rules for making the decisions?
    - How is the decision made, and what is the decision basis (e.g., which procedure, by whom, where, and when)?
    - What are the competing goals and alternative options when making the decision?
    - What are the key factors affecting the decision?
- *Action*: This refers to implementing the decision by interacting with the system to change the scenario direction.
    - What is the basis for performing the tasks (e.g., which procedure), and how are the tasks expected to be performed (by whom, where, and when)?

    - What are the success criteria of the actions?
    - What are the key factors affecting the reliability of completing the actions?
    - Action execution – Are the manual actions physically strenuous?
- *Interteam coordination*: This refers to interactions between multiple entities (individuals, teams, and organizations) involved in the event.
    - What decisionmaking authorities are involved (and what other organizational factors/interactions that might come into play)?
    - How are communications, resource allocations, information, and knowledge managed?

Below are some considerations for the task context:

- Use of computerized HSIs and supporting systems adds work for personnel.
- Multiple, simultaneous events may lead to multitasking, interruption, and distraction.
- Failure or unavailability of operational system components may make event progression unpredictable.
- Unusual event evolution may reduce the time available to perform human actions.
- Complex events often require personnel to perform tasks in distributed locations.
- Personnel may need to perform additional tasks upon failures of automated systems.
- Personnel may make nonrequired changes to system status or interfere with system automation with good intentions, yet the changes may lead to undesirable consequences.

3.2 Step 2 – Analyzing Human Failure Events

The purpose of this step is to model the challenges to human performance of an HFE and identify failure opportunities for HEP quantification. It includes defining HFEs and identifying critical tasks in an HFE. The information obtained and generated from this analysis should be documented in Step 2 of Appendix A.

3.2.1 Defining the Human Failure Events

The purpose of defining HFEs is to identify the scope of analysis for an HFE. HFEs are the human actions included in PRAs as basic events. Thus, the HFEs should have been defined in a PRA model. Yet, HRA analysts should verify the definition and may add specifications for HFEs in the event being analyzed under the given conditions (described in Step 1). The HFE definition should be documented in Step 2.1 of Appendix A.

Guidance for the Definition of Human Failure Events

The HFE is defined at a level that describes the failure of the human action and links it to the affected systems. The definition of the HFE should include, but not be limited to, the following items:

- success criteria that define the desired end states or outcomes of the systems with the success of the human action
- consequence of the HFE occurrence (e.g., the reactor goes to core damage)
- beginning and ending points of the HFE
    - The beginning point of the HFE should be defined using the cue(s) that would prompt the operator to initiate the action (e.g., procedure step or control room alarm), its (their) timing, and operator acknowledgment of the cue(s).
    - The ending point of the HFE is defined when the action execution is complete.
- relevant procedural guidance for the HFE
- cues and indications for initiating the HFE and their timing
- time available to perform the HFE
- time required to perform the HFE

It is important to precisely define these items because for seemingly similar HFEs, variability in HEPs may be caused by differences in the items that define the HFEs. The analysis of the time required to perform the HFE may be iterative. That is, an analyst may need to look at the relevant procedures in more detail as part of the analysis for Step 2.2 through Step 4 and then return to this step to complete the analysis for the time required. All timing estimates should be graphically summarized in an HFE timeline, which is shown as Figure 3-3, or documented as a list or table.

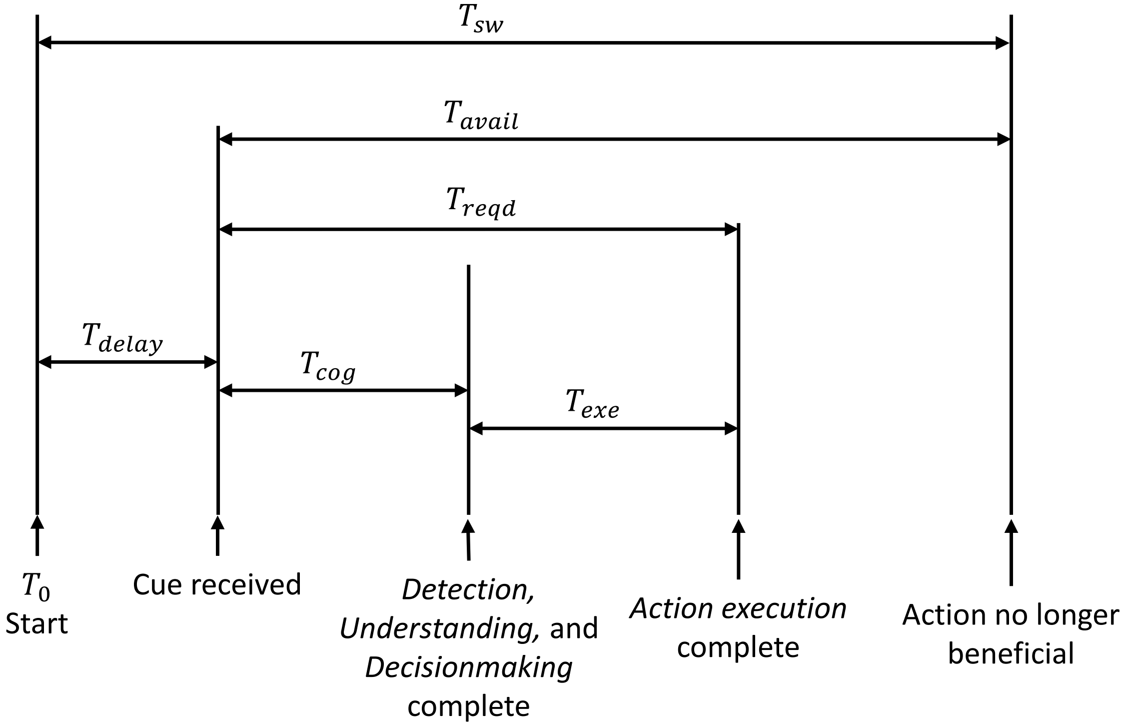


Figure 3-3 HFE Timeline

Figure 3-3 is a structured timeline for an individual HFE that was adapted from Section 4.6.2 of NUREG-1921 [11] to the IDHEAS methodology by using the macrocognitive functions that apply to an individual or a single team. In the case of multiple teams, T_{reqd} also includes *interteam coordination*. The terms in the HFE timeline are defined in the following list [1], [11]:

- T_0 is the start time of the event (or scenario). For NPPs, an example of T_0 is the time that the reactor trips.
- T_{delay} is the time delay, which is the time duration from T_0 until the system generates the cue that would prompt operators to initiate the action and operators acknowledge the cue.
- T_{sw} is the system time window, which is the time duration from T_0 until the action is no longer beneficial (e.g., core damage). For NPPs, T_{sw} is typically derived from thermal-hydraulic analyses. For other nuclear facilities, T_{sw} may be derived from appropriate systems analyses.
- T_{avail} is the time available for the response and is the difference of T_{sw} and T_{delay} (i.e., $T_{sw} - T_{delay}$).
- T_{cog} is the cognition time, which consists of the time for *detection*, *understanding*, and *decisionmaking*.
- T_{exe} is the time for *action execution* and includes the time to travel to the location, collect tools, don personal protective equipment, and manipulate relevant equipment.

- T_{reqd} is the time required for the response and the summation of T_{cog} and T_{exe} (i.e., $T_{cog} + T_{exe}$).

Section 5.3 of NUREG-2198 [1] and Section 4.6.2 of NUREG-1921 [11] present more information about the terms in the HFE timeline.

3.2.2 Task Analysis and Identification of Critical Tasks

The purpose of task analysis is to identify potential failure opportunities in a human action for HEP quantification. The potential failure opportunities in a human action are represented by critical tasks. A human action can be divided into “tasks” and “critical tasks.” A “critical task” is essential to the success of the action and failure of any critical task will result in the occurrence of the HFE. A “task” is not essential to the success of the human action; however, tasks may interfere with the performance of critical tasks. Therefore, tasks should be considered when analyzing critical tasks.

Performing task analysis for an HFE is to understand what it takes for operators to succeed or fail the human action. A task diagram is a tool to graphically represent the tasks and critical tasks needed for the HFE. Moreover, a task diagram can depict the relationship between the critical tasks and the success or failure of the action. In addition, if an HRA credits recovery from failure of the critical tasks, a task diagram should identify the credible recovery opportunities.

It is important that the task diagram represents the tasks from the beginning to the end of the HFE. Typically, an HFE begins with the onset of the cues directing the required human response or the human action. Thus, a task diagram should indicate onset of the cues and the required task for personnel to detect the cues. Also, a task diagram represents not only the execution of the action, but also the tasks such as *understanding* and *decisionmaking* that leads to the *action execution*. When multiple teams are involved in the human action, the task diagram should delineate the relationships of the tasks that require *interteam coordination*.

For the purposes of IDHEAS-ECA, the task diagram/timeline and critical tasks should be documented in Step 2.2 of Appendix A.

An important aspect in identifying critical tasks is the level of breakdown of an HFE into critical tasks. Guidance for this important aspect is provided below.

Guidance for Identifying Critical Tasks and Breaking Down a Human Failure Event into Critical Tasks

Reviewing existing documentation is usually the first step in identifying critical tasks. The critical tasks for an HFE may have already been defined in training programs, quality assurance documents, fault tree analysis, and other efforts. Identification of critical tasks may also consider the error recovery opportunities. Because there may be opportunities for the operating personnel to recover from an error within the time window, the task analysis may also identify opportunities for such error recoveries. Examples of error recovery include additional cues and monitoring system feedback (i.e., indications that the system is not responding as would be expected if the intended action had been completed correctly).

Additional guidance for identifying critical tasks is as follows:

- What is a critical task?
  - A critical task constitutes a recognizable and consequential unit of human activities.
  - A critical task needs to be performed by humans to achieve a desired plant status; failure of a critical task leads to the HFE.
  - Successful performance of a critical task will alter the scenario progression towards a safer plant status.
- Boundaries between critical tasks can be distinguished by any of the following:
  - Clearly defined goal.
  - Clearly defined initial or entry state.
  - Clearly defined ending or exit state (i.e., consequences or outputs).
- The scope of a critical task may be represented with one or several macrocognitive functions.

A critical task usually includes physical manipulations of the systems to change the scenario progression, but human physical manipulations are not a necessity. In some situations, a critical task could be any of the macrocognitive functions.

Breaking an HFE into too many detailed critical tasks tends to hide the context and results in the tedious work of quantifying HEPs for all the critical tasks. Because the critical tasks identified for an HFE are just one way to model the HFE, there are no universally applicable rules on the level of task breakdown. After all, the purpose of representing an HFE with critical tasks is to facilitate PIF assessment and HEP estimation. Following are the guidelines for breaking down an HFE into critical tasks:

- Use as few critical tasks as possible to represent the HFE; that is, begin with the entire HFE as one critical task.
- Break down the HFE into critical tasks only when the PIF attributes vary for different critical tasks of the HFE.
- An HFE should be broken into critical tasks only at a level that retains the context of the HFE and can be represented with macrocognitive functions.
- Stop breaking down the tasks at the level where there are performance indications or empirical data available to inform HEPs. For example, expert judgment has been a prevalent way to estimate HEPs; if expert judgment is used, the HFE should be broken down to critical tasks at the level with which experts are familiar enough to make a judgment.

Chapter 4 of NUREG-2199, Vol.1 [12], provides more detailed guidance on task analysis and offers explicit guidelines on developing task diagrams, identifying recovery paths, and developing timelines. In NUREG-2198 [1], Chapter 4 and Appendix G also contain detailed guidance on identifying critical tasks.

3.3 Step 3 – Modeling Failure of Critical Tasks

The purpose of this step is to model the failure of critical tasks in order to quantify P_c. This is performed for every critical task in an HFE. It includes characterizing a critical task and determining CFMs applicable to the critical task. The information obtained and generated from the analysis should be documented in Step 3 of Appendix A.

3.3.1 Characterization of Critical Tasks

The characterization of a critical task is to specify the conditions relevant to the critical task that can affect the reliability of performing the critical task. Before Step 3, the high-level information about task characterization has been collected and documented in Step 1 for the entire scenario and Step 2 for the whole HFE. Step 3 specifies and refines the information for a given critical task. For example, while the HFE definition may include all the procedures needed for the HFE, every critical task may have its own procedure, or a critical task may not have a procedure. The characterization of a critical task is one of the inputs for assessing PIFs, especially the task-related PIFs, and should be documented in Step 3.1 of Appendix A.

Guidance for the Characterization of Critical Tasks

Characterization of a critical task should include, but is not limited to, assessment of the characteristics listed in Table 3-2.

Table 3-2 Critical Task Characterization for HRA

Critical Task Characteristics	Description
Critical task goal	The expected outcome of the critical task with respect to the desired system states (e.g., reach hot shutdown within 3 hours, flee the building).
Specific requirements	Specifications for the critical task goal such as timing requirements or how the critical task goal should be achieved (e.g., monitoring parameters at a certain time interval, using secondary cues when the primary cues are not available, cooling down the RCS within a certain rate).
Cues and supporting information	The cues to initiate the critical task and key information needed to perform the task. A cue could be an alarm, an indication, a procedure instruction, or others (e.g., onsite report). The supporting information is in addition to the cue required to perform the task.
Cognitive activities	Cognitive activities involved in the task that place demands on corresponding macrocognitive functions. Table 3-3 lists the cognitive activities.
Procedures	Available procedures, guidance, or instructions designed for the critical task.
Personnel	Types of personnel needed for the critical task, minimum staffing required, special skill sets required.
Task support	Job aids, reference materials, and tools and equipment needed.
Location	Where the task is performed, special environmental factors at the location.
Concurrent tasks	Concurrent tasks that compete for personnel's cognition and resources (e.g., tools, job aids).
Interteam coordination considerations	Interteam collaborative activities required for the task and requirements for communication facilities (e.g., equipment, tools, devices).

3.3.2 Identification of Applicable Cognitive Failure Modes

Any critical task can be achieved through one to all five macrocognitive functions. The cognitive failure of a critical task is the result of the failure of any macrocognitive function it demands. Thus, the CFMs are the classifications of the various ways that a critical task may fail. Only the applicable CFMs need to be quantified for HEP estimation purposes in Step 4 (Section 3.4) and Step 5 (Section 3.5).

For the purposes of IDHEAS-ECA, the applicable CFMs should be documented in Step 3.2 of Appendix A.

Guidance for Identifying the Applicable CFMs

The five CFMs used in IDHEAS-ECA are the failure of the macrocognitive functions (the high-level CFMs described in IDHEAS-G [1]). Therefore, once the macrocognitive functions demanded by a critical task are identified, the failure of the identified macrocognitive function(s) is (are) the applicable CFM(s). The CFMs are defined as follows:

- CFM1 – failure of *detection*
- CFM2 – failure of *understanding*
- CFM3 – failure of *decisionmaking*
- CFM4 – failure of *action execution*
- CFM5 – failure of *interteam coordination*

Applicable CFMs for a critical task can be identified by using the three steps listed below, which are followed by guidance for each.

(1) Select applicable CFMs based on the cognitive activities required to perform the task.

Any critical task consists of cognitive activities, such as monitoring parameters or executing procedure steps. The cognitive activities determine the macrocognitive functions required for the critical task and are the basis for identifying the CFMs that apply to the critical task. If a macrocognitive function is needed to perform the critical task, then the corresponding CFM is applicable. The analysts should have a clear understanding and documentation of the actual human activities included in each CFM.

Whether a CFM should be selected for a critical task depends on the nature of the task, not the PIFs. The required macrocognitive functions are critical to accomplish the cognitive activities of a critical task. If a macrocognitive function is required, then the critical task can fail because of the failure of the macrocognitive function. For example, if collecting information or detecting something is necessary to achieve the goal of the critical task, then CFM1, failure of *detection*, applies.

The cognitive activities of a critical task are assessed using the taxonomy of cognitive activities, which is summarized in Table 3-3. The macrocognitive function demanded by the critical task is identified using the assessment of the type of cognitive activities (i.e., the second column of Table 3-3).

Table 3-3 Taxonomy of Cognitive Activities

Macrocognitive function	Types of cognitive activities
Detection	• Detect cues (e.g., through carefully monitoring, searching, inspecting, or comparing). • Acquire information (e.g., by checking, reading, communicating or chatting, or computing).
Understanding	• Maintain situational awareness. • Assess status based on indirect information. • Diagnose problems and resolve conflicts in information. • Make predictions or form expectations for the upcoming situation development.
Decisionmaking	• Make a go/no-go decision for a prespecified action. • Select among multiple options or strategies. • Change or add to a preexisting plan or strategy (e.g., changes of personnel, criteria, subgoals). • Develop a new strategy or plan.
Action Execution	• Execute cognitively simple actions. • Execute cognitively complex actions. • Execute long-lasting actions. • Execute control actions. • Execute fine motor actions. • Execute physically strenuous actions.
Interteam coordination	• Communicate between different groups, teams, or organizations. • Cooperate between different groups, teams, or organizations. • Coordinate (including command and control) between different groups, teams, or organizations.

(2) Use the cognitive processors of a CFM to verify the applicability of the CFM.

IDHEAS-G [1] explains the process of achieving each macrocognitive function, and the elements of the process are referred to as processors. Each processor represents a way that the macrocognitive function fails. It is recommended that HRA analysts use the processors to verify the selection of the applicable CFMs and distinguish between the CFMs of a critical task. Figure 3-4 through Figure 3-8 show the cognitive activities and processors associated with each macrocognitive function, respectively. If a CFM is selected because of a cognitive activity, then achieving the cognitive activity must involve some or all of the processors of the macrocognitive function.

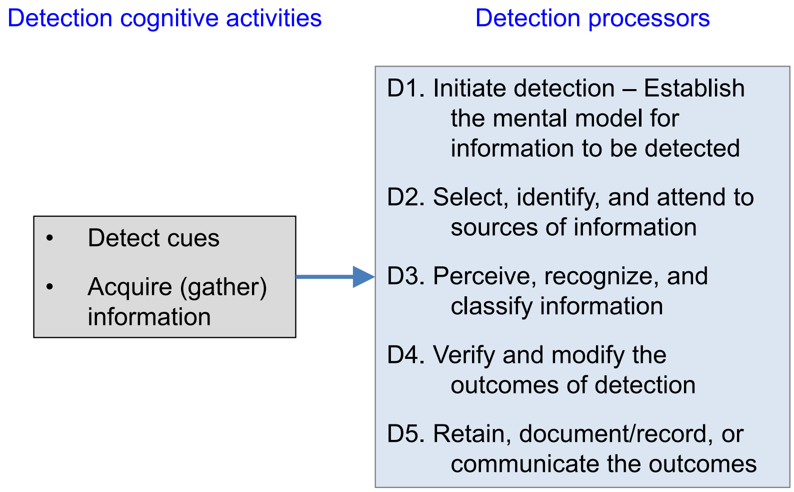


Figure 3-4 **Cognitive Activities and Processors for *Detection***

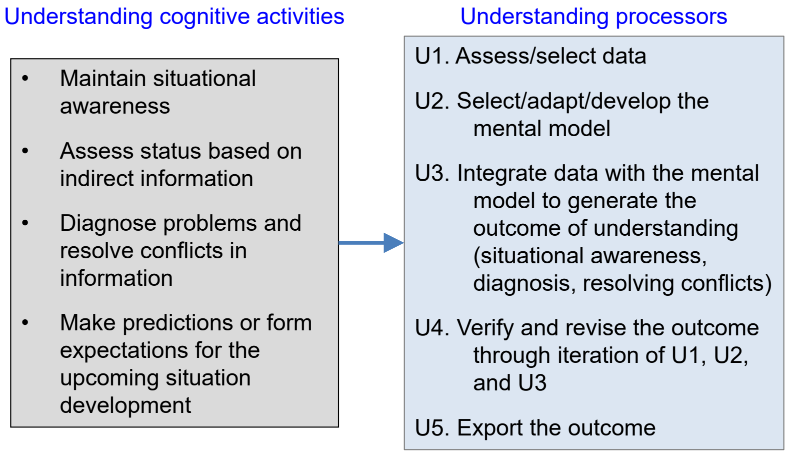


Figure 3-5 **Cognitive Activities and Processors for *Understanding***

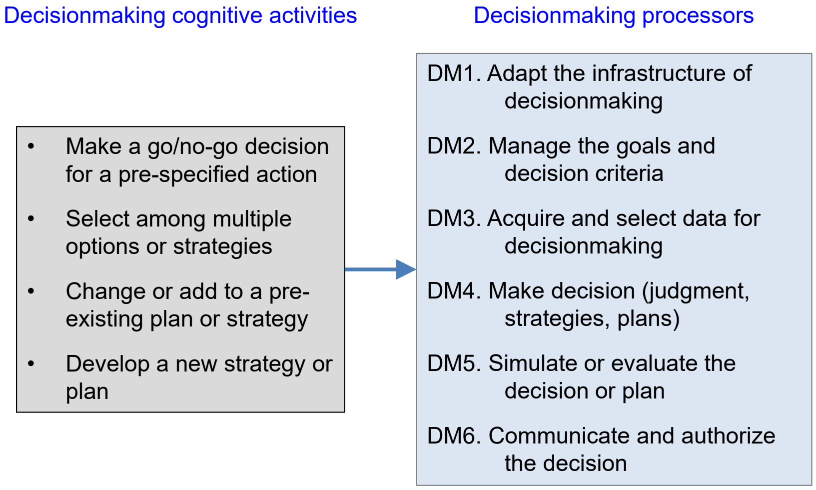


Figure 3-6 **Cognitive Activities and Processors for *Decisionmaking***

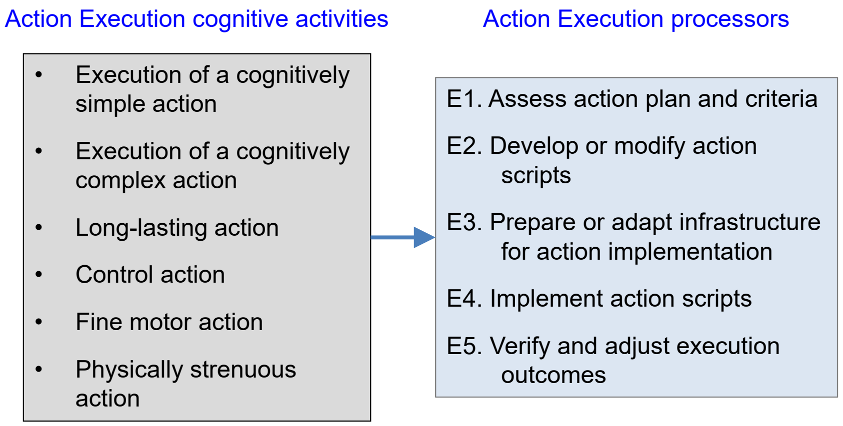


Figure 3-7 Cognitive Activities and Processors for *Action Execution*

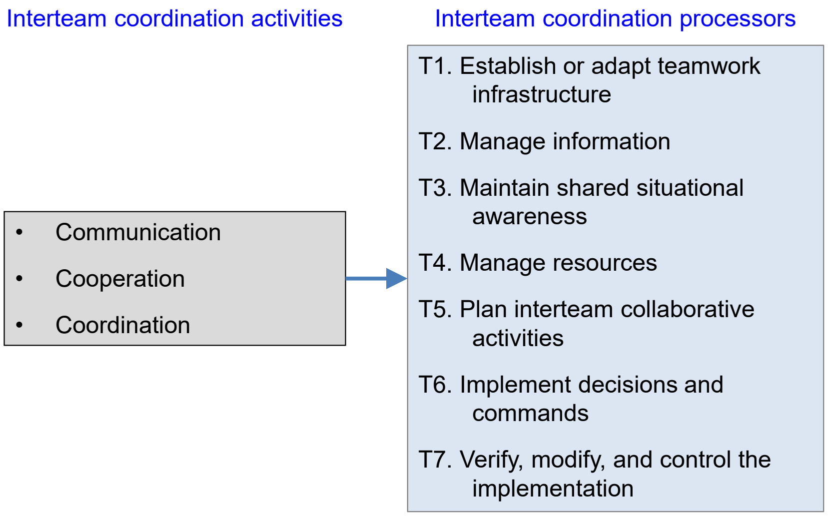


Figure 3-8 Cognitive Activities and Processors for *Interteam Coordination*

(3) Check the boundaries of the selected CFMs to ensure that the selected CFMs are not double counted.

While the cognitive activities involved in the critical task determine the selection of CFMs applicable to a critical task, there may be situations in which the boundaries between CFM1 and CFM2 and between CFM2 and CFM3 are ambiguous. For example, if a critical task involves cognitive activities acquiring multiple pieces of information through checking or reading indicators, then CFM1 is applicable. However, after the pieces of information are correctly acquired, if operators still cannot form a satisfactory understanding of the situation, diagnose the problem, or resolve conflicts in the information, they need to seek additional information. This activity of seeking additional information demands the macrocognitive function of *understanding* because it requires operators to integrate multiple pieces of information to form a coherent mental representation of the situation.

Below are the guidelines to assist HRA analysts in determining applicable CFMs:

- CFM1, if selected, should be checked first. A human action typically begins with detecting the cues. Thus, CFM1 typically applies to the first critical task in the task diagram or timeline of the HFE. If additional cues need to be detected for other critical tasks of the HFE, then CFM1 is applicable to the other critical tasks.
- CFM2 through CFM5 are conditional, assuming that the preceding macrocognitive functions are successful. For example, CFM2 is the failure of personnel to understand the situation assuming that personnel have correctly detected the cues needed to start the critical task.
- CFM1 applies if *detection* is required for detecting cues or gathering information to initiate the human action.
- CFM2 is under the assumption that information or cues are correctly detected, and personnel need to integrate pieces of information with the mental model of the situation to make sense of the situation, maintain the situational awareness, or diagnose a problem. CFM2 is not applicable if no integration is required for the critical task.
- Similarly, CFM3 is under the assumption that personnel already detected the information and reached the correct understanding of the situation. CFM3 is for making decisions under uncertainty or developing plans.
- CFM4 is under the assumption that personnel have correctly detected the cues, made the right diagnosis or correct understanding of the situation, and had the right decision or response plan. As long as manipulation is required, CFM4 cannot be neglected.
- CFM5 is exclusively for failure of interteam coordination, communication, and cooperation. For example, the technical support center fails to coordinate with the emergency response center for allocating some equipment, while intrateam coordination and communication between control room crew members are modeled within the other CFMs. CFM5 is under the assumption that the individual personnel or teams correctly performed the other macrocognitive functions.

3.4 Step 4 – Assessing Performance Influencing Factor Attributes Applicable to Cognitive Failure Modes

The PIFs represent the context of the HFE and facilitate quantification of the HEP. The assessment of PIF attributes is based on the scenario context and list of applicable PIFs (Section 3.1.3), the definition of the HFE (Section 3.2.1), and the characterization of the critical tasks (Sections 3.3.1 and 3.3.2). Appendix B provides the full list of PIF attributes.

While IDHEAS-G [1] defines context as the conditions that challenge or positively affect human performance, the PIFs are defined as neutral. The PIF attributes all have a negative impact on HEPs. The PIFs represent the context in three ways:

(1) No impact – Each PIF has a “no impact” state, which means that the PIF has no observable impact on the HEP.

(2) PIF attributes – A PIF attribute is an assessable characteristic of a PIF and describes a way the PIF challenges the macrocognitive functions of a critical task and, therefore,

increases the likelihood of error in the macrocognitive functions. A PIF attribute represents a negative impact on human performance, which increases the HEP.

(3) Positive impact – Certain contexts may facilitate human performance and thus may have a positive impact on the HEP. The effect of the context on the HEP is represented by the ways that (a) the effect eliminates some PIF attributes and brings the PIF to "no impact" state, and (b) the effect alleviates some attributes of other PIFs. For example, a specific training program on certain types of scenarios can eliminate the attribute "Scenario is unfamiliar" in the PIF Scenario Familiarity. Similarly, some procedures are designed to reduce diagnosis or decisionmaking complexity. Lastly, positive context sometimes may increase the opportunities for personnel to identify and recover from the human errors made in an action.

For the purposes of IDHEAS-ECA, the assessment of PIF attributes should be documented in Step 4 of Appendix A.

Guidance for Assessing PIF Attributes

To identify the applicable PIF attributes, the analyst uses the scenario context, list of applicable PIFs, definition of the HFE, and list of applicable CFMs for every critical task. Assessment of PIFs should always begin with the base PIFs: Scenario Familiarity, Information Availability and Reliability, and Task Complexity. In the IDHEAS human performance model, the base PIFs are applicable because humans are always in a scenario and they describe how a human performs an action in the scenario. Therefore, the attributes of the base PIFs should be assessed.

The assessment of PIF attributes involves the following steps:

(1) Select PIFs within the boundary conditions of the scenario and definition of the HFE — The IDHEAS-G PIF structure provides 20 PIFs (as listed in Table 2-1 and described in Table 2-2 through Table 2-5), which should be the starting point. Defining the boundary conditions in Step 1 is to define the scope of the HRA being performed. Assumptions about the plant and human performance context are made under the boundary conditions. The boundary conditions would include the assumptions that some PIFs have "no impact" on the HEPs for the specific HRA. Based on the scenario context, many PIFs may not be relevant; therefore, they are not selected. If a PIF is not selected, a rationale should be given for why it is not relevant.

(2) Start the PIF assessment with the base PIFs: Scenario Familiarity, Information Availability and Reliability, and Task Complexity. These three PIFs model the overall scenario characteristics and the specific task characteristics. When assessing the remaining PIFs, analysts do not need to select the attributes if they are already represented in the base PIFs.

(3) Represent contexts that challenge human performance – This means to select PIF attributes relevant to the CFMs for the given scenario. Certainly, only a portion of PIF attributes are applicable. Analysts should evaluate every attribute of a PIF and eliminate the ones that are not applicable. If the reason for eliminating a PIF attribute is not obvious, a rationale should be given for the elimination.

(4) Represent contexts that positively affect human performance — The contexts that positively affect human performance are represented by eliminating or alleviating some

PIF attributes. For example, the no impact attribute of training means that training in the aspect of responding to the scenario being analyzed is good enough and would not increase HEPs. The context that training is better than the baseline and specific to the scenario of analysis means that the training may alleviate some PIF attributes such as those in Scenario Familiarity and Teamwork and Organizational Factors.

(5) Assess the level of multi-scale PIF attributes — The effect of an attribute on HEP may vary continuously with the quantitative measure of the attribute. IDHEAS-ECA models the continuous effect by simplifying it to discrete scales. Multiple discrete scales are used to model those attributes, which are referred as "multi-scale attributes" because they have multiple scales instead of being just present versus absent. The PIF tables in Appendix B present several measures for such attributes. The IDHEAS-ECA software uses those measures as benchmark scales and allows HRA analysts to select a scale value between 1 to 10, with 1 being the lower limit and 10 being the upper limit of the attribute being modeled. For each scale selected, the software assigns the corresponding base HEP or PIF weight based on a linear interpolation between the benchmarks.

While PIFs model the context that can increase or decrease the likelihood of human errors, they do not model personnel's comfort or discomfort in performing the action unless the comfort or discomfort exceeds some threshold leading to an increase or decrease in human errors. For example, the working room may be hot and humid because it is out of ventilation, but not to the extent that personnel make more errors than they would make in a ventilated room. In this case the Coldness/Heat/Humility PIF is considered as "no impact."

It is important to begin the PIF assessment using the three base PIFs. Some of the PIF attribute descriptions in Appendix B appear to represent similar contexts. Analysts should carefully select PIF attributes in a way that avoids double counting the challenge of the human action context. For example, the attribute of PIF Task complexity "C22 – Multiple alternative strategies to choose" appears similar to the attribute in Procedures, Guidance, Instructions "PG2 – Procedure requires judgment." While C22 represents the demands of the actual task and PG2 represents the difficulty interpreting the procedure, the descriptions of the two PIF attributes appear to overlap. This could potentially lead to double counting of the challenge or choosing different PIF attributes to the same context. To solve this issue, the recommendation is to first assess the attributes of the base PIFs. If a procedure has multiple alternative strategies for operators to choose, then C22 is applicable and PG2 is not needed, although choosing the strategy from multiple alternatives does require judgment. In other words, C22 is a stronger attribute that includes "requiring judgment."

3.5 Step 5 – Estimation of P_C – the Sum of Human Error Probabilities of Cognitive Failure Modes

The purpose of this step is to estimate the probability of an HFE (i.e., the HEP) attributing to the CFMs of the critical tasks. The estimation of the overall HEP has two parts: estimating the error probabilities attributed to the CFMs (P_c) and estimating the error probability attributed to the uncertainties and variability in the time available and time required to perform the action (P_t). The estimation of the HEP is the probabilistic sum of P_c and P_t:

$$P = 1 - (1 - P_c)(1 - P_t) \tag{3.1}$$

In Equation (3.1), P is the probability of the HFE being analyzed (i.e., the HEP), and P_c and P_t have already been defined. Note the following:

- P_t can also be viewed as the probability that the time required to perform an action exceeds the time available for that action, as determined by the success criteria. P_t assumes that actions are performed at a normal pace without complications and does not account for the increased likelihood of a human error due to time pressure. Time pressure is treated as a PIF and contributes to P_c.
- P_c assumes that the time to perform the action is sufficient. Sufficient time means that the action can be successfully performed within the time window that the system allows. P_c captures the probability that the human action does not meet the success criteria because of human errors made in the problem-solving process.

The information obtained and generated from the analysis should be documented in Step 5 of Appendix A. HRA analysts may choose to use the IDHEAS-ECA software to perform this step and document the results.

3.5.1 Estimation of P_c

P_c is the probabilistic sum of the error probabilities of every critical task and is estimated as follows:

$$P_c = 1 - \prod_{i=1}^{m}\left(1 - P_{CT_i}\right) = 1 - \left(1 - P_{CT_1}\right)\left(1 - P_{CT_2}\right)\ldots\left(1 - P_{CT_m}\right) \tag{3.2}$$

where m is the total number of critical tasks and P_{CT_i} is the error probability of the i^{th} critical task. The error probability of the i^{th} critical task (P_{CT_i}) is the probabilistic sum of the probabilities of all the applicable CFMs and is estimated as follows:

$$P_{CT_i} = 1 - \prod_{j=1}^{n}\left(1 - P_{CFM_j}\right) = 1 - \left(1 - P_{CFM_1}\right)\left(1 - P_{CFM_2}\right)\ldots\left(1 - P_{CFM_n}\right) \tag{3.3}$$

where n is the total number of CFMs applicable to the critical task, and P_{CFM_j} is the probability of the j^{th} CFM applicable to the critical task. The probability of a CFM applicable to the critical task is a function of the PIF attributes associated with the critical task. The calculation of the probability of a CFM for any given set of PIF attributes, provided that all the PIF impact weights and base HEPs are obtained, is estimated as follows:

$$\begin{aligned} P_{CFM} &= P_{CFM_{Base}} \cdot \left(1 + \sum_{i=1}^{n}(w_i - 1)\right) \cdot \frac{1}{Re} \\ &= \frac{P_{CFM_{Base}} \cdot \left(1 + (w_1 - 1) + (w_2 - 1) + \cdots + (w_n - 1)\right)}{Re} \end{aligned} \tag{3.4}$$

The terms in Equation (3.4) are defined as follows:

- $P_{CFM_{Base}}$ is the base HEP of a CFM for the given attributes of the following three PIFs: *information availability and reliability*, *scenario familiarity*, and *task complexity*. $P_{CFM_{Base}}$ is also calculated as the probabilistic sum of the base HEPs for the three PIFs:

  $$P_{CFM_{Base}} = 1 - [(1 - P_{INF})(1 - P_{SF})(1 - P_{TC})] \tag{3.5}$$

  where P_{INF}, P_{SF}, and P_{TC} are the base HEPs for *information availability and reliability*, *scenario familiarity*, and *task complexity*, respectively. Table B-1 through Table B-3, respectively, provide the base HEPs for *information availability and reliability*, *scenario familiarity*, and *task complexity*.

- Notice that in Table B-1 through Table B-3, when a base PIF is "no impact" (that is, none of its attributes is applicable), a lowest HEP is assigned to each CFM. This lowest HEP is assumed to be the lowest error probability that a team or a crew with peer checking and supervision can achieve for a task.

- w_i is the PIF impact weight for the given attributes of the remaining 17 PIFs and is calculated as follows:

  $$w_i = \frac{ER_{PIF}}{ER_{PIF_{Base}}} \tag{3.6}$$

  where ER_{PIF} is the human error rate at the given PIF attribute and $ER_{PIF_{Base}}$ is the human error rate when the PIF attribute has no impact. The human error rates used in Equation (3.6) are obtained from empirical studies in the literature or operational databases that measured the human error rates while varying the PIF attributes of one or more PIFs. Appendix B provides the values of the ratio $ER_{PIF}/ER_{PIF_{Base}}$ for different PIFs in Table B-4 through Table B-15. It is noted that Table B-4 contains all the PIFs in the environment and situation context category, and Table B-14 contains the PIFs mental fatigue, and stress and time pressure.

- Re is a factor that accounts for the potential recovery from failure of a critical task, and it is set to 1 by default. IDHEAS-ECA allows analysts to determine the Re value based on their judgment of the chance of recovering a critical task for the given CFM.

For the purposes of IDHEAS-ECA, the selected PIF attributes and the estimation of P_c should be documented in Step 4 and Step 5 of Appendix A, respectively.

Guidance for Estimating P_c

P_c is calculated using the equations in this section and the tables in Appendix B. Alternatively, P_c can be calculated using the IDHEAS-ECA software.

Guidance for Crediting Recovery Effect in P_c

PRA defines recovery actions as human actions that, on an as needed basis, provide a more realistic evaluation of significant accident sequences. Operator actions can be credited to restore functions, systems or components; to do this, operator recovery actions should restore failed equipment or find alternative equipment or configurations within the time period required.

Significant recovery actions may be evaluated through the same process as all other HFEs when it is important to provide additional justification for the credit assumed. Repair of components, meaning the restoration of a failed SSC by correcting the failure and returning the component to operability is typically quantified using empirical data (if credited at all) and is not treated using HRA techniques. These actions to restore functions, systems, or components are new basic events that would be added to the PRA, not to be confused with the "recovery" of an HFE, which is credited in the probability of the HFE.

IDHEAS-ECA credits recovery in the HEP of the critical tasks of an HFE. The task diagram of an HFE shows a success path on which one or several critical tasks are performed to achieve the success of the human action being modeled. No matter what the reason for failure of a critical task, the assumption is made that following the failure, the operators continue other critical tasks. Consequently, operators have opportunities to detect the failure and correct the errors made. Such recovery mechanisms are typically credited in the evaluation of the HEP for the HFE, and not modeled explicitly as separate basic events in the PRA model. A recovery opportunity viewed in isolation is essentially another way of achieving success. The opportunities for recovery can come from a number of sources. The error correction opportunities refer to the potential for placing the crew on an alternative success path or acting as additional cues to perform the correct task. In addition, plant conditions may evolve and generate new alarms or key parameter changes that crews would normally be monitoring, which would serve as cues for identifying the need for a different response.

Crediting recovery should first assess the feasibility of recovering (e.g., whether the recovery opportunity occurs sufficiently early to allow time for the appropriate response to be executed). If the cues that could be used to correct the error would not occur before the end point of the HFE, then there is no opportunity for recovery. However, if the recovery is clearly feasible in that the cues for recovery would occur in time for diagnosis and recovery to the correct path, and time for the remaining tasks (e.g., any additional decisions or response execution activities) would also still remain available, then there is an opportunity for recovery. The following criteria are used to assess the feasibility of crediting recovery of an HFE:

1) A recovery path exists. It should be demonstrated that the event progression allows personnel to go back to the failure point to correctly perform the failed critical task. Some critical tasks may be irreversible and thus cannot be credited for recovery.

2) Cues or indicators are available to personnel so they can recognize the failure and need for recovery.

3) At least one crew member is responsible for monitoring the plant status and detecting the cues of the failure.

4) The time of the cue or the time taken to reach a procedural step that indicates the need for recovery is early enough to allow adequate time for recovery.

Recovery is feasible if all the criteria are met. If a critical task is recoverable, IDHEAS-ECA allows analysts to assign a recovery factor specific to each CFM of the critical task because the potential for recovery is dependent on the failure mode. For example, the error correction opportunities of manipulation tasks will primarily arise from a monitoring activity that is capable of detecting that the plant is not responding as would be expected if the intended action had been completed correctly. These opportunities focus on the crew's assessment of the plant feedback.

The recovery factor, Re, in the HEP calculation varies from 1 to any positive number, with 1 being no potential for recovery. IDHEAS-ECA does not provide reference values of the recovery factor mainly because recovery potential is situation specific. The potential for recovery can be quite different for well-practiced procedural tasks performed in a control room than for rarely performed tasks outside the control room. Below are some recovery mechanisms that can influence recovery potential:

- procedure design – late procedure steps require operators to check and verify the correct performance of important earlier steps
- training, work process, and conduct of operation (e.g., plant status check performed for shift turnover)
- unexpected instrument responses to an action
- new alarms that provide cues to indicate potential errors
- multiple, diverse cues for recognition of the deed for recovery

In principle, the analyses to evaluate potential recovery are the same as those needed to evaluate the initial (un-recovered) HEP. The numerical combination of recovery factor Re and the initial HEP answers the question "What HEP applies after considering the effects from possible recovery in the context of this scenario?" Thus, the assigned value of recovery factor Re should be derived from a systematic assessment of human performance in the context of the scenario-specific HFE. It is not, and should not be, just a number that is applied generically to reduce the HEP. Furthermore, the dependency methodology that is summarized in Appendix K to NUREG-2198 [1] and the dependency analysis guidance documented in RIL 2021-14 [4] provide additional guidance for these assessments, because the evaluation of recovery factor Re is functionally similar to a dependency analysis.

When assessing recovery and estimating the recovery factor Re in the IDHEAS methodology, analysts should be aware that IDHEAS-ECA already credits certain human error recovery potentials in the HEP quantification model. The base HEPs and PIF weights used (as shown in Appendix B) are based on human error data in which personnel perform tasks with self-verification or peer checking. Moreover, a lowest HEP applies to a CFM when all PIFs are set to their “no impact” state. Thus, the analyst’s scenario-specific evaluations of the relevant PIF attributes and their associated weights may effectively account for the numerical effects from most sources of recovery (e.g., procedural reminders, self-checking, supervisory oversight, recognition of unexpected system responses). Assigning recovery factor Re may inappropriately “double-count” those effects. A separate evaluation of factor Re is needed only when there are specific mechanisms in personnel’s work process to prompt opportunities for recovery.

Finally, analysts should consider the dependency between the error made and recovery. If the recovery relies on the same context as that for the early failure of the critical task, then the recovery potential is reduced because of the dependence. In reality, there are no truly independent opportunities to correct the errors. To actually credit recovery and especially the recovery in multiple CFMs and critical tasks, analysts should carefully review the timeline of the specific recovery paths and identify opportunities for recovery.

3.6 Step 6 – Estimation of P_t – the Convolution of the Distribution of Time Available and Time Required

P_t uses the time available (T_{avail}) and time required (T_{reqd}) to perform an action. To calculate P_t, T_{reqd} is represented by its cumulative distribution function $F_{T_{reqd}}(t)$, and T_{avail} is represented by its probability density function $f_{T_{avail}}(t)$, and P_t is estimated as the convolution of the two probability distributions; that is [13]—

$$P_t = P\left(T_{reqd} > T_{avail}\right) = \int_0^{\infty} \left(1 - F_{T_{reqd}}(t)\right) \cdot f_{T_{avail}}(t)\, dt \tag{3.7}$$

HRA analysts need to estimate the probability distribution (central tendency and dispersion) of T_{reqd} and T_{avail}, for which guidance is provided below.

For the purposes of IDHEAS-ECA, the estimation and justification of the probability distributions for T_{avail} and T_{reqd} are documented in Step 6 of Appendix A, and the calculation of P_t should be performed with the IDHEAS-ECA software or any general-purpose computation software.

Guidance on Selecting a Time Distribution

In general, T_{avail} and T_{reqd} can be viewed as "duration times" as discussed in NUREG/CR-6823 [14] for which a probability distribution must be estimated. Ways to estimate a probability distribution are to assume the distribution form (e.g., lognormal, Weibull) or use a nonparametric distribution [14]. For a specific human action in a specific context, these ways to estimate a probability distribution require T_{avail} and T_{reqd} data. However, these data may not be available. This is the reason why the NRC staff proposes an option to estimate the T_{avail} and T_{reqd} ranges and then estimate the distribution parameters based on the percentiles or confidence level. Details about this option are discussed below in the guidance for estimating the distribution parameters of T_{avail} and T_{reqd}. Overall, the justification for the T_{avail} and T_{reqd} ranges and the corresponding percentiles or confidence levels that the true T_{avail} and T_{reqd} are in the estimated T_{avail} and T_{reqd} ranges, respectively, should be documented.

Ways to select a probability distribution are from experience and using multiple distributions to assess the best fit [15]. The work by Pacific Northwest National Laboratory (PNNL) [16] used several probability distributions (i.e., exponential, Weibull, lognormal, and truncated normal) to assess the best fit to the completion times data in EPRI NP-6937-L [17] and found the lognormal distribution to be the best fit for T_{reqd}.

The observed completion times for most crews are typically clustered around a central value (i.e., the median response time). However, the times for a small number of crews often deviate substantially from that behavior. In particular, a small number of crews often need much more time to complete the desired action. There are many reasons for these deviations (i.e., not only differences in training), and they often depend on the context of the specific response scenario. The shape and the range of the distribution for T_{reqd} should account for this observed behavior. Thus, it is often appropriate to characterize the uncertainty in T_{reqd} with a skewed distribution, such as gamma, Weibull, or lognormal. It is important for the shape and the range of the uncertainty distribution to account for these "outlier" effects. The quantification results for P_t can be affected significantly by the “overlap” in the low-probability “tails” of the distributions for T_{avail} and T_{reqd}.

Based on the analysis by PNNL [16], and taking into consideration the analysis of loss of offsite power recovery times [18], the NRC staff recommends using the lognormal distribution for T_{reqd}.

For T_{avail}, there is not enough information to recommend a particular probability distribution. Therefore, the NRC staff suggests using the lognormal distribution as a base case to calculate P_t and the overall HEP. Then, analysts should explore the sensitivity of P_t (and the overall HEP) to the lognormal distribution assumption by calculating P_t using the normal, Weibull, and gamma distributions as the distribution of T_{avail}.

Guidance for Estimating the Distribution Parameters of Time Available

Consistent with the HFE timeline in Figure 3-3 used in the HFE definition, T_{avail} is the difference between T_{sw} and T_{delay}. For NPPs, T_{sw} is typically estimated based on thermal-hydraulic studies or computer simulations and represents the time lapse from time zero to the time that a selected key parameter would cross its safety threshold without human intervention. T_{delay} is the time when the system generates the cue that would prompt operators to initiate the action and operators acknowledge the cue. In some instances, cues can be generated when a parameter reaches a threshold (e.g., a certain level in a steam generator (SG)), which then can be estimated using thermal-hydraulic calculations. In other instances, cues are procedure-driven, that is, the time it takes operators to reach a step in a pertinent procedure. T_{sw}, T_{delay}, and T_{avail} can never be exactly known “because of variability in plant conditions and because our knowledge is imperfect” [13]. In the context of calculating P_t, the NRC staff proposes two options for estimating the parameters of the T_{avail} distribution.

Option 1: At a high level, the parameters of the probability distribution of T_{avail} can be estimated in two steps:

(1) Estimate a range of values for T_{avail}: The T_{avail} range may be based on (a) several thermal-hydraulic code runs, (b) first-principles engineering calculations, (c) expert-elicited values, or (d) an appropriate combination of approaches (a), (b), and (c).

Performing several thermal-hydraulic code runs is typically not feasible because of the level of effort needed to set up the calculations and the time it takes for these codes to run. However, performing several runs may be appropriate for human actions that significantly affect the risk metrics (e.g., core damage frequency) calculated using the PRA [13]. An example of a first-principles engineering calculation is estimating how much time it takes to reach a given level in a tank based on volumetric flow rates, different pump configurations taking suction from the tank, initial tank level, and total tank volume. As explained by Bley et al. [13], these different engineering calculations, which can be viewed as sensitivity studies, allow analysts to evaluate the effects of the uncertainties and the variability associated with plant operation.

(2) Assume a probability distribution and estimate the parameters: The T_{avail} range in Step (1) should have lower and upper estimates. These estimates can be assumed to be percentiles of any probability distribution with the lower estimate being at a lower percentile than the upper estimate. Alternatively, an analyst can assume a confidence

level[1] that the true T_{avail} is in the estimated T_{avail} range. Appendix C explains the process for calculating the probability distribution parameters for several two-parameter probability distributions.

For scenarios that have multiple human actions, estimation of the T_{avail} distribution should also consider the effect of human performance, which is the time dependency between important human actions in a scenario. Studies show that there is significant crew-to-crew variability in performance time [19], [20]. Some crews moved through the response efficiently, resulting in more time available for subsequent actions. Other crews responded less efficiently than expected, resulting in less time available for subsequent actions. Therefore, any time dependency between the actions in a scenario may affect the estimated T_{avail} range and therefore the probability distribution of T_{avail}.

Option 2: If estimating a range for T_{avail} is not feasible, a single value for T_{avail} may be used to calculate P_t, and it can be based on the same approaches discussed above (e.g., engineering calculations). Note that using this option will result in P_t being underestimated.

Although IDHEAS-ECA does not limit the probability distributions that may be used to calculate P_t, the IDHEAS-ECA software offers six options to represent T_{avail}: (1) normal distribution,[2] (2) lognormal distribution, (3) gamma distribution, (4) Weibull distribution, (5) five-point estimation of a probability distribution, and (6) single-value threshold.

With respect to the five-point estimation of a probability distribution, often the time available for an action does not fall into a parameterized probability distribution. HRA analysts can estimate five points of the time distribution at the 5th, 25th, 50th, 75th, and 95th percentiles. The IDHEAS-ECA software interpolates the full distribution based on these estimates using the step function. In the IDHEAS-ECA software, the probability density functions of between zero to 5th percentile are specified as a half of the probability density function of between the 5th and 25th percentiles, and the probability density function between the 95th and 100th percentile is specified as a half of the probability density functions of between the 75th and 95th percentiles.

Guidance for Estimating the Distribution Parameters of Time Required

The time required to perform the action (T_{reqd}) should account for the entire time that is needed to achieve the desired plant conditions. Estimates of T_{reqd} should not account only for the time that is needed to initiate the desired action (e.g., to open a valve, start a pump). In particular, T_{reqd} includes the subsequent time that is needed to achieve the plant conditions that determine the functional success criteria for the modeled action. For example, the success criteria may require that the operators must cool down and reduce pressure below a certain value. After the decision is made, the total execution time is the time needed to manipulate the relevant controls to begin the cooldown, plus the time needed to achieve the desired temperature and pressure,

---

[1] In this case, the confidence level is a subjective probability, and it is consistent with the Bayesian interpretation of the confidence interval (see Table 6.1 of NUREG/CR-6823 [14]).

[2] Special caution is needed when the probability distributions of T_{avail} and T_{reqd} are assumed to be normal (Gaussian): "Since a normally distributed [random variable] can take on a value from the $(-\infty, +\infty)$ range, it has limited applications in reliability problems that involve time-to-failure estimations because time cannot take on negative values. However, for cases where the mean μ is positive and is larger than σ [i.e., the standard deviation] by several folds, the probability that the [random variable] T takes negative values can be negligible. For cases where the probability that [random variable] T takes negative values is not negligible, the respective truncated normal distribution can be used" [21].

as determined by allowable cooldown rates, scenario-specific thermal-hydraulic response, and other factors. That time is typically much longer than time needed to initiate the cooldown. It is also affected by scenario-specific limitations such as the number of available cooling water trains, pressure relief valves, and other factors. That total execution time determines whether the functional success criteria are achieved within the available time window, and it should be included in the estimate for T_{reqd}.

Many factors can affect the time required to complete an action. Estimating the distribution of T_{reqd} should consider three key aspects: nominal contributors, uncertainty factors, and bias factors. HRA analysts should keep in mind the HFE definition (see Section 3.2.1) when estimating the distribution parameters of T_{reqd} for which the NRC staff proposes two options.

Option 1: Adopt a two-step approach similar to that used for estimating the distribution parameters of T_{avail}; that is, (1) estimate a range for T_{reqd} and (2) assume a probability distribution and calculate the parameters based on two percentiles or a confidence level as explained in Appendix C.

One approach to estimate the T_{reqd} range is to review operational and simulator data and interview operators. HRA analysts should collect a range of times (using multiple independent estimates to the extent possible). Average crew response times should be obtained, as well as an estimate of the time by which the slowest and fastest operating crews would be expected to complete the actions.

A second approach to estimate the T_{reqd} range consists of first determining how much time it takes to detect information, understand it, make a decision based on the understanding of the information, and execute the action considering any interteam and intrateam interactions based on the factors shown in Table 3-4. Then, the resulting T_{reqd} estimate can be “transformed” into a range by considering the uncertainty factors shown in Table 3-5. As an example of this second approach, assume a hypothetical scenario in which the time to detect, understand, decide, and execute the use of a portable generator was determined to be 30 minutes. Next, by considering the staff experience in Table 3-5, this 30-minute estimate could be 25 minutes if highly experienced staff perform the action or 40 minutes if less experienced staff perform the action. The parameters of the T_{reqd} distribution can be based on the 25-to-40-minute or 30-to-40-minute T_{reqd} range.

The percentiles associated with the lower and upper estimates in the T_{reqd} range may be based on the responses to the questions:

- What percentage (or fraction) of crews would perform the action by the lower estimate of the T_{reqd} range? (the “faster” crews)
- What percentage (or fraction) of crews would perform the action by the higher estimate of the T_{reqd} range? (the “not-so-fast” crews in addition to the “faster” crews)

To illustrate the potential responses to these questions, consider the 30-to-40-minute T_{reqd} range in the example above in which about 50 percent of crews complete the action in 30 minutes and an additional 45 percent of crews complete the action in 40 minutes. This means that the 30- and 40-minute estimates represent the 50th and 95th percentiles of the T_{reqd} distribution, respectively. If the action significantly affects the risk metrics calculated using the

PRA (e.g., core damage frequency), the estimation of the T_{reqd} range should involve more resources and oversight.

Table 3-4 Typical Factors Contributing to T_{reqd}

Macrocognitive Function	Factors Contributing to Time Required
Detection	Travel to the location to obtain the information. Prepare and calibrate equipment needed for detection. Detect and attend to an indication. Confirm and verify the indicators. Record and communicate the detected information.
Understanding	Assess the information needed for diagnosis, such as knowledge and status of equipment. Integrate low-level information to create or determine high-level information. Identify plant status or conditions based on several parameters, symptoms, and associated knowledge; collect information and delineate complex information such as a mass or energy flow with which two or more systems interact with each other. Delineate conflicting information and unstable trends of parameters (e.g., interpret SG pressure trends when one train has failed). Wait for continuous or dynamic information from the system to complete diagnosis. Verify the diagnosis results or reach a team consensus.
Decisionmaking	Prioritize goals; establish decision criteria; collect, interpret, and integrate data to reach a satisfactory decision. Make decision based on parameters, choose strategies, or develop a plan. Coordinate the decisionmakers (especially with hierarchy of decisionmaking or distributed decisionmaking team), achieve consensus needed for the decision, or wait for certain information to make a decision. Simulate or evaluate the outcome of the decision.
Action execution	Evaluate the action plan and coordinate staff. Travel and gain access to the action site. Acquire (deploy, install, calibrate) the tools and equipment (e.g., put on gloves) to perform the actions. Implement the action steps or continuous action and required timing of steps. Confirm completion of the actions and wait for system feedback.
Interteam coordination	Allocate resources needed for individual teams to perform actions. Implement command and control, including authorizing decisions through the authorization chains. Communicate key information between teams.

Table 3-5 Uncertainty Factors that May Change T_{reqd}

Uncertainty Factors	Considerations
Environmental factors	Environmental factors that affect allowable time for work. Delay in personnel and equipment movement because of external hazards (e.g., bad weather makes it take longer than usual to move personnel and equipment). Limited continuous habitation (e.g., high radiation and dose exposure limits or external hazards reduce the habitable duration a worker can spend in the work area).
Plant condition	Simultaneous multiple events that demand the same set of resources. Multiunit events (e.g., an external hazard impacts multiple units at the same site). Plantwide conditions that may distract supervisors' and operators' attention or introduce competing demands and delays.
Work site accessibility	Different travel paths to worksite (e.g., the shortest path to the work area may not be available so workers need to travel alternative paths). Hurdles to access the worksite (e.g., security system denies access).
Information availability	Visibility of information. Familiarity with the sources of information.
Procedures/ instructions applicability and training	Applicability of procedures or instructions. Recency of training.
Decisionmakers	Variability of decisionmakers. Variability in decision infrastructure. Communication in distributed decisionmaking.
Staff	Staff adequacy (e.g., whether concurrent activities would reduce the staff available for the action or whether tasks can be performed concurrently with more than adequate staff). Certain skill requirements may apply to the staff. Command and control structure. Staff experience (e.g., whether less trained, nonregular staff is used).
Equipment, tools, parts, and keys	Familiarity with setting up and operating the equipment. The availability and the time required to obtain the needed parts, fuel, and keys to set up and operate the equipment.
Scenario familiarity	Familiarity with the scenario.
Fatigue (mental and physical)	Time of day. Duration of having been on shift.
Crew-to-crew variability	Crew-to-crew variability in time required to perform the same actions; different crews may take different procedure paths, which leads to variability in time required.

Option 2: PNNL staff proposed a method to develop the distribution of T_{reqd} based on a data analysis of operator action completion times (time required) in EPRI NP-6937-L [17]. PNNL's proposed method is summarized as follows [16]:

- Given a point estimate for an operator action T_{reqd}:
    - Set the point estimate as the median of the lognormal distribution and calculate the scale parameter as $\ln(median)$.
    - Use 0.28 as the shape parameter of the lognormal distribution.
- Given a conservative (i.e., 95th percentile) estimate for an operator action T_{reqd}:
    - Set $95^{th}\ percentile/1.585$ as the median of the lognormal distribution[3] and calculate the scale parameter as $\ln(median)$.
    - Use 0.28 as the shape parameter of the lognormal distribution.

The shape parameter of 0.28 was derived from operator actions performed inside the control room of NPPs (i.e., in-control-room actions). For operator actions outside the control room of an NPP (i.e., ex-control-room actions), the shape parameter of 0.28 may be used as well. However, P_t results for ex-control-room actions may be too optimistic because the T_{reqd} variability (represented by the shape parameter) of ex-control-room actions could be greater than the T_{reqd} variability of in-control-room actions.

Again, IDHEAS-ECA does not limit the probability distributions that may be used to calculate P_t. To support the calculation of P_t, the IDHEAS-ECA software offers five options to represent T_{reqd}: (1) normal distribution,[4] (2) lognormal distribution, (3) gamma distribution, (4) Weibull distribution, and (5) five-point estimation of a probability distribution.

With respect to the five-point estimation of probability distribution, if operational data are not adequate for confident estimation of the parameters of an assumed parametric probability distribution, or if evidence suggests that a parametric distribution is not appropriate for the situation (for example, the personnel modeled fall into two distinctive groups), HRA analysts can estimate five points of the time distribution at the 5th, 25th, 50th, 75th, and 95th percentiles. The IDHEAS-ECA software interpolates the full distribution based on the five-point estimates.

Note that the IDHEAS-ECA software does not provide the option of entering a single number for T_{reqd}. This is because the time required to perform an action can vary with a variety of time contributing factors such as those listed in Table 3-4 and with a variety of time uncertainty factors such as those listed in Table 3-5.

Guidance for Calculating P_t

Assuming that the HRA analyst estimates the parameters of the probability distributions (central tendency and dispersion) for T_{reqd} and T_{avail}, P_t is calculated using Equation (3.7) and any general-purpose computation software. The IDHEAS-ECA software has a function to calculate P_t for the assumed distributions and parameters of T_{avail} and T_{reqd}. Table 3-6 shows an example of the implementation of Equation (3.7) using OpenBUGS [22] or MultiBUGS [23], [24]

---

[3] The 1.585 value is the error factor (EF) of the lognormal distribution with a shape parameter of 0.28 (i.e., $EF = \exp(1.645 \times 0.28) \approx 1.585$). According to Section A.7.3 of NUREG/CR-6823 [14], the ratio of the 95th percentile and the error factor results in the median.

[4] See footnote 2.

for the base case (i.e., T_{reqd} and T_{avail} are lognormally distributed) and several sensitivity cases. The distribution parameters for T_{reqd} and T_{avail} were calculated using the equations in Appendix C assuming that 20 minutes and 24 minutes are the 50th (median) and 95th percentiles of the T_{reqd} distribution, respectively, and 30 minutes and 35 minutes are the 50th and 95th percentiles of the T_{avail} distribution, respectively.

Table 3-6 Example Implementation of Equation (3.7) Using OpenBUGS [22] or MultiBUGS [23], [24]

```
model {
t.reqd ~ dlnorm(mu.t.reqd.lnorm, tau.t.reqd.lnorm) # distribution of time required, lognormal

t.avail.lnorm ~ dlnorm(mu.t.avail.lnorm, tau.t.avail.lnorm) # distribution of time available, lognormal (base case)
t.avail.norm ~ dnorm(mu.t.avail.norm, tau.t.avail.norm) # distribution of time available, normal (sensitivity 1)
t.avail.weib ~ dweib(alpha.t.avail.weib, lambda.t.avail.weib) # distribution of time available, Weibull (sensitivity 2)
t.avail.gamma ~ dgamma(alpha.t.avail.gamma, theta.t.avail.gamma) # distribution of time available, gamma (sensitivity 3)

tau.t.reqd.lnorm <- pow(sigma.t.reqd.lnorm, -2) # time required lognormal dist parameter conversion
tau.t.avail.lnorm <- pow(sigma.t.avail.lnorm, -2) # time available lognormal dist parameter conversion
tau.t.avail.norm <- pow(sigma.t.avail.norm, -2) # time available normal dist parameter conversion
lambda.t.avail.weib <- pow(beta.t.avail.weib, -alpha.t.avail.weib) #time available Weibull dist parameter conversion
theta.t.avail.gamma <- pow(beta.t.avail.gamma, -1) # time available gamma dist parameter conversion

Pt.base <- step(t.reqd - t.avail.lnorm) #base case, monitor this node, gives P(Treqd lognormal > Tavail lognormal)
Pt.sens.a <- step(t.reqd - t.avail.norm) #sensitivity 1, monitor this node, gives P(Treqd lognormal > Tavail normal)
Pt.sens.b <- step(t.reqd - t.avail.weib) #sensitivity 2, monitor this node, gives P(Treqd lognormal > Tavail Weibull)
Pt.sens.c <- step(t.reqd - t.avail.gamma) #sensitivity 3, monitor node, gives P(Treqd lognormal > Tavail gamma)
Pt.sens.d <- step(t.reqd - mu.t.avail.norm) #sensitivity 4, monitor node, gives P(Treqd lognormal > fixed Tavail)

}
data
list(mu.t.reqd.lnorm=3.0, sigma.t.reqd.lnorm=0.11, mu.t.avail.lnorm=3.4, sigma.t.avail.lnorm=0.094,
mu.t.avail.norm=30, sigma.t.avail.norm=3.04, alpha.t.avail.weib=9.50, beta.t.avail.weib=31.18,
alpha.t.avail.gamma=108.4, beta.t.avail.gamma=0.28)
```

Table 3-7 shows the results of running the script in Table 3-6 using 1 million samples. The script in Table 3-6 may be modified for other probability distributions supported by OpenBUGS or MultiBUGS considering the appropriate parameterization of the selected probability distributions.

Table 3-7 P_t Results for Example in Table 3-6

Case	T_{reqd} Distribution	T_{avail} Distribution	P_t
Base Case	Lognormal	Lognormal	2.9×10^{-3}
Sensitivity 1	Lognormal	Normal	5.9×10^{-3}
Sensitivity 2	Lognormal	Weibull	2.5×10^{-2}
Sensitivity 3	Lognormal	Gamma	2.9×10^{-3}
Sensitivity 4	Lognormal	Not applicable (fixed)	1.3×10^{-4}

Sensitivity 4 in Table 3-7 can also be calculated by using Equation (3.8), which is a reduction of Equation (3.7) when T_{avail} is fixed [13].

$$P_t = P(T_{reqd} > T_{avail}) = 1 - \mathrm{F}_{\mathrm{T_{reqd}}}(T_{avail}) \tag{3.8}$$

In Equation (3.8), $\mathrm{F}_{\mathrm{T_{reqd}}}(T_{avail})$ is the cumulative distribution function of T_{reqd} evaluated using the T_{avail} estimate. Equation (3.8) can also be thought of as a nonresponse probability; that is, the action could not be completed in time; and therefore the action failed [16]. It should be noted that using a fixed T_{avail} will underestimate the resulting P_t.

In the special case where both T_{avail} and T_{reqd} are normally distributed, Equation (3.7) can be calculated as follows [21]:

$$P_t = 1 - \Phi\left[\frac{\mu_{T_{avail}} - \mu_{T_{reqd}}}{\sqrt{\sigma^2_{T_{avail}} + \sigma^2_{T_{reqd}}}}\right] \tag{3.9}$$

which results in $P_t \approx 5.1 \times 10^{-3}$ and can be viewed as an additional sensitivity case to those shown in Table 3-7. In Equation (3.9), $\Phi[\cdot]$ is the standard normal cumulative distribution function[5] for the term inside the brackets. Figure 3-9 shows a graphical representation of P_t for the base case in which both T_{reqd} and T_{avail} are lognormally distributed. P_t is proportional to the area under the intersection of the two probability distributions.

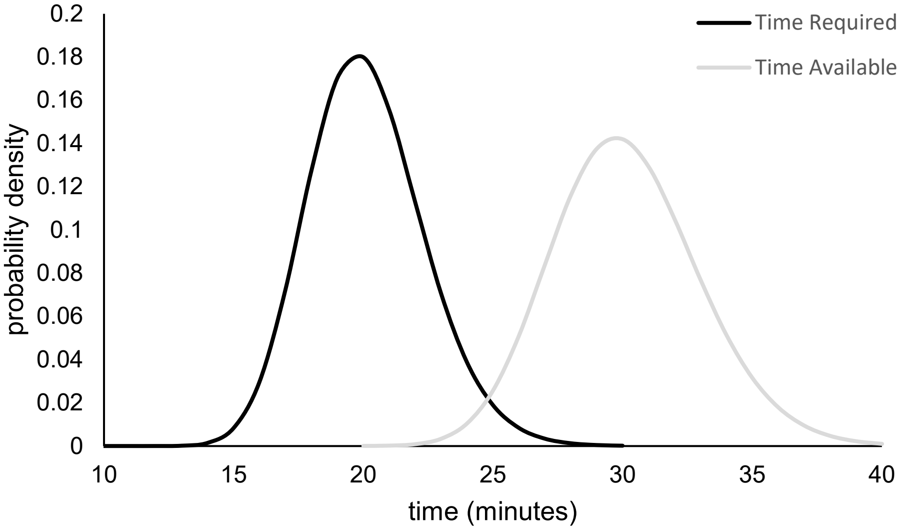


Figure 3-9 Graphical Representation of P_t

---

[5] In Microsoft Excel, the function for the standard normal cumulative distribution function is "=norm.s.dist(z,true)" where z is the term inside the brackets in Equation (3.9).

3.7 Step 7 – Calculate the Overall Human Error Probability

Using the results from Step 5 (P_c) and Step 6 (P_t), the overall HEP is calculated using Equation (3.1). The IDHEAS-ECA software performs this calculation. Alternatively, it can be performed using any general calculation software or manually.

3.8 Step 8 – Analyze Uncertainties, Perform Sensitivity and Dependency Analyses, and Document the Results

PRA is a probabilistic model that characterizes the aleatory uncertainty associated with accidents at NPPs in that the results are given in terms of the likelihoods of accident sequences. The purpose of the uncertainty analysis performed as part of the PRA process is to characterize uncertainties associated with the results of the PRA model. NUREG-1855 [25] provides guidance for treatment of three types of uncertainty in PRA: parameter uncertainty, model uncertainty, and completeness uncertainty. The assessment of uncertainty in HEPs is a required part of the PRA.

Assessment of the uncertainty in the HEPs should be performed (at least for the significant HEPs) to the extent that these uncertainties need to be understood and addressed to make appropriate risk-informed decisions. Step 8 of IDHEAS-ECA is to analyze uncertainties associated with the obtained mean HEPs and perform the sensitivity analysis. This step adapts the guidance for HRA good practices (NUREG-1792 [26]), as follows:

(1) *Systematically analyze and document uncertainties in Steps 1–5*. The uncertainties should include (a) those epistemic uncertainties existing because of lack of knowledge of the true expected performance of the human for a given context and associated set of PIFs, and (b) consideration of the combined effect of the relevant aleatory (i.e., random) factors to the extent that they are not specifically modeled in the PRA and to the extent that they could alter the context and PIFs for the HFE.

(2) *Develop uncertainty distributions for the significant HEPs to capture the center, body, and range of an HEP associated with the uncertainty factors.* If different and significant levels of an uncertainty factor, for example *training and experience*, are known to exist, it is random as to which personnel will perform the action at any given time. Thus, the mean for the single HFE/HEP should represent the average training and experience level, and the uncertainty should reflect the uncertainty attributable to the variation of the levels and any other relevant factors.

(3) *Perform sensitivity analyses that demonstrate the effects on the risk results for extreme estimates in the HEPs based on at least the expected uncertainty range*. Analysts may propagate the extreme HEPs of the distributions through the quantitative analysis of the entire PRA, such as by a Monte Carlo technique. For the uncertainty that results from whether a PIF attribute should be included in the HEP calculation, IDHEAS-ECA recommends using sensitivity analysis or bounding analysis for HFEs that have significant impact on the risk (at the PRA level). Note that a sensitivity analysis should examine the PIF attributes that are important contributors to the HEP, even though such attributes might have been omitted with justifications. Omission of the PIF attribute may inappropriately suppress the importance of specific HFEs that would have been significant if the attribute had been included in the analysis. Thus, to examine the sensitivity to an omitted PIF attribute, it is necessary to add the attribute, requantify the HEPs for all affected HFEs (regardless of their nominal significance), and then requantify

the PRA model to determine the corresponding change (increase) in risk. In some cases, it may be sufficient to address the uncertainties only with qualitative arguments without the need to specifically quantify them (e.g., justifying why a change in the HEP has little relevance to the risk-informed decision to be made). In other cases, the HEP uncertainties may have significant impact on the risk-informed decision to be made. Analysts may choose to explicitly model the HFE as two or more different events, one for each representative situation. For example, one HFE is for the situation when a less experienced crew is on shift and one for the situation when a more experienced crew is on shift.

In IDHEAS-ECA, various sources of information are used to assess the impact of PIF attributes on HEPs. These sources collectively represent a range of the impacts of the PIFs. The IDHEAS-ECA method derives a best-estimate impact (i.e., the base HEPs and PIF weights) from a variety of available human error data and uses the best estimate impact for point estimates. A future development in IDHEAS-ECA uncertainty analysis will be to use an uncertainty distribution to represent PIF impacts. Monte Carlo sampling can be used to calculate the integrated uncertainty distribution of multiple PIF attributes with uncertainty distributions.

3.9 Summary of IDHEAS-ECA

Relationship among the IDHEAS-ECA Steps

IDHEAS-ECA consists of eight steps. Performing an HRA with IDHEAS-ECA entails carrying out all eight steps and documenting the results of each step. The results of one step serve as the input to subsequent steps. Below is the outline of the relationship among the steps:

(1) The process begins with analyzing the event scenario. The results of the analysis include scenario definition, operational narrative, scenario context, and a list of HFEs in the event. The results from Step 1 serve as the inputs to all other steps.

(2) Step 2 focuses on each HFE identified in Step 1. The results of the analysis include the HFE definition, which contains an HFE timeline; the task diagram, which graphically illustrates the success and failure paths of an action; and the critical tasks that must be completed for the success of the action.

(3) Step 3 focuses on critical tasks. The results include the characterization of every critical task and the identification of the applicable CFMs determined by the macrocognitive functions required to perform the cognitive activities in the task. Task characterization specifies the information in Step 1 and Step 2 (i.e., the operational narrative and context of the scenario, the HFE definition, and the task diagram/timeline) for individual critical tasks.

(4) Step 4 focuses on determining PIF attributes applicable to individual CFMs. The results are the applicable PIF attributes for every CFM. The determination of applicable PIF attributes is based on the scenario context, HFE definition, and task characterization.

(5) Step 5 calculates the HEPs of each applicable CFM; these HEPs are probabilistically summed and result in P_c. This step uses the CFMs identified in Step 3 and PIF attributes identified in Step 4 as the input to the calculation.

(6) Step 6 focuses on calculating P_t by estimating the parameters of the probability distributions of time available and time required for the HFE.

(7) Step 7 takes the results from Steps 5 and 6 and calculates the overall HEP using Equation (3.1).

(8) Step 8 performs uncertainty, sensitivity, and dependency analyses and documents the overall HRA results.

Steps 1, 2, 3, and 4 all require information collection. These steps are equivalent to the qualitative analysis portion in many HRA methods. They transform the qualitative information that analysts collect for the HRA into structured elements that assist HRA quantification in later steps. Steps 5, 6, and 7 consist of HRA quantification. The quantification is based on the specific formats of IDHEAS-ECA qualitative analysis steps. After completing and documenting the results of Steps 1 through 3 (e.g., by using the IDHEAS-ECA worksheet in Appendix A), the IDHEAS-ECA software assists HRA analysts with Steps 4, 5, 6, and 7.

IDHEAS-ECA Summary

Table 3-8 summarizes what is needed for every IDHEAS-ECA step, including the object of the analysis, key outputs, and the corresponding function of the IDHEAS-ECA software. Notice that the IDHEAS-ECA software has the additional function of generating an analysis report that summarizes the results. Also, Appendix A provides a worksheet to document the results.

Table 3-8 Summary of the IDHEAS-ECA HRA Process

Step	Input (Object of analysis)	Output (Analysis Results)	IDHEAS-ECA Software
Step 1: Scenario Analysis	The scenario	Operational narrative, scenario context, and list of HFEs	Not applicable (N/A)
Step 2: Analyzing HFEs	An HFE	HFE definition, task diagrams, and list of critical tasks	N/A
Step 3: Modeling Failure of Critical Tasks	A critical task	Task characterization and applicable CFMs	N/A
Step 4: Assessment of PIF Attributes Applicable to CFMs	CFMs	PIF attributes applicable to the CFMs	The software helps go through the CFMs and PIF attributes and select them.
Step 5: Estimation of P_c	An HFE with all critical tasks, CFMs, and PIF attributes	Probability of every CFM, failure probability of every critical task, and P_c	The software calculates P_c based on the selected critical tasks, CFMs, and PIF attributes.
Step 6: Estimation of P_t	An HFE	Parameters for the distributions of T_{avail} and T_{reqd}, and the calculated P_t	The software allows specification of the probability distributions for T_{avail} and T_{reqd} and, given the distribution parameters, calculates P_t.

Table 3-8 Summary of the IDHEAS-ECA HRA Process

Step	Input (Object of analysis)	Output (Analysis Results)	IDHEAS-ECA Software
Step 7: Calculate the Overall HEP	The values of P_c and P_t	The overall HEP	The software calculates the overall HEP using Equation (3.1).
Step 8: Analyze Uncertainties, Perform Sensitivity and Dependency Analyses, and Document the Results	Information and analyst's epistemic uncertainty from previous steps (e.g., other PIF attribute selections), and other HFEs (if any)	Documentation of results from all previous steps and their justification, including sensitivity of HEP results to analyst's epistemic uncertainty and dependent HFE(s)	The software generates a summary report for analysts to document the justification, uncertainties, and results.

4 DISCUSSION AND CONCLUDING REMARKS

4.1 From IDHEAS-G to IDHEAS-ECA

IDHEAS-G is a general HRA methodology from which application-specific HRA methods can be developed. IDHEAS-G consists of a cognitive basis structure, an HRA process implementing the cognitive basis structure, supplementary guidance for performing the HRA process, and an interface (Human Error Tables) for generalizing human error data. IDHEAS-G is intended to be general enough so that it can be adapted to all nuclear HRA applications. It has the following features [1]:

- IDHEAS-G has a basic set of CFMs at three levels of detail and 20 PIFs each with a comprehensive list of attributes. These allow the modeling of the variety of human actions and contexts in NPP HRA applications. Yet, using all the detailed CFMs and PIF attributes can be very time consuming for HRA analysts.

- IDHEAS-G provides multiple approaches for estimating HEPs. It is intended that different approaches may be adapted for specific HRA applications, depending on the available resources and data.

- IDHEAS-G establishes a set of Human Error Tables that generalize human error data from various sources to the IDHEAS-G CFMs and PIFs. Yet, using the data in the tables to inform HEPs requires integrating the data for the specific HEP estimation approach.

Developing an application-specific HRA method from IDHEAS-G is to have a method specific for the application, concise and easy to use, and ideally having a HEP model that allows analysts to calculate HEPs. IDHEAS-G recommends the following approach for developing an application-specific HRA method:

- Define the scope of the application, requirements, and available sources for the intended use.

- Keep the qualitative analysis the same as that in IDHEAS-G.

- Develop application-specific sets of CFMs, PIFs, and an HEP calculation model.

The NRC defines the development of IDHEAS-ECA method as the following:

- Scope: The method should allow for the performance of event and condition assessments for NPP HRA applications. Specifically, it should be able to model operator actions outside control rooms under severe operating conditions, such as implementation of FLEX strategies.

- Requirements: The method should be easy to use and should not overburden HRA analysts. It should allow HRA analysts to quickly explore “what-if” questions in an HRA.

- Data sources: The data sources are IDHEAS-DATA and the data in the NRC’s Scenario Authoring, Characterization, and Debriefing Application (SACADA) database.

With the above definition, the following approach was taken to develop the IDHEAS-ECA method:

- Adapt the same guidance for the scenario, HFE, and task analysis, as well as the guidance for time uncertainty analysis, as those in IDHEAS-G.
- Use the five high-level CFMs (failure of D, U, DM, E, and T) to model failure of a critical task.
- Use all 20 PIFs but with a consolidated subset of the attributes.
- Use the HEP calculation model in IDHEAS-G for analysts to directly calculate HEPs of CFMs for any selection of PIF attributes.
- Integrate the available human error data to obtain the base HEPs and PIF weights needed in the HEP calculation model.

Table 4-1 summarizes the commonality and differences between IDHEAS-ECA and IDHEAS-G. The left column shows the elements in IDHEAS-G. The right column highlights how the IDHEAS-G element is implemented in the eight-step process of IDHEAS-ECA.

Table 4-1 Summary of IDHEAS-ECA Development from IDHEAS-G

IDHEAS-G	IDHEAS-ECA
Scenario analysis	Step 1: • Same guidance as in IDHEAS-G • Specifications on guiding questions for identifying context
HFE and task analysis	Step 2: • Same as in IDHEAS-G • Specific guidance and options on estimating time distribution
Modeling the failure of the critical tasks in an HFE – three levels of CFMs in progressively greater detail	Step 3: • Use the five high-level CFMs (i.e., failure of the macrocognitive functions) • Specific guidance on assessing applicable CFMs
Modeling context with PIFs – 20 PIFs each with a comprehensive list of attributes	Step 4: • All 20 PIFs preserved • A compressed set of PIF attributes based on human error data available (combining attributes with similar effects) • Specific guidance on assessing PIF attributes
HEP estimation – Several approaches to estimate HEPs along with generalized human error data	Steps 5 and 7 • Use the HEP calculation model in IDHEAS-G • Have all the base HEPs and PIF attribute weights by integrating the generalized human error data
Time uncertainty analysis	Steps 6 and 7 • Same as in IDHEAS-G

Table 4-1 Summary of IDHEAS-ECA Development from IDHEAS-G

IDHEAS-G	IDHEAS-ECA
	• Specific guidance and options on estimating time distribution
Uncertainty documentation and sensitivity analysis	Step 8 • Same as in IDHEAS-G with concise guidance

Regardless of HRA application, Steps 1, 2, and 3 of the methodology involve the qualitative analyses of the scenario context and timing, definition of the HFEs and their associated critical tasks, and identification of the CFMs that apply for each critical task. The scenario context also determines which PIFs apply for each HFE, and it affects how analysts evaluate specific PIF attributes for each CFM. Thus, Steps 1, 2, and 3 are the fundamental elements of the methodology.

The experience from practical analyses and benchmark studies has shown that comprehensive and systematic qualitative analyses are essential for realism and fidelity in the HRA process [19], [20]. Benchmark studies have also shown that differences in the qualitative analyses are an important source of analyst-to-analyst variability when any HRA methodology is used. In fact, deficiencies in most contemporary guidance for the performance of those qualitative analyses were one of the primary motivations for developing the IDHEAS methodology.

4.2 Integration of Human Error Data for IDHEAS-ECA

IDHEAS-G generalized human error data from various sources into IDHEAS-DATA (to be published as a RIL), which consists of multiple human error data tables, each documenting human error rates with respect to PIFs, PIF interaction, lowest HEPs, and other elements in HRA. The tables document human error data that are generalized into the IDHEAS-G taxonomy (the CFMs and PIF attributes). The generalized data are used to inform HEPs in various approaches to HEP estimation. In developing IDHEAS-ECA, the NRC staff integrated the available data as of July 2019 in the Human Error Tables to develop the base HEPs and PIF weights for every CFM and PIF attribute in IDHEAS-ECA. Because of the limited amount of data, the integration involves interpolation, reasoning, and engineering judgment. Appendix B to this report presents the integrated base HEPs and PIF weights. Below are some general strategies the NRC staff used in the integration:

- Multiple data points for a base HEP or PIF weight

  The human error data are first evaluated for their uncertainties and practicality in the source documents. The NRC staff considered that the NPP operational data that were systematically collected for HRA had the highest practicality while cognitive experiments performed in research laboratories with students were the least practical. The NRC staff used data with high practicality to anchor a base HEP or PIF weight and used other data points to adjust the uncertainties in the high-practicality data points.

- Data points on the combined effects of several CFMs and/or PIF attributes

  When there were multiple data points with combined effects of two or three CFMs or PIF attributes, the NRC staff performed data fitting to get the best-fit base HEP or PIF weight. When there were only a few data points or a variety of CFMs and PIFs were involved in the data points, the staff combined the data points to estimate the range then used the middle of the range as the base HEP or PIF weight.

- No data point for a PIF weight

  The available data in IDHEAS-DATA do not have numeric human error information for many attributes in the PIFs such as *work process* and *teamwork and organizational factors*. Yet, studies have demonstrated that those attributes impact human performance in measures other than human error rates, such as increasing personnel workload or reducing situational awareness. The NRC staff assigned the PIF weight as 1.1 or 1.2 for those attributes, pending future updates as relevant human error data become available.

- Consistency checking and adjustment with benchmark values

  After the initial base HEPs and PIF weights are developed, they are checked for internal consistency against the literature that ranks the likelihood of certain types of human errors and the contribution of various PIFs.

In the future, the process of synthesizing and using the data points in IDHEAS-DATA database should use the approach of Bayesian techniques. The data points in the existing database can provide the underlying prior distribution for each HEP and each PIF weight. Those without any data points so far could be based on the experience and judgment of the subject matter experts. The uncertainties in those estimates may be rather large, but the distributions should have reasonable bounds and shapes. In other words, the experts' knowledge may not necessarily be well-represented by something like a purely noninformative Jeffreys prior distribution. As more relevant data are compiled, the effects from those data will systematically update the prior estimates and will (usually) reduce the associated uncertainties. The NRC uses this process to estimate equipment reliability (e.g., as in NUREG/CR-6928 [27]), and it is accepted and used throughout the risk assessment community. Thus, the use of Bayesian techniques would provide a systematic, well-accepted method for updating the databases as more information becomes available, and it would provide consistent, technically justified estimates for the uncertainty in each parameter value.

4.3 IDHEAS-ECA Limitations

The users of this report should be aware of the IDHEAS-ECA limitations:

(1) IDHEAS-ECA models failure of human actions using five macrocognitive functions, and it models event context using 20 PIFs, each with a set of attributes. Those attributes address various ways that PIFs challenge human performance in HRA applications. Yet, new HRA applications in the future, such as cybersecurity HRA, may require modeling certain human actions or context in greater detail than what is modeled with the five cognitive failure modes and current PIF attributes. Those situations may require refining the CFMs and PIF attributes. NUREG-2198 [1] describes the guidance on developing application-specific IDHEAS methods and adding PIF attributes.

(2) HEP calculation in IDHEAS-ECA is based on human error data in the IDHEAS-DATA database. Some PIF attributes in IDHEAS-DATA have no quantitative human error data. The impacts of such PIF attributes on HEPs are assigned to a 10 or 20 percent increase to the HEP. The actual impact could be less or more than the assigned value. Those need to be updated as pertinent human error data become available.

(3) IDHEAS-ECA allows the modeling of recovery from human errors. This document has guidance on evaluating recovery opportunities, but it has limited information on quantifying the likelihood of recovery. Future work is needed to develop more specific guidance on crediting human error recovery.

4.4 Future Development and Improvement

The many areas for future development and improvement of the method include the following:

(1) Continuous effort on use of human error data to inform HEPs

The base HEPs and PIF weights in this report are the first version of integrating the data generalized using IDHEAS-DATA. Because of the limited amount of data available, the NRC staff used interpolation, judgment, and benchmarking to develop the full set of base HEPs and PIF weights. In the long-term, generalizing human error data as new data become available should be a continuous effort, and there should be periodic integration and updates of the base HEPs and PIF weights based on the up-to-date available data in the Human Error Tables.

The NRC collects operator simulator training data using the SACADA program. The SACADA program continuously generates operator performance data classified as satisfactory, unsatisfactory, or deviated from the training objectives. The frequency of unsatisfactory performance is considered as human errors. Operator simulator data collection programs are also going on in other organizations such as the Korea Atomic Energy Research Institute. Several research organizations, such as the Organization for Economic Co-operation and Development Halden Reactor Project, have been conducting human performance experiments with nuclear reactor simulators. The experimental results provide human error data relevant to NPP operations. The NRC also plans to reach out to other sources of human performance data. The NRC staff intends to continuously generalize accessible data and add the data to IDHEAS-DATA.

Even if there are multiple data points for a base HEP or PIF weight, judgment and reasoning are still needed in generalizing and integrating the human error data because of uncertainties and complications in the data sources. The data sources, as well as the process and considerations in generating the base HEPs and PIF weights, should be documented. The NRC staff will develop such documentation aside from this method report.

(2) Probability distribution of base HEPs and PIF weights

The base HEPs and PIF weights in this version are single point numbers. In reality, those numbers inherit the uncertainties and variability in the source data, as well as additional uncertainties in the process of data generalization and integration. In the future, it is desirable to develop the probabilistic distribution of the base HEPs and PIF weights to represent their center, body, and range of the numbers.

(3) Supplementary guidance and examples to inform assessment of PIF attributes

To model scenario context with the IDHEAS-ECA PIFs, analysts need to assess the applicability of relevant attributes. This requires engineering judgment. Analyst-to-analyst variability arises from the uncertainties in the information available for analysts to make judgments, as well as from their interpretation of the attributes. The definitions of the attributes in this version of the method are kept concise and general for broad applications. They should be periodically updated for clarification and precision. Moreover, additional attributes may be needed to model new HRA applications or unusual events.

(4) Assessment of recovery

The HEP quantification model in IDHEAS-ECA allows analysts to assign a recovery factor to credit recovery of HFEs in the HEP. The method provides the criteria for crediting recovery and qualitative guidance on assessing the recovery factor. However, a caveat is that the method does not provide guidance on numeric values of recovery factors that should be assigned to a critical task in a given scenario.

The NRC staff did not provide reference numeric values for crediting recovery because the staff had not thoroughly studied this topic to build a solid technical basis for the likelihood of recovery. Some existing HRA methods provide numeric values for crediting recovery. For example, the Standardized Plant Analysis Risk-HRA (SPAR-H) method [28]–[30] credits recovery based on time available. It assigns a recovery factor (multiplier) of 0.1 for “Extra Time” and a factor of 0.01 for “Expansive Time.” Yet, other recovery mechanisms are not weighted in these recovery factors. In the IDHEAS At-Power method (NUREG-2199 [12]), the failure modes for which recovery is feasible are associated with numeric values of the recovery factor for different combinations of applicable PIF attributes. Those numbers were estimated through formal expert judgment. The estimated recovery factors range from 2 to 20. However, those numbers were estimated specifically for the context that licensed NPP crews perform well-trained procedures in control rooms in internal, at-power events. The Cause-Based Decision Tree method [31] also provides numeric values for crediting recovery, while the technical basis and application scope of those numbers are unclear. It is premature to provide numeric recovery factors for a method that is intended for a broad range of HRA applications.

The recommendation for the IDHEAS-ECA method is for analysts to judge the recovery factors and document the basis and justification for recovery feasibility and the assigned number.

(5) PIF interaction

The IDHEAS-ECA HEP quantification model adapts the effects of the three base PIFs on HEPs approximated with a linear relationship, as are the effects of the modification PIFs. The relationship between the base PIFs and modification PIFs is nonlinear and approximated with multiplication. In NUREG-2198 [1],Section 6.2.3 and Appendix D address composite effects that may occur from interactions among multiple PIFs. Appendix D to NUREG-2198 contains some examples which illustrate that the linear sum of PIF weights may not always provide a good estimate for how overall human performance is affected by possibly interrelated PIFs. Future development needs to explicitly identify and model nonlinear interaction between certain PIFs.

(6) Testing and validating the method

In 2019, the NRC held a workshop in which six HRA analysts used the IDHEAS-ECA software to calculate HEPs of the HFEs in implementing FLEX strategies [32]. The analysts were not required to fill out the IDHEAS-ECA worksheets and started from the software. Thus, the analysts essentially performed Steps 4, 5, 6, and 7 of the IDHEAS-ECA process without performing Steps 1, 2, 3, and 8. Note that the exercise requiring analysts to perform only Steps 4, 5, 6, and 7 is neither verification nor validation of the IDHEAS-ECA method. It confirms that people can use the tables in Appendix B and the IDHEAS-ECA software to calculate a numerical value for a HEP. The tables and the software assist the analysts in computing a number after the fundamental elements of the analysis are completed. Nevertheless, that exercise provided useful feedback on whether the software interface is user friendly and whether analysts can follow the quantification process.

In 2021, the NRC staff formed a work group to develop the IDHEAS dependency analysis guidance. Six analysts applied IDHEAS-ECA and the dependency guidance (RIL 2021-14 [4]) to six HRA examples.

4.5 Concluding Remarks

Overall, IDHEAS-ECA is developed as a complete, off-the-shelf HRA method. IDHEAS-ECA is used to analyze human events and estimate HEPs in PRA applications. IDHEAS-ECA builds on existing HRA methods by providing a systematic process and guidelines to analyze and model human actions and the associated scenario context. Further, it uses a human error database to calculate HEPs and includes an extensive set of PIFs to represent the context of scenarios under various operational conditions, such as using FLEX equipment.

IDHEAS-ECA is envisioned for use in the NRC's risk-informed activities. The intent is for the method to be applicable to the same situations that existing HRA methods model (e.g., NPP internal events while at power) and beyond (e.g., external events, low-power and shutdown events, spent fuel storage and transportation, and events involving FLEX equipment). Given the wide range of contextual factors included in its model, it is feasible that IDHEAS-ECA could also be used for applications beyond the nuclear domain.

5 REFERENCES

[1] J. Xing, Y. J. Chang, and J. DeJesus Segarra, “The General Methodology of an Integrated Human Event Analysis System (IDHEAS-G),” U.S. Nuclear Regulatory Commission, NUREG-2198 (ADAMS Accession No. ML21127A272), May 2021.

[2] U.S. Nuclear Regulatory Commission, “Staff Requirements – Meeting with Advisory Committee on Reactor Safeguards, 2:30 p.m., Friday, October 20, 2006, Commissioners’ Conference Room, One White Flint North, Rockville, Maryland (Open to Public Attendance),” U.S. Nuclear Regulatory Commission, SRM M061020 (ADAMS Accession No. ML063120582), Nov. 2006.

[3] A. M. Whaley *et al.*, “Cognitive Basis for Human Reliability Analysis,” U.S. Nuclear Regulatory Commission, NUREG-2114 (ADAMS Accession No. ML16014A045), Jan. 2016.

[4] M. Kichline, J. Xing, and Y. J. Chang, “Integrated Human Event Analysis System Dependency Analysis Guidance (IDHEAS-DEP),” U.S. Nuclear Regulatory Commission, RIL 2021-14 (ADAMS Accession No. ML21316A107), Nov. 2021.

[5] U.S. Nuclear Regulatory Commission, “Acceptability of Probabilistic Risk Assessment Results for Risk-Informed Activities,” U.S. Nuclear Regulatory Commission, Regulatory Guide 1.200, Rev. 3 (ADAMS Accession No. ML20238B871), Dec. 2020.

[6] U.S. Nuclear Regulatory Commission, “Acceptability of Probabilistic Risk Assessment Results for Non-Light-Water Reactor Risk-Informed Activities,” U.S. Nuclear Regulatory Commission, Regulatory Guide 1.247 (ADAMS Accession No. ML21235A008), Mar. 2022.

[7] U.S. Nuclear Regulatory Commission, “NRC Incident Investigation Program,” Management Directive 8.3 (ADAMS Accession No. ML18073A200), Jun. 2014.

[8] American Society of Mechanical Engineers and American Nuclear Society, “Addenda to ASME/ANS RA-S–2008 Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications,” ASME/ANS RA-Sa–2009, Feb. 2009.

[9] American Society of Mechanical Engineers and American Nuclear Society, “Probabilistic Risk Assessment Standard for Advanced Non-Light Water Reactor Nuclear Power Plants,” ASME/ANS RA-S-1.4-2021, Feb. 2021.

[10] M. Barriere *et al.*, “Technical Basis and Implementation Guidelines for A Technique for Human Event Analysis (ATHEANA),” U.S. Nuclear Regulatory Commission, NUREG-1624, Rev. 1 (ADAMS Package No. ML003736288), May 2000.

[11] S. Lewis *et al.*, “EPRI/NRC-RES Fire Human Reliability Analysis Guidelines,” Electric Power Research Institute and U.S. Nuclear Regulatory Commission, EPRI 1023001/NUREG-1921 (ADAMS Accession No. ML12216A104), Jul. 2012.

[12] J. Xing, G. Parry, M. Presley, J. Forester, S. Hendrickson, and V. Dang, “An Integrated Human Event Analysis System (IDHEAS) for Nuclear Power Plant Internal Events At-Power Application,” U.S. Nuclear Regulatory Commission and Electric Power Research Institute, NUREG-2199, Vol. 1 (ADAMS Accession No. ML17073A041), Mar. 2017.

[13] D. C. Bley, D. R. Buttemer, and J. W. Stetkar, “Light water reactor sequence timing: its significance to probabilistic safety assessment modeling,” *Reliab. Eng. Syst. Saf.*, vol. 22, no. 1–4, pp. 27–60, Jan. 1988, doi: 10.1016/0951-8320(88)90066-X.

[14] C. L. Atwood *et al.*, “Handbook of Parameter Estimation for Probabilistic Risk Assessment,” U.S. Nuclear Regulatory Commission, NUREG/CR-6823 (ADAMS Accession No. ML032900131), Sep. 2003.

[15] A. N. O’Connor, M. Modarres, and A. Mosleh, *Probability Distributions Used in Reliability Engineering*. College Park, MD, USA: Center for Risk and Reliability, University of Maryland, 2016. Accessed: May 31, 2022. [Online]. Available: https://crr.umd.edu/books

[16] R. Prasad, G. A. Coles, P. P. Mirick, C. K. Fallon, B. A. Jefferson, and A. C. Dalton, “IDHEAS-DATA Verification: Distribution of Time Needed for Nuclear Power Plant Tasks – Task 2 Deliverable,” Pacific Northwest National Laboratory, PNNL-32384, Rev. 1, Mar. 2022.

[17] A. J. Spurgin *et al.*, “Operator Reliability Experiments Using Power Plant Simulators, Volume 3: Appendices,” Electric Power Research Institute, EPRI NP-6937-L, Volume 3, Jan. 1991. Accessed: May 31, 2022. [Online]. Available: https://www.epri.com/research/products/NP-6937-LV3

[18] N. Johnson and Z. Ma, “Analysis of Loss-of-Offsite-Power Events: 2020 Update,” Idaho National Laboratory, INL/EXT-21-64151, Nov. 2021. Accessed: May 31, 2022. [Online]. Available: https://nrcoe.inl.gov/publicdocs/LOSP/loop-summary-update-2020.pdf

[19] J. Forester *et al.*, “The International HRA Empirical Study: Lessons Learned from Comparing HRA Methods Predictions to HAMMLAB Simulator Data,” U.S. Nuclear Regulatory Commission, NUREG-2127 (ADAMS Accession No. ML14227A197), Aug. 2014.

[20] J. Forester *et al.*, “The U.S. HRA Empirical Study – Assessment of HRA Method Predictions against Operating Crew Performance on a U.S. Nuclear Power Plant Simulator,” U.S. Nuclear Regulatory Commission, NUREG-2156 (ADAMS Accession No. ML16179A124), Jun. 2016.

[21] M. Modarres, M. P. Kaminskiy, and V. Krivtsov, *Reliability Engineering and Risk Analysis: A Practical Guide*, 3rd ed. Boca Raton, FL: CRC Press, 2017.

[22] *OpenBUGS, Version 3.2.3 rev 1012*. 2014. [Online]. Available: https://www.mrc-bsu.cam.ac.uk/software/bugs/openbugs/

[23] R. J. B. Goudie, R. M. Turner, D. De Angelis, and A. Thomas, “MultiBUGS: A Parallel Implementation of the BUGS Modeling Framework for Faster Bayesian Inference,” *J. Stat. Softw.*, vol. 95, no. 7, 2020, doi: 10.18637/jss.v095.i07.

[24] *MultiBUGS, Version 2.0*. 2020. [Online]. Available: https://www.multibugs.org/

[25] M. Drouin *et al.*, “Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decisionmaking,” U.S. Nuclear Regulatory Commission, NUREG-1855, Rev. 1 (ADAMS Accession No. ML17062A466), Mar. 2017.

[26] A. Kolaczkowski, J. Forester, E. Lois, and S. Cooper, “Good Practices for Implementing Human Reliability Analysis,” U.S. Nuclear Regulatory Commission, NUREG-1792 (ADAMS Accession No. ML051160213), Apr. 2005.

[27] S. A. Eide, T. E. Wierman, C. D. Gentillon, D. M. Rasmuson, and C. L. Atwood, “Industry-Average Performance for Components and Initiating Events at U.S.

Commercial Nuclear Power Plants," U.S. Nuclear Regulatory Commission, NUREG/CR-6928 (ADAMS Accession No. ML070650650), Feb. 2007.

[28] D. Gertman, H. Blackman, J. Marble, J. Byers, and C. Smith, "The SPAR-H Human Reliability Analysis Method," U.S. Nuclear Regulatory Commission, NUREG/CR-6883 (ADAMS Accession No. ML051950061), Aug. 2005.

[29] R. L. Boring and H. S. Blackman, "The Origins of the SPAR-H Method's Performance Shaping Factor Multipliers," in *2007 IEEE 8th Human Factors and Power Plants and HPRCT 13th Annual Meeting*, Monterey, CA, USA, Aug. 2007, pp. 177–184. doi: 10.1109/HFPP.2007.4413202.

[30] A. M. Whaley, D. L. Kelly, R. L. Boring, and W. J. Galyean, "SPAR-H Step-by-Step Guidance," Idaho National Laboratory, INL/EXT-10-18533, Rev. 2 (ADAMS Accession No. ML112060305), May 2011.

[31] G. W. Parry, A. J. Spurgin, P. Moieni, and A. Beare, "An Approach to the Analysis of Operator Actions in Probabilistic Risk Assessment," Electric Power Research Institute, TR-100259, Jun. 1992. Accessed: May 31, 2022. [Online]. Available: https://www.epri.com/#/pages/product/TR-100259/?lang=en-US

[32] S. Cooper and C. Franklin, "Applying HRA to FLEX – Using IDHEAS-ECA," U.S. Nuclear Regulatory Commission, RIL 2020-13, Vol. 2 (ADAMS Accession No. ML21032A119), Dec. 2020.

[33] J. Xing and S. Morrow, "White Paper: Practical Insights and Lessons Learned on Implementing Expert Elicitation," U.S. Nuclear Regulatory Commission, (ADAMS Accession No. ML16287A734), Oct. 2016.

[34] J. D. Cook, "Determining distribution parameters from quantiles," The University of Texas M. D. Anderson Cancer Center, Jan. 2010. Accessed: May 31, 2022. [Online]. Available: https://www.johndcook.com/quantiles_parameters.pdf

[35] J. Corson *et al.*, "Confirmatory Thermal-Hydraulic Analysis to Support Specific Success Criteria in the Standardized Plant Analysis Risk Models—Byron Unit 1, Chapters 1 to 8 - Appendices A to C," U.S. Nuclear Regulatory Commission, NUREG-2187, Volume 1 (ADAMS Accession No. ML16021A423), Jan. 2016.

[36] U.S. Nuclear Regulatory Commission IMC 0609, "The Significance Determination Process", (ADAMS Accession No. ML18187A187), Jan. 2019.

APPENDIX A
IDHEAS-ECA WORKSHEET

This worksheet is intended to be used in conjunction with Chapter 3 of this report. Everything highlighted in yellow is supplemental guidance and intended to be replaced by the analyst.

Human Failure Event (HFE) name: [Insert HFE name.]

HFE description: [Insert HFE description.]

Summary of HFE Analysis

HFE	[Insert HFE name.]
Critical Task	[Insert description of critical task within the HFE. If there is more than one critical task within the HFE, duplicate this table.]
CFMs and PIFs	Detection (CFM1) • Scenario familiarity – [Insert assessment of PIF attributes from Step 4.] • Task complexity – [Insert assessment of PIF attributes from Step 4.] • Modification PIFs – [Insert assessment of PIF attributes from Step 4.] Understanding (CFM2) • Scenario familiarity – [Insert assessment of PIF attributes from Step 4.] • Information availability and reliability – [Insert assessment of PIF attributes from Step 4.] • Task complexity – [Insert assessment of PIF attributes from Step 4.] • Modification PIFs – [Insert assessment of PIF attributes from Step 4.] Decisionmaking (CFM3) • Scenario familiarity – [Insert assessment of PIF attributes from Step4] • Information availability and reliability – [Insert assessment of PIF attributes from Step 4.] • Task complexity – [Insert assessment of PIF attributes from Step 4.] • Modification PIFs – [Insert assessment of PIF attributes from Step 4.] Action execution (CFM4) • Scenario familiarity – [Insert assessment of PIF attributes from Step 4.] • Task complexity – [Insert assessment of PIF attributes from Step 4.] • Modification PIFs – [Insert assessment of PIF attributes from Step 4.] Interteam coordination (CFM5) • Task complexity – [Insert assessment of PIF attributes from Step 4.] • Modification PIFs – [Insert assessment of PIF attributes from Step 4.]
Recovery	[If recovery credit is given on a CFM, insert a brief rationale and the value of the recovery factor.]
P_c	[Insert the estimated/calculated value of P_c from Step 5.]
Timing	[If a timing analysis is performed, insert the estimated values for the parameters of the time available and time required distributions from Step 6.]
P_t	[Insert the estimated/calculated value of P_t from Step 6.]
HEP	[Insert the estimated/calculated value of the overall HEP from Step 7.]

Step 1 – Scenario Analysis

Step 1.1 Develop the Operational Narrative

The operational narrative describes the scenario and is based on the probabilistic risk assessment (i.e., the event tree where the HFE is being credited). See Section 3.1.1 for more details about the operational narrative.

[Insert the operational narrative.]

Step 1.2 Identify the Human Failure Events

Section 3.1.2 provides details about the identification of the HFEs.

[Insert the HFE name and its description.]

Step 1.3 Identify the Scenario/Event Context

The scenario/event context describes the conditions that challenge or facilitate the performance of the operator actions. The scenario/event context is documented in the four categories listed below along with the answers to the probing questions and considerations for each context category identified in Section 3.1.3.

- Environment and situation – [Insert brief analysis of this PIF context category and determine whether the PIFs in this context category are applicable (or not applicable) to the HFE and the rationale for such determination.]

- System – [Insert brief analysis of this PIF context category and determine whether the PIFs in this context category are applicable (or not applicable) to the HFE and the rationale for such determination.]

- Personnel – [Insert brief analysis of this PIF context category and determine whether the PIFs in this context category are applicable (or not applicable) to the HFE and the rationale for such determination.]

- Task – [Insert brief analysis of this PIF context category and determine whether the PIFs in this context category are applicable (or not applicable) to the HFE and the rationale for such determination.]

Step 2 – Analyzing Human Failure Events

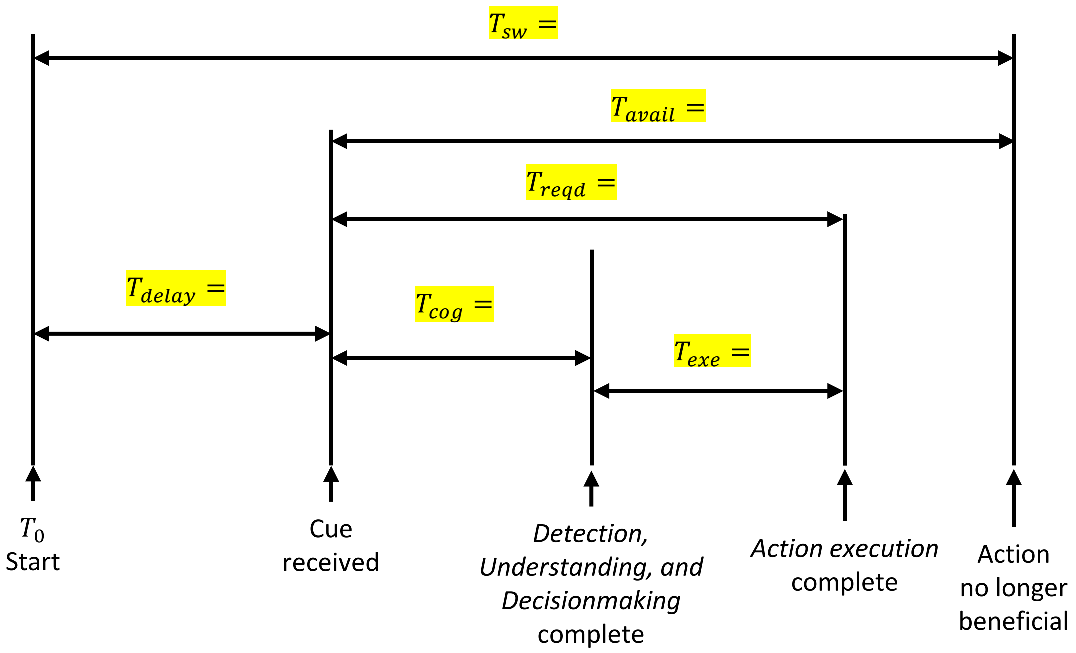
Step 2.1 Defining the Human Failure Events

The definition of the HFE describes the scope of the analysis using the items listed below (see Section 3.2.1).

- Success criteria – [Insert the success criteria in terms of the needed equipment, systems, and operator actions.]

- Consequence – [Insert the consequences of the occurrence of the HFE (i.e., failure of the operator action).]

- Beginning and ending points – [Insert the cue(s) that would prompt the operator to initiate the action and the point at which the operator action ends.]
- Relevant procedure guidance – [List the procedures (if any) that operators would use to perform the action.]
- Cues and indications for initiating the operator action and timing – [Identify the cue that would lead operators to start the action and, based on thermal-hydraulic analyses (or engineering judgment), estimate the time delay ($\mathrm{T_{delay}}$). Note that $\mathrm{T_{delay}}$ may be estimated as a range; for example, $5\ \text{minutes} < \mathrm{T_{delay}} < 15\ \text{minutes}$.]
- Available time to perform the operator action – [Based on thermal-hydraulic analyses (or engineering judgment), estimate the system time window ($\mathrm{T_{sw}}$) and then estimate the time available ($\mathrm{T_{avail}}$) as $\mathrm{T_{sw}} - \mathrm{T_{delay}}$. Note that $\mathrm{T_{sw}}$ may also be estimated as a range, which would result in a range for $\mathrm{T_{avail}}$.]
- Time required to perform the operator action – [Based on the relevant procedure guidance or job performance measures, estimate the time required ($\mathrm{T_{reqd}}$). This may be estimated directly, that is, $\mathrm{T_{reqd}}$ or estimated by adding the estimated time for cognition ($\mathrm{T_{cog}}$) (i.e., *detection*, *understanding*, and *decisionmaking*) and time for *action execution* ($\mathrm{T_{exe}}$). Again, $\mathrm{T_{reqd}}$ may be estimated as a range. Summarize all the time estimates in the figure below. Note that this analysis may be iterative, that is, an analyst may need to look at the relevant procedure guidance or job performance measures in more detail as part of analysis for Step 2.2 through Step 4 and then return to this step to complete the timing analysis.]



Step 2.2 Task Analysis and Identification of Critical Tasks

Section 3.2.2 provides guidance on the task analysis and breaking the HFE into critical tasks.

[Insert how many critical tasks are being defined and the rationale for defining them. For example, in case only one critical task is defined a statement such as the following may be used: "For simplicity, only one critical task is defined and that is, {insert description of HFE}. Also, the HFE is modeled as one critical task because the same context applies from the beginning to the end points of the HFE."]

Step 3 – Modeling Failure of Critical Tasks

Step 3.1 Characterization of Critical Tasks

The characterization of a critical task specifies the relevant conditions that affect the performance of the critical task. These characteristics are listed below (see Section 3.3.1).

- Critical task goal – [Insert suggested information described in Section 3.3.1.]
- Specific requirements – [Insert suggested information described in Section 3.3.1.]
- Cues and supporting information – [Insert suggested information described in Section 3.3.1.]
- Procedures – [Insert suggested information described in Section 3.3.1.]
- Personnel – [Insert suggested information described in Section 3.3.1.]
- Task support – [Insert suggested information described in Section 3.3.1.]
- Location – [Insert suggested information described in Section 3.3.1.]
- Cognitive activities – See Step 3.2.
- Concurrent tasks – [Insert suggested information described in Section 3.3.1.]
- Interteam coordination considerations – [Insert suggested information described in Section 3.3.1. If no multiple teams are not involved in the critical task, the following statement may be used: "Multiple teams are involved in the critical task."]
- Additional task characteristics [If there are no additional task characteristics, delete this bullet item and the sub-bullet item below.]
  - [Insert additional task characteristics, for example, recovery of a CFM.]

Step 3.2 Identification of Applicable Cognitive Failure Modes

The applicable cognitive failure modes (CFMs) are identified by assessing the cognitive activities of the critical task that are associated with each macrocognitive function. Table 3-3 aids in the assessment of the cognitive activities of the critical task. See Section 3.3.2 for more information.

- Detection – [Depending on the critical task being analyzed, insert the types of cognitive activities from Table 3-3 that are used in the critical task being analyzed.]

    - [Insert a brief statement describing how the type of cognitive activity is used in the critical task being analyzed.]
    - CFM1 – failure of detection [APPLIES or DOES NOT APPLY] to the critical task
- Understanding – [Depending on the critical task being analyzed, insert the types of cognitive activities from Table 3-3 that are used in the critical task being analyzed.]
    - [Insert a brief statement describing how the type of cognitive activity is used in the critical task being analyzed.]
    - CFM2 – failure of understanding [APPLIES or DOES NOT APPLY] to the critical task
- Decisionmaking – [Depending on the critical task being analyzed, insert the types of cognitive activities from Table 3-3 that are used in the critical task being analyzed.]
    - [Insert a brief statement describing how the type of cognitive activity is used in the critical task being analyzed.]
    - CFM3 – failure of decisionmaking [APPLIES or DOES NOT APPLY] to the critical task
- Action Execution – [Depending on the critical task being analyzed, insert the types of cognitive activities from Table 3-3 that are used in the critical task being analyzed.]
    - [Insert brief statement describing how the type of cognitive activity is used in the critical task being analyzed.]
    - CFM4 – failure of action execution [APPLIES or DOES NOT APPLY] to the critical task
- Interteam coordination – [Depending on the critical task being analyzed, insert the types of cognitive activities from Table 3-3 that are used in the critical task being analyzed.]
    - [Insert brief statement describing how the type of cognitive activity is used in the critical task being analyzed.]
    - CFM5 – failure of interteam coordination [APPLIES or DOES NOT APPLY] to the critical task

Step 4 – Assessing Performance Influencing Factor Attributes Applicable to Cognitive Failure Modes

The PIF attributes for *scenario familiarity*, *information availability and reliability*, and *task complexity* and their corresponding base HEPs are located in Table B-1 through Table B-3, respectively. For the remaining (modification) PIFs, the PIF attributes and corresponding PIF weights are in Table B-4 through Table B-15. The guidance for this step is located in Section 3.4.

1. CFM1 – failure of detection → [Insert calculation of $\mathrm{P}_{\mathrm{CFM1}}$ based on the assessment of PIF attributes.]
    - Scenario familiarity (Table B-1): [Insert PIF attribute identifier, its description, and Base HEP.]
        - Justification – [Insert justification for selecting the PIF attribute.]
    - Information availability and reliability (Table B-2): This PIF does not apply to this CFM (see the “NA” under the “D” column of Table B-2).
    - Task complexity (Table B-3): [Insert PIF attribute identifier, its description, and Base HEP.]Task complexity (Table B-3): [Insert PIF attribute identifier, its description, and Base HEP.]
        - Justification – [Insert justification for selecting the PIF attribute.]
    - [OPTIONAL – Insert recovery credit for this CFM and its justification. If there is no recovery credit, then delete this line/bullet item.]

- Modification PIFs – [Insert results of assessment of modification PIF attributes.] (see summary of PIF attributes assessment (below))

2. CFM2 – failure of understanding → [Insert calculation of $\mathrm{P}_{\mathrm{CFM2}}$ based on the assessment of PIF attributes.]
   - Scenario familiarity (Table B-1): [Insert PIF attribute identifier, its description, and Base HEP.]
     - Justification – [Insert justification for selecting the PIF attribute.]
   - Information availability and reliability (Table B-2): [Insert PIF attribute identifier, its description, and Base HEP.]
     - Justification – [Insert justification for selecting the PIF attribute.]
   - Task complexity (Table B-3): [Insert PIF attribute identifier, its description, and Base HEP.]
     - Justification – [Insert justification for selecting the PIF attribute.]
   - [OPTIONAL – Insert recovery credit for this CFM and its justification. If there is no recovery credit, then delete this line/bullet item.]
   - Modification PIFs – [Insert results of assessment of modification PIF attributes.] (see summary of PIF attributes assessment (below))

3. CFM3 – failure of decisionmaking → [Insert calculation of $\mathrm{P}_{\mathrm{CFM3}}$ based on the assessment of PIF attributes.]
   - Scenario familiarity (Table B-1): [Insert PIF attribute identifier, its description, and Base HEP.]
     - Justification – [Insert justification for selecting the PIF attribute.]
   - Information availability and reliability (Table B-2): [Insert PIF attribute identifier, its description, and Base HEP.]
     - Justification – [Insert justification for selecting the PIF attribute.]
   - Task complexity (Table B-3): [Insert PIF attribute identifier, its description, and Base HEP.]
     - Justification – [Insert justification for selecting the PIF attribute.]
   - [OPTIONAL – Insert recovery credit for this CFM and its justification. If there is no recovery credit, then delete this line/bullet item.]
   - Modification PIFs – [Insert results of assessment of modification PIF attributes.] (see summary of PIF attributes assessment (below))

4. CFM4 – failure of action execution → [Insert calculation of $\mathrm{P}_{\mathrm{CFM4}}$ based on the assessment of PIF attributes.]
   - Scenario familiarity (Table B-1): [Insert PIF attribute identifier, its description, and Base HEP.]
     - Justification – [Insert justification for selecting the PIF attribute.]
   - Information availability and reliability (Table B-2): This PIF does not apply to this CFM (see the “NA” under the “E” column of Table B-2).
   - Task complexity (Table B-3): [Insert PIF attribute identifier, its description, and Base HEP.]
     - Justification – [Insert justification for selecting the PIF attribute.]

- [OPTIONAL – Insert recovery credit for this CFM and its justification. If there is no recovery credit, then delete this line/bullet item.]
- Modification PIFs – [Insert results of assessment of modification PIF attributes.] (see summary of PIF attribute assessment (below))

5. CFM5 – failure of interteam coordination → [Insert calculation of $\mathrm{P}_{\mathrm{CFM5}}$ based on the assessment of PIF attributes.]

- Scenario familiarity (Table B-1): This PIF does not apply to this CFM (see the “NA” under the “T” column of Table B-1).
- Information availability and reliability (Table B-2): This PIF does not apply to this CFM (see the “NA” under the “T” column of Table B-2).
- Task complexity (Table B-3): [Insert PIF attribute identifier, its description, and Base HEP.]
  - Justification – [Insert justification for selecting the PIF attribute.]
- [OPTIONAL – Insert recovery credit for this CFM and its justification. If there is no recovery credit, then delete this line/bullet item.]
- Modification PIFs – [Insert results of assessment of modification PIF attributes.] (see summary of PIF attribute assessment (below))

Summary of PIF attribute assessment for the remaining (modification) PIFs for all applicable CFMs:

- Environmental PIFs (Table B-4) – [Insert PIF attribute identifier, its description, PIF weight, and the justification for the PIF attribute selection. If the PIF(s) is (are) not applicable the following statement may be used: “As noted in Step 1.3, the PIFs in the environment and situation context do not apply to this HFE. Therefore, for the purpose of quantification, the no impact (**ENV0**) PIF attribute is assigned.”]
- System and Instrumentation and Control (I&C) Transparency (Table B-5) – [Insert PIF attribute identifier, its description, PIF weight, and the justification for the PIF attribute selection. If the actions are performed in the main control room (MCR), the following statement may be used: “No impact (**SIC0**) for all applicable CFMs because the actions are performed in the MCR and the system response and I&C should be transparent to the operators due to their training.”]
- Human-System Interface (HSI) (Table B-6) – [Insert PIF attribute identifier, its description, PIF weight, and the justification for the PIF attribute selection. If the actions are performed in the main control room (MCR), the following statement may be used: “No impact (**HSI0**) for all applicable CFMs because the actions are performed in the MCR and the MCR’s design complies with regulatory requirements.”]
- Equipment and Tools (Table B-7) – [Insert PIF attribute identifier, its description, PIF weight, and the justification for the PIF attribute selection. If the actions are performed in the main control room (MCR), the following statement may be used: “No impact (**TP0**) for all applicable CFMs because the equipment and tools that are used to perform the actions (i.e., switches, buttons, etc.) are assumed to be well maintained.”]
- Staffing (Table B-8) – [Insert PIF attribute identifier, its description, PIF weight, and the justification for the PIF attribute selection. If staffing that is compliant with regulatory requirements, the following statement may be used: “No impact (**STA0**) for all applicable CFMs because adequate staffing is assumed.”]

- Procedures, Guidance, and Instructions (Table B-9) – [Insert PIF attribute identifier, its description, PIF weight, and the justification for the PIF attribute selection. If the actions are performed in accordance with the emergency operating procedures, the following statement may be used: “No impact (**PG0**) for all applicable CFMs because operators are following the emergency operating procedures.”]
- Training (Table B-10) – [Insert PIF attribute identifier, its description, PIF weight, and the justification for the PIF attribute selection. If the actions are performed in the main control room (MCR) by trained operators, the following statement may be used: “No impact (**TE0**) for all applicable CFMs because the MCR operators performing the actions are assumed to licensed and have adequate training.”]
- Teamwork and Organizational Factors (Table B-11) – [Insert PIF attribute identifier, its description, PIF weight, and the justification for the PIF attribute selection. If the actions are performed in the main control room (MCR) by trained operators, the following statement may be used: “No impact (**TF0**) for all applicable CFMs because the teamwork and organizational factors are assumed to be adequate.”]
- Work Processes (Table B-12) – [Insert PIF attribute identifier, its description, PIF weight, and the justification for the PIF attribute selection. If the actions are performed in the main control room (MCR) by trained operators, the following statement may be used: “No impact (**WP0**) for all applicable CFMs because the work processes are performed by licensed personnel with assumed good practices.”]
- Multitasking, Interruption, and Distraction (Table B-13) – [Insert PIF attribute identifier, its description, PIF weight, and the justification for the PIF attribute selection. If the actions are performed in the main control room (MCR) by trained operators, the following statement may be used: “No impact (**MT0**) for all applicable CFMs because all attention by the MCR operators is directed at bringing the reactor to a safe and stable condition.”]
- Mental Fatigue, and Time Pressure and Stress (Table B-14) – [Insert PIF attribute identifier, its description, PIF weight, and the justification for the PIF attribute selection.]
- Physical Demands (Table B-15) – [Insert PIF attribute identifier, its description, PIF weight, and the justification for the PIF attribute selection. If the actions are performed in the main control room (MCR), the following statement may be used: “No impact (**PD0**) for CFM4 (failure of action execution) because MCR actions are not expected to require extraordinary efforts. Note that the PIF physical demands do not affect CFM1 (failure of detection), CFM2 (failure of understanding), and CFM3 (failure of decisionmaking).”]

Step 5 – Estimation of Pc – the Sum of Human Error Probabilities of Cognitive Failure Modes

The estimation of P_c relies on the assessment of the PIF attributes performed in Step 4. [The following statement is only applicable if there is only one critical task: “Since in Step 2.2 we defined the HFE as having only one critical task, P_c is equal to the error probability of the critical task.”] The error probability of the critical task is estimated using Equation (3.3) as:

$$P_c = P_{CT1} = 1 - [(1 - P_{CFM1}) \cdot (1 - P_{CFM2}) \cdot (1 - P_{CFM3}) \cdot (1 - P_{CFM4}) \cdot (1 - P_{CFM5})] = ?$$

This calculation can also be performed using the IDHEAS-ECA software.

Step 6 – Estimation of Pt – the Convolution of the Distribution of Time Available and Time Required

Time available

[Insert analysis to estimate the probability distribution parameters of time available.]

Time required

[Insert analysis to estimate the probability distribution parameters of time required.]

Calculation of P_t

[Otherwise, insert the result for P_t obtained from the IDHEAS-ECA software or any other general calculation software.]

Step 7 – Calculate the Overall Human Error Probability

The overall HEP is calculated using Equation (3.1), which is implemented in the IDHEAS-ECA software, as follows:

P([insert HFE name]) $= 1 - (1 - P_c) \cdot (1 - P_t) = 1 - (1 - ?) \cdot (1 - ?)$

$= ?$

Step 8 – Analyze Uncertainties, Perform Sensitivity and Dependency Analyses, and Document the Results

[Insert uncertainties in the analysis, below is an example. See Section 3.8 for more guidance.]

There are a few uncertainties in this analysis, which are as follows:

- Manual reactor trip vs. automatic reactor trip – If the reactor is manually tripped (e.g., operators may detect a trend in an important parameter that will compel them to trip the reactor), operators have more time to initiate feed and bleed cooling. That is, they have about 40 minutes to perform the action. The current analysis assumes that the reactor trips automatically.
- Operators may hesitate to initiate feed and bleed cooling. This would be reflected in CFM3 (failure of decisionmaking) by assigning PIF attribute C25 to Task Complexity. The current analysis assumes that operators do not hesitate to perform the action.
- The recovery factor assigned to CFM1 (i.e., $\mathrm{Re} = 2$) was based on analyst judgment; however, this assignment did not significantly impact the estimation of P_c and the overall HEP.

References

[OPTIONAL but recommended – insert references, below is an example.]

[1] J. Xing, J. Chang, and J. DeJesus, “Integrated Human Event Analysis System for Event and Condition Assessment (IDHEAS-ECA),” U.S. Nuclear Regulatory Commission, RIL-2020-02 (ADAMS Accession No. ML20016A481), Feb. 2020.

APPENDIX B
BASE HUMAN ERROR PROBABILITIES AND PERFORMANCE INFLUENCING FACTOR WEIGHTS

This appendix presents the base human error probabilities (HEPs) of the three base performance influencing factors (PIFs) *Scenario Familiarity*, *Information Availability and Reliability*, and *Task Complexity* in Table B-1, Table B-2, and Table B-3, respectively. Table B-4 through Table B-15 present the PIF weights for the modification PIFs. In general, each table corresponds to one PIF except that Table B-4 contains the PIF weights for several PIFs in the environmental context PIF category, and Table B-14 contains PIF weights for two PIFs, *Mental Fatigue* and *Time Pressure and Stress*.

Each row in a table is for one attribute, with the first row for the “no impact” state of a PIF. The first column in a table is an identifier assigned for a PIF attribute. For example, the attributes for the PIF *Scenario Familiarity* have the identifiers SF1, SF2, SF3, and SF4 while “SF0” is the identifier for “no impact,” the base state of the PIF. The second column is the description of every PIF attribute. The remaining five columns contain the base HEP of a cognitive failure mode (CFM) or the PIF weight on the CFM imposed by the PIF attribute of the row. These five columns are for failure of *detection* (**D**), *understanding* (**U**), *decisionmaking* (**DM**), *action execution* (**E**), and *interteam coordination* (**T**), respectively. The one exception is Table B-3 in which the base HEPs are separately presented for each CFM.

The base HEPs for the “No impact” states of the base PIFs in Table B-1, Table B-2, and Table B-3 (i.e., SF0, Inf0, C0, C10, C20, C30, and C40) are shown as zero. However, in the case that the three base PIFs are in their “No impact” state, $P_{CFM_{Base}}$ (see Equation (3.5)) is not zero and should be assigned a value of the lowest HEP of a CFM, which is 1×10^{-4} for failure of Detection or Action Execution, and 1×10^{-3} for failure of Understanding, Decisionmaking, or Interteam coordination.

The base HEPs and PIF weights in Table B-1 through Table B-15 are based on human error data generalized in the IDHEAS-DATA database with the following exceptions:

1) A PIF weight of 1.1 is used as a placeholder to represent the effect of a PIF attribute on a CFM when there is qualitative evidence in the literature showing that the PIF attribute adversely impacts the macrocognitive function, but no quantitative data were identified.

2) A PIF weight of 1.2 is used as a placeholder to represent the effect of a PIF attribute on a CFM when there are human performance data in the literature showing that the PIF attribute adversely impacts the macrocognitive function, but there is not sufficient information to convert the human performance measures to human error rates.

Table B-1 Base HEPs for Scenario Familiarity

PIF Attribute		D	U	DM	E	T
SF0	No-impact • frequently performed tasks in well-trained scenarios, • routine tasks	0	0	0	0	0
SF1	Unpredictable dynamics in known scenarios • shifting task objectives, • dynamic decisionmaking is required	6.6E-4	6.6E-3	6.6E-3	6.6E-4	NA
SF2	Unfamiliar elements in the scenario • nonroutine, infrequently performed tasks, • unlearn a technique and apply one that requires the application of an opposing philosophy	5E-3	5E-2	5E-2	5E-3	NA
SF3	Scenarios trained on but infrequently performed	E-3	E-2	E-2	E-3	NA
	Scenario is unfamiliar, rarely performed • notice adverse indicators that are not part of the task at hand • notice incorrect status that is not a part of the routine tasks	1.2E-2	E-1	E-1	3.3E-2	NA
	Extremely rarely performed • lack of plans, policies, and procedures to address the situation • no existing mental model for the situation • rare events such as the Fukushima accident	3.3E-2	3E-1	3E-1	3.5E-1	NA
SF4	Bias or preference for wrong strategies exists, mismatched mental models	NA	2.6E-2	2.6E-2	NA	NA

Table B-2 Base HEPs for Information Availability and Reliability

PIF Attribute		D	U	DM	E	T
Inf0	No impact – Key information is reliable and complete.	0	0	0	0	0
Inf1	Information is temporarily incomplete or not readily available. Inadequate updates of information: • Feedback information is not available in time to correct a wrong decision or adjust the strategy implementation • Different sources of information are not well organized thus personnel cannot readily access all the information needed • Primary source of information is not available and secondary source of the information is in lower resolution	NA	5E-3	5E-3	NA	NA
	Information is moderately incomplete – a small portion of key information is missing	NA	5E-2	5E-2	NA	NA
	Information is largely incomplete • Key information is masked • Key indication is missing	NA	2E-1	2E-1	NA	NA

Table B-2 Base HEPs for Information Availability and Reliability (continued)

PIF Attribute		D	U	DM	E	T
Inf2	Low unreliable or uncertain • Personnel are aware that source of information could be temporarily unreliable • Pieces of information change over time; thus, they become uncertain by the time personnel use them	NA	E-2	E-2	NA	NA
	Moderately unreliable or uncertain • Source of information could be unreliable and personnel likely recognize this • Conflicts in key information	NA	5E-2	5E-2	NA	NA
	Highly unreliable • Key information is highly uncertain	NA	E-1	E-1	NA	NA
	Extremely unreliable • Key information is misleading • Key information is inaccurate	NA	3E-1	3E-1	NA	NA

Table B-3 Base HEPs for Task Complexity

PIF Attribute		Detection
C0	No impact on HEP	0
C1	Detection overload with multiple competing signals - track the states of multiple systems, - monitor many parameters, - memorize many pieces of information detected - many types or categories of information to be detected	Few (<7) 3E-3 Multiple (7~11) 1E-2 Many (11~20) 1E-1 Excessive amount (>20) 3E-1
C2	Detection is moderately complex - criteria are not straightforward, - information of interest involves complicated mental computation - comparing for abnormality is necessary	E-3
C3	Detection demands for high attention - need split attention - need sustained attention over a period of time - need intermittent attention	E-3
C4	Detection criteria are highly complex - multiple criteria must be met in complex logic, - information of interest must be determined based on other pieces of information - detection criteria are ambiguous and need subjective judgment	E-2
C5	Cues for detection are not obvious - detection is not directly cued by alarms or instructions and personnel need to actively search for the information	5E-2
C6	No cue or mental model for detection - no rules / procedures / alarms to cue the detection; detection of the critical information is entirely based on personnel's experience and knowledge	E-1

Table B-3 Base HEPs for Task Complexity (continued)

PIF Attribute		Understanding
C10	No impact – straightforward diagnosis with clear procedures or rules	0
C11	Working memory overload - need to decipher numerous messages (indications, alarms, spoken messages) - Multiple causes for situation assessment: Multiple independent ‘influences’ affect the system and system behavior cannot be explained by a single influence alone	E-2 for <11 messages 5E-2 for 11~15 E-1 for 15-20 3E-1 for > 20
C12	Relational complexity (number of unchunkable topics or relations in one understanding task) - Relations involved in a human action are very complicated for understanding - Need to integrate (use together) multiple relations	2E-2 for 2 relations 4.5E-2 for 3 relations E-1 for 4 relations 3E-1 for more than 4 relations
C13	Understanding complexity - requiring high level of comprehension	E-2
C14	Potential outcome of situation assessment consists of multiple states and contexts (not a simple yes or no)	E-2
C15	Ambiguity associated with assessing the situation - Key information for understanding is cognitively masked - Pieces of key information are intermingled or coupled	E-1
C16	Conflicting information, cues, or symptoms	E-1

Table B-3 Base HEPs for Task Complexity (continued)

PIF Attributes		Decisionmaking
C20	No impact – simple, straightforward choice	0
C21	Transfer step in procedure –integrating a few cues	4.5E-3
C22	Transfer procedure (multiple alternative strategies to choose) – integrating multiple cues	1.2E-2
C23	Decision criteria are intermingled, ambiguous, or difficult to assess	1E-2
C24	Multiple goals difficult to prioritize (e.g., advantage for incorrect strategies)	3.3E-2
C25	Competing or conflicting goals (e.g., choosing one goal will block achieving another goal, low preference for correct strategy, reluctance and viable alternative)	1.4E-1
C26	Decisionmaking involves developing strategies or action plans	5E-2
C27	Decisionmaking requires diverse expertise distributed among multiple individuals or parties who may not share the same information or have the same understanding of the situation	1E-1
C28	Integrating a large variety of types of cues with complex logic	1.7E-1

Table B-3 Base HEPs for Task Complexity (continued)

PIF Attributes		Action Execution
C30	No impact – simple execution with a few steps	0
C31	Straightforward procedure execution with many steps	E-3
C32	Nonstraightforward procedure execution - Very long procedures, voluminous documents with checkoff provision - Multiple procedures needed	5E-3
C33	Simple continuous control that requires monitoring parameters	3.4E-4
C34	Continuous control that requires manipulating dynamically	2.6E-3
C35	Long-lasting action, repeated discontinuous manual control (need to monitor parameters from time to time)	2E-2
C36	No immediacy to initiate execution - time span between annunciation (decision for execution made) and operation	5E-3
C37	Complicated or ambiguous execution criteria - multiple, coupled criteria - restrictive, irreversible order of multiple steps - open to misinterpretation	E-2
C38	Action execution requires close coordination of multiple personnel at different locations	5E-2
C39	Unlearn or break away from automaticity of trained action scripts	1E-1

Table B-3 Base HEPs for Task Complexity (continued)

PIF Attributes		Interteam Coordination
C40	No impact – Clear, streamlined, crew-like communication and coordination	0
C41	Complexity of information communicated – simple (e.g., notifying / requesting to ex-MCR) - 1.5E-3 Moderate - E-2 High – 5E-2 Extremely high – E-1	
C42	Complex or ambiguous command-and-control	E-2
C43	Complex or ambiguous authorization chain	E-2
C44	Coordinate activities of multiple diverse teams or organizations	E-2

Table B-4 PIF Weights for Environmental PIFs

PIF Attribute		D	U	DM	E	T
ENV0	No impact – nominal weather and environmental factors	1	1	1	1	1
ENV1	Coldness on action execution Moderate cold (<5°C) – 1.5 Extreme coldness on manipulating instrumentation - 2 Extreme coldness on physically demanding execution -5 Extreme coldness on high precision manipulations (e.g., connecting lines to pump, remove air from lines and pumps) - 20	NA	NA	NA	1.5 2 5 20	NA
ENV2	Moderate coldness (<5°C) for nonexecution	1.15	1.15	1.15	NA	1.15
ENV2	Extreme coldness for nonexecution	2	2	1.15	NA	2
ENV3	Heat (>33°C) or high humidity	1.15	1.15	1.15	1.5	1.15
ENV4	Poor lighting, low luminance (L=0.15, compared to no impact L=1.5) for reading information or execution	2	NA	NA	2	NA
ENV5	Strong ambient light, glare, reflection	2	NA	NA	1.5	NA
ENV6	Very low visibility (e.g., heavy smoke or fog) for detecting targets or execution	5	NA	NA	5	NA
ENV7	Loud or burst noise	1.7	1.15	1.15	1.15	1.15
ENV8	Wearing heavy protective clothes and/or gloves	NA	NA	NA	1.5	NA
ENV9	Slippery surface (e.g., icing)	NA	NA	NA	1.5	NA
ENV10	Strong winds, rain, or objects close to road on physically demanding tasks	NA	NA	NA	1.5	NA
ENV11	Strong winds, rain, or objects close to road impeding vehicle movement	NA	NA	NA	2	NA
ENV12	High or chaotic traffic impeding vehicle movement	NA	NA	NA	1.5	NA
ENV13	Unstable or vibrating surface or work site	NA	NA	NA	2	NA

Table B-5 PIF Weights for System and I&C Transparency

PIF Attribute		D	U	DM	E	T
SIC0	No impact	1	1	1	1	NA
SIC1	System or I&C does not behave as intended under special conditions	1.1	1.1	1.1	1.1	NA
SIC2	System or I&C does not reset as intended	1.1	1.1	1.1	10	NA
SIC3	System or I&C is complex or nontransparent for personnel to predict its behavior	NA	2	NA	NA	NA
SIC4	System or I&C failure modes are not transparent to personnel	NA	2	NA	NA	NA

Table B-6 PIF Weights for Human-System Interface

PIF Attribute		D	U	DM	E	T
HSI0	No impact – well designed HSI supporting the task	1	1	1	1	1
HSI1	Indicator is similar to other sources of information nearby	1.5	NA	NA	NA	NA
HSI2	No sign or indication of technical difference from adjacent sources (meters, indicators)	3	NA	NA	NA	NA
HSI3	Related information for a task is spatially distributed, not organized, or cannot be accessed at the same time	1.5	2	NA	NA	NA
HSI4	Unintuitive or unconventionnel indications	2	NA	NA	NA	NA
HSI5	Poor salience of the target (indicators, alarms, alerts) out of the crowded background	3	NA	NA	NA	NA
HSI6	Inconsistent formats, units, symbols, or tables	5	NA	NA	NA	NA
HSI7	Inconsistent interpretation of displays	NA	5.7	NA	NA	NA
HSI8	Similarity in elements - Wrong element selected in operating a control element on a panel within reach and similar in design in control room	NA	NA	NA	1.2	NA
HSI9	Poor functional localization – 2~5 displays / panels needed to execute a task	NA	NA	NA	2	NA
HSI10	Ergonomic deficits - Controls are difficult to maneuver - Labeling and signs of controls are not salient among crowd - Inadequate indications of states of controls - Small unclear labels, difficult reading scales - Maneuvers of controls are unintuitive or unconventional	NA	NA	NA	3.38	NA
HSI11	Labels of the controls do not agree with document nomenclature, confusing labels	NA	NA	NA	5	NA
HSI12	Controls do not have labels or indications	NA	NA	NA	10	NA
HSI13	Controls provide inadequate or ambiguous feedback (i.e., lack of or inadequate confirmation of the action executed (incorrect, no information provided, measurement inaccuracies, delays))	NA	NA	NA	4.5	NA
HSI14	Confusion in action maneuver states (e.g., automatic resetting without clear indication)	NA	NA	NA	10	NA
HSI15	Unclear functional allocation (between human and automation)	NA	NA	NA	9	NA

Table B-7 PIF Weights for Equipment and Tools

PIF Attribute		D	U	DM	E	T
TP0	No impact – tools and parts are well maintained under proper administrative control	1	1	1	1	1
TP1	Tools/parts are complex or difficult to use	1.1	NA	NA	1.1	NA
TP2	Failure modes or operational conditions of the tools are not clearly presented (e.g., ranges, limitations, and requirements)	1.1	NA	NA	1.1	NA
TP3	Tool does not work properly due to aging, lack of power, incompatibility, improper calibration, etc.	1.1	NA	NA	1.1	NA
TP4	Document nomenclature does not agree with equipment labels	2	NA	NA	2	NA
TP5	Personnel are unfamiliar or rarely use the tool/parts	2	NA	NA	2	NA
TP6	Tools or parts lack proper administrative control (so could be missing or temporarily not available)	2	NA	NA	2	NA

Table B-8 PIF Weights for Staffing

PIF Attribute		D	U	DM	E	T
STA0	No impact – adequate staffing	1	1	1	1	1
STA1	Shortage of staffing (e.g., key personnel are missing, unavailable or delayed in arrival, staff pulled away to perform other duties)	1.1	1.1	1.1	1.1	1.1
STA2	Lack of backup/lack of peer check or cross-checking (e.g., an overseer or independent reviewer is not available)	1.1	1.1	1.1	1.1	1.1
STA3	Ambiguous or incorrect specification of staff roles and responsibilities	1.1	1.1	1.1	1.1	1.1
STA4	Inappropriate staff assignment (e.g., lack of skills)	1.1	1.1	1.1	1.1	1.1
STA5	Key decisionmaker's knowledge and ability are inadequate to make the decision (e.g., lack of required qualifications or experience)	1.1	1.1	1.1	1.1	1.1
STA6	Lack of administrative control of fitness-for-duty	1.1	1.1	1.1	1.1	1.1

Table B-9 PIF Weights for Procedures, Guidance, and Instructions

PIF Attribute		D	U	DM	E	T
PG0	No impact – well validated procedures like most EOPs	1	1	1	1	1
PG1	Procedure design is less than adequate (difficult to use) - requires calculation (e.g., unit conversion) - no placeholders - graphics or symbols not intuitive - inconsistency between procedure and displays	1.2	1.1	1.1	1.2	1.1
PG2	Procedure wording requires judgment	1.6	1.6	1.6	3	1.1
PG3	Procedure lacks details	2.2	2.2	2.2	2.2	1.1
PG4	Procedure is ambiguous, confusing	1.5	5	5	3	5
PG5	Mismatch - Procedure is available but does not match the situation (e.g., needs deviation or adaptation)	1.1	17	17	1.1	10
PG6	No verification in procedure for verifying key parameters for detection or execution	20	NA	NA	20	10
PG7	No guidance to seek confirmatory data when data may mislead for diagnosis or decisionmaking	NA	30	30	NA	10

Table B-10 PIF Weights for Training

PIF Attribute		D	U	DM	E	T
TE0	No impact - professional staff have adequate training required	1	1	1	1	1
TE1[a]	Inadequate training frequency/refreshment	Frequent (<6 months) - 1 Infrequent (6-12m) – 1.2 Highly infrequent (> 4 years) - 5	Frequent (<6 months) - 1 Infrequent (6-12m) – 1.2 Highly infrequent (> 4 years) - 10	Frequent (<6 months) - 1 Infrequent (6-12m) – 1.2 Highly infrequent (> 4 years) - 10	Frequent (<6 months) - 1 Infrequent (6-12m) – 1.2 Highly infrequent (> 4 years) - 10	Frequent (<6 months) - 1 Infrequent (6-12m) – 1.2 Highly infrequent (> 4 years) -5
TE2	Inadequate training practicality – no hands-on training • not drilled together • training on parts, not whole scenario together	1.5	1.5	1.5	1.5	1.5
TE3	Inadequate training on procedure adaptation: Training focuses on following procedures without adequately training personnel to seek alternative interpretations, evaluate the pros and cons of alternatives, and adapt the procedure for the situation	1.1	2	2	2	NA
TE4	Inadequate amount of training - no qualification exam • less than adequate training specification / requirement	1.8	3	3	6.1	NA
TE5	Operator inexperienced (e.g., a newly qualified tradesman, but not an “expert”)	3	3	3	3	NA

Table B-10 PIF Weights for Training (continued)

PIF Attribute		D	U	DM	E	T
TE6	Poor administrative control on training (e.g., not included in the Systematic Approach to Training Program)	2	2	10	10	NA
TE7	Inadequate training or experience with sources of information (such as applicability and limitations of data or the failure modes of the information sources)	14	NA	NA	NA	NA
TE8	Inadequate specificity on urgency and the criticality of key information such as key alarms	20	NA	NA	NA	NA
TE9	Not trained to seek confirmatory information when dismissing critical data	NA	10	10	NA	NA
TE10	Premature termination of critical data collection in diagnosis due to inadequate training on system failure modes	NA	15	NA	NA	NA
TE11	Poor training on assessing action margin in deciding implementation delay	NA	NA	5	NA	NA
TE12	Poor training on interpreting procedure in the context of the scenario for decisionmaking	NA	NA	11	NA	NA
TE13	Poor training on the importance of data in frequently checking data for execution	NA	NA	NA	10	NA

Notes

a. U.S. nuclear power plants use a Systematic Approach to Training (SAT) process to determine the training frequency. When assessing attribute TE1 for operator actions in a nuclear power plant where SAT is in place, analysts may link the assessment of TE1 to the SAT levels such as the following, instead of using the anchoring training frequencies suggested in the table:
   - ☐ Frequent – SAT standard backbone
   - ☐ Infrequent – SAT infrequent
   - ☐ Highly infrequent – Not in SAT

Table B-11 PIF Weights for Teamwork and Organizational Factors

PIF Attribute		D	U	DM	E	T
TF0	No impact – adequate, crew-like teams	1	1	1	1	1
TF1	Inadequate team • inadequate teamwork resources (short of personnel, knowledge gaps) • distributed, or dynamic teams • poor team cohesion ((e.g., newly formed teams, lack of drills or experience together)	2	2	2	2	2
TF2	Poor command and control • unclear allocation of functions and responsibilities • inadequate coordination between site personnel and decisionmakers (e.g., adapt or modify planned actions based on site situation) • inadequately verify the plan with decisionmakers • inadequate supervision of overseeing action execution and questioning current mission	1.5	1.5	1.5	1.5	1.5
TF3	Poor information management in multiple-team tasks	NA	NA	NA	NA	2
TF4	Poor communication capabilities between teams	NA	NA	NA	NA	2
TF5	Competing resources available for multiple teams	NA	NA	NA	NA	1.5

Table B-12 PIF Weights for Work Processes

PIF Attribute		D	U	DM	E	T
WP0	No impact – licensed personnel with good work practices	1	1	1	1	1
WP1	Lack of practice of self- or cross-verification (e.g., three-way communication)	10	1.15	1.15	10	1.1
WP2	Lack of or ineffective peer-checking or supervision	10	1.1	1.1	10	1.1
WP3[a]	Poor work prioritization, scheduling	10	50	50	10	1.1
WP4	Lack of or ineffective instrumentation (e.g., prejob briefing) for personnel to be aware of potential pitfalls in performing the tasks	1.1	1.1	1.1	1.1	1.1
WP5	Lack of or ineffective instrumentation (e.g., supervision) for safety issue monitoring and identification	1.1	1.1	1.1	1.1	1.1
WP6	Lack of or ineffective instrumentation for safety reporting	1.1	1.1	1.1	1.1	1.1
WP7	Hostile work environment	1.1	1.1	1.1	1.1	1.1

Notes

a. In 2021, three subject matter experts estimated he PIF weights for WP3 by using a formal expert elicitation process described by Xing and Morrow [33]. If this attribute is used in a HRA using IDHEAS-ECA, analysts shall document the uncertainty associated with this attribute.

Table B-13 PIF Weights for Multitasking, Interruption, and Distraction

	PIF Attribute	D	U	DM	E	T
MT0	No impact	1	1	1	1	1
MT1	Distraction by other ongoing activities that demand attention	Weak - 1.2 Moderate - 2 High - 2.8	1.15	1.15	Weak - 1.2 Moderate - 2 High - 2.8	Weak - 1.2 Moderate - 2 High - 2.8
MT2	Interruption taking away from the main task	Weak – 1.15 Moderate – 2.8 Frequent or long - 4	Weak – 1.15 Moderate – 1.5 Frequent or long– 1.7	Weak – 1.15 Moderate – 1.5 Frequent or long– 1.7	Weak – 1.15 Moderate – 2.8 Frequent or long - 4	Weak – 1.1 Moderate – 2.8 Frequent or long - 4
MT3	Concurrent visual detection and other tasks	Low demanding -2 Moderate demanding – 5 High demanding - 10	NA	NA	NA	NA
MT4	Concurrent auditory detection and other tasks	Auditory / visual -10 Auditory / auditory - 20	NA	NA	NA	NA
MT5	Concurrent diagnosis and other tasks	NA	Low demanding – 3 High demanding - 30	NA	NA	NA
MT6	Concurrent go/no-go decisionmaking	NA	NA	2	NA	NA
MT7	Concurrently making intermingled complex decisions/plans	NA	NA	5	NA	NA
MT8	Concurrently executing action sequence and performing another attention/working memory task	NA	NA	NA	2.3	NA
MT9	Concurrently executing intermingled or interdependent action plans	NA	NA	NA	5	NA
MT10	Concurrently communicating or coordinating multiple distributed individuals or teams	NA	NA	NA	NA	5

Table B-14 PIF Weights for Mental Fatigue and Time Pressure and Stress

PIF Attribute		D	U	DM	E	T
MF0	No impact	1	1	1	1	1
MF1	Sustained (>30mins) high-demanding cognitive activities requiring continuous attention (e.g., procedure-situation mismatches demand constant problem-solving and decisionmaking; information changes over time and requires sustained attention to monitor or frequent checking.)	2.5	1.15	1.15	2.5	1.1
MF2	Time pressure due to perceived time urgency	2	2	1.15	3	1.1
MF3	Lack of self-verification due to need to rush the task completion (speed-accuracy tradeoff)	10	2	2	10	2
MF4	Reluctance to execute an action plan due to potential negative impacts (e.g., adverse economic impact, or personal injury)	NA	NA	NA	2	NA
MF5	Long working hours (greater than 4 hours) with high cognitively demanding tasks	1.5	1.5	1.2	1.5	1.2
MF6	Sudden increase in workload from a long period of low to high	1.2	1.2	NA	1.2	1.2
MF7	Sudden decrease in workload from high to normal	1.8	1.1	NA	1.8	1.2
MF8	Emotional stress (e.g., anxiety, frustration)	1.2	1.2	1.2	1.2	1.2
MF9	Physical stress or fatigue (e.g., long hours of exposure to ambient noise, disturbed dark and light rhythms, air pollution, disruption of normal work-sleep cycles, ill health)	1.25	1.1	1.1	1.21	1.1
MF10	Sleep deprivation	2	1.21	1.11	2	1.2

Table B-15 PIF Weights for Physical Demands

PIF Attribute		D	U	DM	E	T
PD0	No impact				1	
PD1	Physically strenuous - possibly exceeding physical limits (e.g., lifting heavy objects, moving heavy things, opening/closing rusted or stuck valves)	NA	NA	NA	1.5	NA
PD2	High spatial or temporal precision	NA	NA	NA	2	NA
PD3	Precise motor coordination of multiple persons	NA	NA	NA	2	NA
PD4	Unusual, unevenly balanced loads (e.g., reaching high parts)	NA	NA	NA	5	NA
PD5	Loading or unloading objects using crane/hoist	NA	NA	NA	10	NA

APPENDIX C
CALCULATION OF PROBABILITY DISTRIBUTION PARAMETERS GIVEN TWO PERCENTILES

C.1 Introduction

The purpose of this appendix is to show how to calculate the parameters of several two-parameter probability distributions given two percentiles (quantiles). The essence of the derivation is having two equations with two unknowns. This appendix is mostly based on the work by Cook [34] with a detailed explanation of the equations to calculate the parameters.

The general idea is that analysts (or experts) can be asked to estimate or give their judgment on the following:

(1) A range of values (i.e., lower and upper estimates) where the true value for a quantity (or random variable) of interest may exist; that is, x_1 and x_2.

(2) The percentiles (e.g., 5th and 95th) corresponding to the lower and upper estimates, respectively; that is, p_1 and p_2.

Based on this information and a justified probability distribution assumption, the probability distribution parameters can be calculated. The requirements are that $p_2 > p_1$ and $x_2 > x_1$. Recall that $0 \leq p_1 \leq 1$ and $0 \leq p_2 \leq 1$.

Alternatively, instead of asking analysts for the percentiles of their estimates (i.e., Item 2 above), analysts can be asked how confident they are about the true value of the quantity being in the range that they provided or estimated. Then, Equations (C.1) and (C.2) can be used to calculate the percentiles.

$$p_1 = \frac{1 - confidence\ level}{2} \tag{C.1}$$

$$p_2 = \frac{1 + confidence\ level}{2} \tag{C.2}$$

As an example, consider that an analyst is 80 percent confident (i.e., $confidence\ level = 0.8$) that the true value of the quantity is within a range; therefore, the percentiles are $p_1 = (1 - 0.8)/2 = 0.1$ and $p_2 = (1 + 0.8)/2 = 0.9$. In other words, in addition to the range of the quantity of interest, the analyst is asked for one piece of information (i.e., the confidence level), instead of two pieces of information (i.e., p_1 and p_2).

This appendix is organized as follows. Section C.2 shows the derivation for the parameters of the normal distribution. Section C.3 discusses several parameterizations for the lognormal distribution and how to calculate those parameters. Sections C.4 and C.5 calculate the parameters for the Weibull and gamma distributions, respectively.

C.2 Normal Distribution

Consider the cumulative distribution function (cdf) of the normally distributed random variable X:

$$F_X(x) = \mathrm{P}(X \leq x) = \Phi\left[\frac{x-\mu}{\sigma}\right] = p \tag{C.3}$$

where x is the value of random variable X, μ is the mean of X, σ is the standard deviation of X, p is the percentile (which is related to the value of the cdf), and $\Phi[\cdot]$ is the standard normal cdf[1] of the term inside the brackets. Next, take the inverse of Equation (C.3) to obtain:[2]

$$\begin{aligned} \frac{x-\mu}{\sigma} &= \Phi^{-1}[p] \\ x-\mu &= \sigma \cdot \Phi^{-1}[p] \\ x &= \sigma \cdot \Phi^{-1}[p] + \mu \end{aligned} \tag{C.4}$$

Then, apply Equation (C.4) to two percentiles, p_1 and p_2, with their corresponding random variable values x_1 and x_2.

$$x_1 = \sigma \cdot \Phi^{-1}[p_1] + \mu \tag{C.5}$$

$$x_2 = \sigma \cdot \Phi^{-1}[p_2] + \mu \tag{C.6}$$

Now, solve Equations (C.5) and (C.6) for σ, equate them because they represent the same probability distribution, and solve for μ as follows:

$$\begin{aligned} \frac{x_2-\mu}{\Phi^{-1}[p_2]} &= \frac{x_1-\mu}{\Phi^{-1}[p_1]} \\ (x_2-\mu)\cdot\Phi^{-1}[p_1] &= (x_1-\mu)\cdot\Phi^{-1}[p_2] \\ x_2\cdot\Phi^{-1}[p_1] - \mu\cdot\Phi^{-1}[p_1] &= x_1\cdot\Phi^{-1}[p_2] - \mu\cdot\Phi^{-1}[p_2] \\ \mu\cdot\Phi^{-1}[p_2] - \mu\cdot\Phi^{-1}[p_1] &= x_1\cdot\Phi^{-1}[p_2] - x_2\cdot\Phi^{-1}[p_1] \\ \mu\{\Phi^{-1}[p_2] - \Phi^{-1}[p_1]\} &= x_1\cdot\Phi^{-1}[p_2] - x_2\cdot\Phi^{-1}[p_1] \\ \mu &= \frac{x_1\cdot\Phi^{-1}[p_2] - x_2\cdot\Phi^{-1}[p_1]}{\{\Phi^{-1}[p_2] - \Phi^{-1}[p_1]\}} \end{aligned} \tag{C.7}$$

Similarly, solve Equation (C.5) and (C.6) for μ, equate them because they represent the same probability distribution, and solve for σ as follows:

---

[1] In Excel, the standard normal cdf is "=norm.s.dist(z)," where z is the value of the term inside the brackets in Equation (C.3).

[2] In Excel, the inverse of the standard normal cdf is "=norm.s.inv(p)," where p is the value of the cdf (probability), which is related to the percentile.

$$x_1 - \sigma \cdot \Phi^{-1}[p_1] = x_2 - \sigma \cdot \Phi^{-1}[p_2]$$

$$\sigma \cdot \Phi^{-1}[p_2] - \sigma \cdot \Phi^{-1}[p_1] = x_2 - x_1$$

$$\sigma\{\Phi^{-1}[p_2] - \Phi^{-1}[p_1]\} = x_2 - x_1 \tag{C.8}$$

$$\sigma = \frac{x_2 - x_1}{\{\Phi^{-1}[p_2] - \Phi^{-1}[p_1]\}}$$

C.3 Lognormal Distribution

If the random variable Y is lognormally distributed, the transformation $X = \ln(Y)$ transforms Y into a normally distributed random variable X.[3] Then, the cdf of the lognormally distributed random variable Y can be calculated using the standard normal cdf as follows:

$$F_{\ln(Y)}(\ln(y)) = P(\ln(Y) \le \ln(y)) = \Phi\left[\frac{\ln(y) - \mu}{\sigma}\right] \tag{C.9}$$

Equation (C.9) means that the lognormally distributed random variable Y can be parameterized using the mean and standard deviation of the normal distribution (i.e., μ and σ).[4] Using Equations(C.7) and (C.8) with the transformation $x_i = \ln(y_i)$, Equations (C.10) and (C.11), respectively, calculate the mean and standard deviation of the normal distribution.

$$\mu = \frac{ln(y_1) \cdot \Phi^{-1}[p_2] - ln(y_2) \cdot \Phi^{-1}[p_1]}{\{\Phi^{-1}[p_2] - \Phi^{-1}[p_1]\}} \tag{C.10}$$

$$\sigma = \frac{ln(y_2) - ln(y_1)}{\{\Phi^{-1}[p_2] - \Phi^{-1}[p_1]\}} \tag{C.11}$$

The reader should not confuse the parameters calculated using Equations (C.10) and (C.11) with the mean and standard deviation of the lognormal distribution (i.e., μ_Y and σ_Y), which can be defined as a function of the parameters μ and σ [14], [21]:

$$\mu_Y = \exp\left(\mu + \frac{\sigma^2}{2}\right) \tag{C.12}$$

$$\sigma_Y = \mu_Y \cdot \sqrt{\exp(\sigma^2) - 1} \tag{C.13}$$

If μ_Y and σ_Y are known, the parameters μ and σ can be calculated as follows [21]:

---

[3] Equivalently, if random variable X is normally distributed, the transformation $Y = \exp(X)$ transforms it into a lognormally distributed variable Y.

[4] Alternatively, μ and σ may be referred to as the "mean of the natural logarithm data" and "standard deviation of the natural logarithm data," respectively.

$$\mu = \ln\left(\frac{\mu_Y}{\sqrt{1+\left(\frac{\sigma_Y^2}{\mu_Y^2}\right)}}\right) \tag{C.14}$$

$$\sigma = \sqrt{\ln\left(1+\left(\frac{\sigma_Y^2}{\mu_Y^2}\right)\right)} \tag{C.15}$$

Also, the reader should be aware that different software packages may use different parameters to define the lognormal distribution. For example, Microsoft Excel uses the parameters μ and σ in its "lognorm.dist()" and "lognorm.inv()" functions. Other software packages may use the median of the lognormal distribution (y_{median}) and the error factor (EF), which are calculated using Equations (C.16) and (C.17), respectively [14].

$$y_{median} = \exp(\mu) \tag{C.16}$$

$$EF = \exp(1.645\,\sigma) \tag{C.17}$$

C.4 Weibull Distribution

The cdf for a Weibull distributed random variable X is given by:

$$F_X(x) = P(X \le x) = 1 - \exp\left(-\left(\frac{x}{\beta}\right)^{\alpha}\right) = p \tag{C.18}$$

where x is the value of the random variable X, α is the shape parameter, β is the scale parameter, and p is the percentile (which is related to the value of the cdf).[5] Solve for x in Equation (C.18) as follows:

$$\begin{aligned} \exp\left[-\left(\frac{x}{\beta}\right)^{\alpha}\right] &= 1-p \\ -\left(\frac{x}{\beta}\right)^{\alpha} &= \ln(1-p) \\ \left(\frac{x}{\beta}\right)^{\alpha} &= -\ln(1-p) \\ \frac{x}{\beta} &= [-\ln(1-p)]^{1/\alpha} \end{aligned} \tag{C.19}$$

---

[5] Caution – The reader should be aware of how the software being used to implement the result of these equations parameterizes the Weibull distribution. For example, Excel uses the parameterization shown in Equation (C.18). In contrast, MATLAB (version R2021b) uses the following parameterization: $P(X \le x) = 1 - \exp\left(-\left(\frac{x}{A}\right)^{B}\right)$, where B is the shape parameter and A is the scale parameter.

$$x = \beta[-\ln(1-p)]^{1/\alpha}$$

Apply Equation (C.19) to two percentiles, p_1 and p_2, with their corresponding random variable values x_1 and x_2.

$$x_1 = \beta[-\ln(1-p_1)]^{1/\alpha} \tag{C.20}$$

$$x_2 = \beta[-\ln(1-p_2)]^{1/\alpha} \tag{C.21}$$

Solve Equations (C.20) and (C.21) for the scale parameter β, equate them because they represent the same probability distribution, and solve for the shape parameter α as follows:

$$\frac{x_2}{[-\ln(1-p_2)]^{1/\alpha}} = \frac{x_1}{[-\ln(1-p_1)]^{1/\alpha}}$$

$$\frac{x_2}{x_1} = \frac{[-\ln(1-p_2)]^{1/\alpha}}{[-\ln(1-p_1)]^{1/\alpha}}$$

$$\frac{x_2}{x_1} = \left[\frac{-\ln(1-p_2)}{-\ln(1-p_1)}\right]^{1/\alpha}$$

$$\frac{x_2}{x_1} = \left[\frac{\ln(1-p_2)}{\ln(1-p_1)}\right]^{1/\alpha}$$

$$\left(\frac{x_2}{x_1}\right)^{\alpha} = \frac{\ln(1-p_2)}{\ln(1-p_1)} \tag{C.22}$$

$$\ln\left[\left(\frac{x_2}{x_1}\right)^{\alpha}\right] = \ln\left[\frac{\ln(1-p_2)}{\ln(1-p_1)}\right]$$

$$\alpha \ln\left(\frac{x_2}{x_1}\right) = \ln\left[\frac{\ln(1-p_2)}{\ln(1-p_1)}\right]$$

$$\alpha = \frac{\ln\left[\frac{\ln(1-p_2)}{\ln(1-p_1)}\right]}{\ln\left(\frac{x_2}{x_1}\right)}$$

If the same approach to find the shape parameter α is used to determine the scale parameter β, the scale parameter β cancels out. Therefore, the scale parameter β must be calculated as a function of the shape parameter α using Equation (C.20) or Equation (C.21) with the result from Equation (C.22).

$$\beta = \beta(\alpha) = \frac{x_1}{[-\ln(1-p_1)]^{1/\alpha}} \tag{C.23}$$

C.5 Gamma Distribution

The cdf for a gamma distributed random variable X is given by:

$$F_X(x) = P(X \leq x) = \frac{1}{\Gamma(\alpha)\beta^{\alpha}} \int_{0}^{x} t^{\alpha-1} \exp(-t/\beta)\, dt \tag{C.24}$$

where x is the value of random variable X, $\Gamma(\alpha)$ is the gamma function, and α and β are the gamma distribution parameters. In this case, using the same approach as in the previous sections to find the distribution parameters is complicated. Rather, the analysts can use the insights from the work by Cook [34] to calculate the distribution parameters. First, the parameter α can be calculated numerically based on Equation (1) in the work by Cook [34], which is shown as Equation (C.25).

$$\frac{F^{-1}(p_2; \alpha, 1)}{F^{-1}(p_1; \alpha, 1)} = \frac{x_2}{x_1} \tag{C.25}$$

where $F^{-1}(p_2; \alpha, 1)$ and $F^{-1}(p_1; \alpha, 1)$ are the inverse gamma cdf with parameters α and a "pseudo-β" equal to 1 at percentiles p_2 and p_1, respectively. Once Equation (C.25) is numerically solved for α, the parameter β can be calculated using Equation (C.26) or Equation (C.27).

$$\beta = \frac{x_1}{F^{-1}(p_1; \alpha, 1)} \tag{C.26}$$

$$\beta = \frac{x_2}{F^{-1}(p_2; \alpha, 1)} \tag{C.27}$$

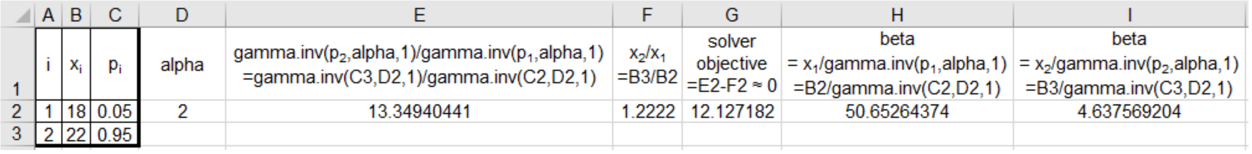
C.5.1 Demonstration of Approach To Calculate the Gamma Distribution Parameters

As an example, consider that an analyst estimates the time available to initiate feed and bleed cooling to be between 18 and 22 minutes and is 90 percent confident that the "true" time available is in the provided range. Based on Equations (C.1) and (C.2), $p_1 = 0.05$ and $p_2 = 0.95$. For this example, the analyst can use the Solver Add-in in Microsoft Excel to numerically calculate the value of the parameter α.[6] A suggested procedure is given below.

(1) Input the analyst estimates for the time available, the derived percentiles, an initial estimate for the parameter α, and the information related to Equations (C.25) through (C.27) in an Excel spreadsheet. Figure C-1 shows the results of this step.

---

[6] The following web site shows how to define and solve a problem using Solver: https://support.microsoft.com/en-us/office/define-and-solve-a-problem-by-using-solver-5d1a388f-079d-43ac-a7eb-f63e45925040 (accessed on May 31, 2022). If the Solver Add-in is not available to the reader in the Microsoft Excel installation, the following web site shows how to load the Solver Add-in in Excel: https://support.microsoft.com/en-us/office/load-the-solver-add-in-in-excel-612926fc-d53b-46b4-872c-e24772f078ca (accessed on May 31, 2022).



	A	B	C	D	E	F	G	H	I
1	i	x_i	p_i	alpha	gamma.inv(p_2,alpha,1)/gamma.inv(p_1,alpha,1) =gamma.inv(C3,D2,1)/gamma.inv(C2,D2,1)	x_2/x_1 =B3/B2	solver objective =E2-F2 ≈ 0	beta = x_1/gamma.inv(p_1,alpha,1) =B2/gamma.inv(C2,D2,1)	beta = x_2/gamma.inv(p_2,alpha,1) =B3/gamma.inv(C3,D2,1)
2	1	18	0.05	2	13.34940441	1.2222	12.127182	50.65264374	4.637569204
3	2	22	0.95						

Figure C-1 Screenshot Illustrating the Initial Setup after Step 1

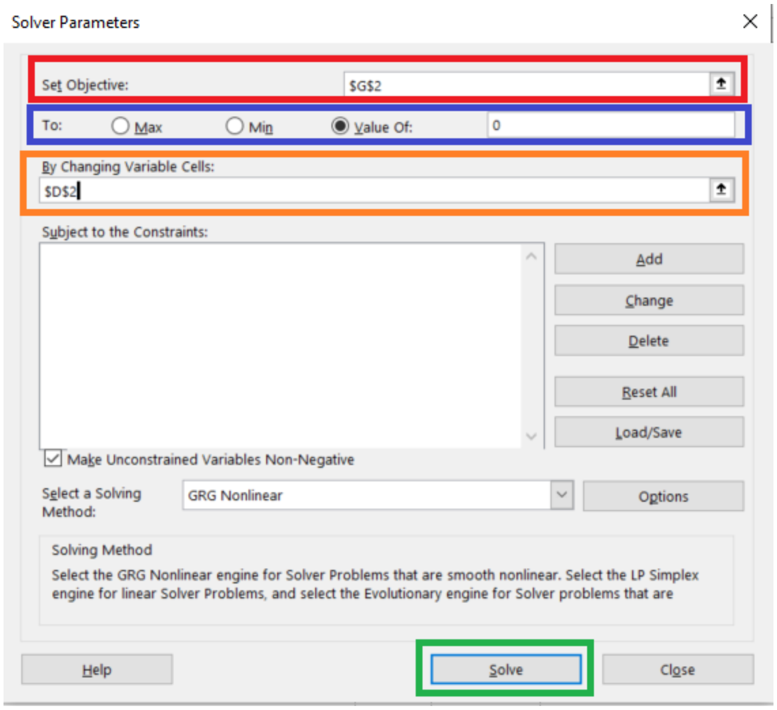
(2) In Excel, go to Data → Solver and the "Solver Parameters" window should open.

(3) Select cell G2 as the "Set Objective" (see the red rectangle in Figure C-2).

(4) Change the "To:" to "Value Of:" and ensure the value is zero (0) (see the blue rectangle in Figure C-2).

(5) Select cell D2 as the "By Changing Variable Cells" (see the orange rectangle in Figure C-2).

(6) Select "Solve" (see the green rectangle in Figure C-2).



Solver Parameters

Set Objective: G2

To: ○ Max ○ Min ● Value Of: 0

By Changing Variable Cells: D2

Subject to the Constraints:

☑ Make Unconstrained Variables Non-Negative

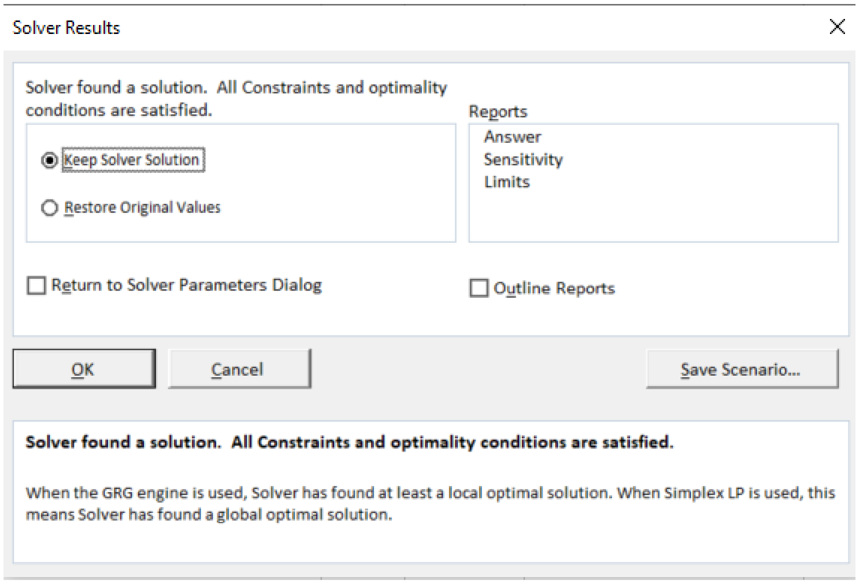
Select a Solving Method: GRG Nonlinear

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are

Figure C-2 Screenshot Illustrating the Setup of the "Solver Parameters" Window (Step 3 through Step 6)

(7) If Solver finds a solution that satisfies all conditions, a "Solver Results" window similar to the one shown as Figure C-3 should appear. Select OK. Otherwise, change the initial estimate for the parameter α (cell D2 in Figure C-1) and repeat Step 2 through Step 6.



Solver found a solution. All Constraints and optimality conditions are satisfied.

● Keep Solver Solution

○ Restore Original Values

☐ Return to Solver Parameters Dialog

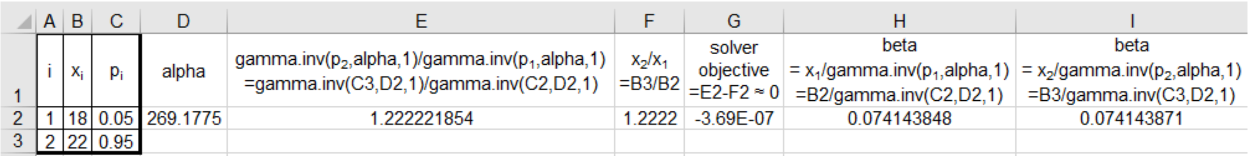
☐ Outline Reports

Solver found a solution. All Constraints and optimality conditions are satisfied.

When the GRG engine is used, Solver has found at least a local optimal solution. When Simplex LP is used, this means Solver has found a global optimal solution.

Figure C-3 Screenshot Illustrating the "Solver Results" Window (Step 7)

(8) The results for the parameters α and β are shown in cells D2 and H2 (or I2) of Figure C-4, respectively.



	A	B	C	D	E	F	G	H	I
1	i	x_i	p_i	alpha	gamma.inv(p_2,alpha,1)/gamma.inv(p_1,alpha,1) =gamma.inv(C3,D2,1)/gamma.inv(C2,D2,1)	x_2/x_1 =B3/B2	solver objective =E2-F2 ≈ 0	beta = x_1/gamma.inv(p_1,alpha,1) =B2/gamma.inv(C2,D2,1)	beta = x_2/gamma.inv(p_2,alpha,1) =B3/gamma.inv(C3,D2,1)
2	1	18	0.05	269.1775	1.222221854	1.2222	-3.69E-07	0.074143848	0.074143871
3	2	22	0.95						

Figure C-4 Screenshot Illustrating the Results for Parameters α and β of the Gamma Distribution

Note the change in value for the parameter α from an initial estimate of 2 (cell D2 in Figure C-1) to a calculated value of 269.1775 (≈ 269.18) (cell D2 in Figure C-4). Given that these parameters were calculated numerically instead of analytically, it is a good idea to verify that the calculated parameters return the analyst's estimates. In this example, the verification can be implemented using the "gamma.inv()" Excel function as follows:

- gamma.inv(0.05,269.18,0.0741) = 17.99 minutes ≈ 18 minutes
- gamma.inv(0.95,269.18,0.0741) = 21.99 minutes ≈ 22 minutes

Based on this example, the time available to initiate feed and bleed cooling may be modeled as a gamma distributed random variable with parameters $\alpha = 269.18$ and $\beta = 0.0741$ (i.e., $T_{avail} \sim gamma(\alpha = 269.18, \beta = 0.0741)$).

APPENDIX D
INTRODUCTION TO THE IDHEAS-ECA SOFTWARE

Performing a human reliability analysis (HRA) with IDHEAS-ECA (Integrated Human Event Analysis System – Event and Condition Assessment) has eight steps:

Step 1. Analyze the event scenario. This includes defining the scenario being analyzed, developing the operational narrative, determining the scenario context, and identifying the human failure events (HFEs) to be modeled.

Step 2. Analyze the HFE. This includes defining the HFE, analyzing the tasks in the HFE with a task diagram, timeline, or both, and identifying critical tasks for human error probability (HEP) quantification.

Step 3. Model the failure of the critical tasks in the HFE. This includes characterizing the critical tasks, identifying cognitive activities required to achieve the tasks, and subsequently identifying cognitive failure modes (CFMs) applicable to the tasks.

Step 4. Assess the performance-influencing factors (PIFs) applicable to every CFM. This step uses the results of the scenario context, HFE definition, and task characterization to select the applicable PIF attributes for every CFM.

Step 5. Calculate P_c for an HFE. P_c is the probabilistic sum of the HEPs of all the CFMs of the critical tasks.

Step 6. Analyze and quantify P_t for an HFE. P_t is the HEP attributed to uncertainty in time available and time required for performing the HFE.

Step 7. Calculate the overall HEP of an HFE by probabilistically adding P_c and P_t

Step 8. Analyze uncertainties in the HRA results and perform sensitivity analysis as needed.

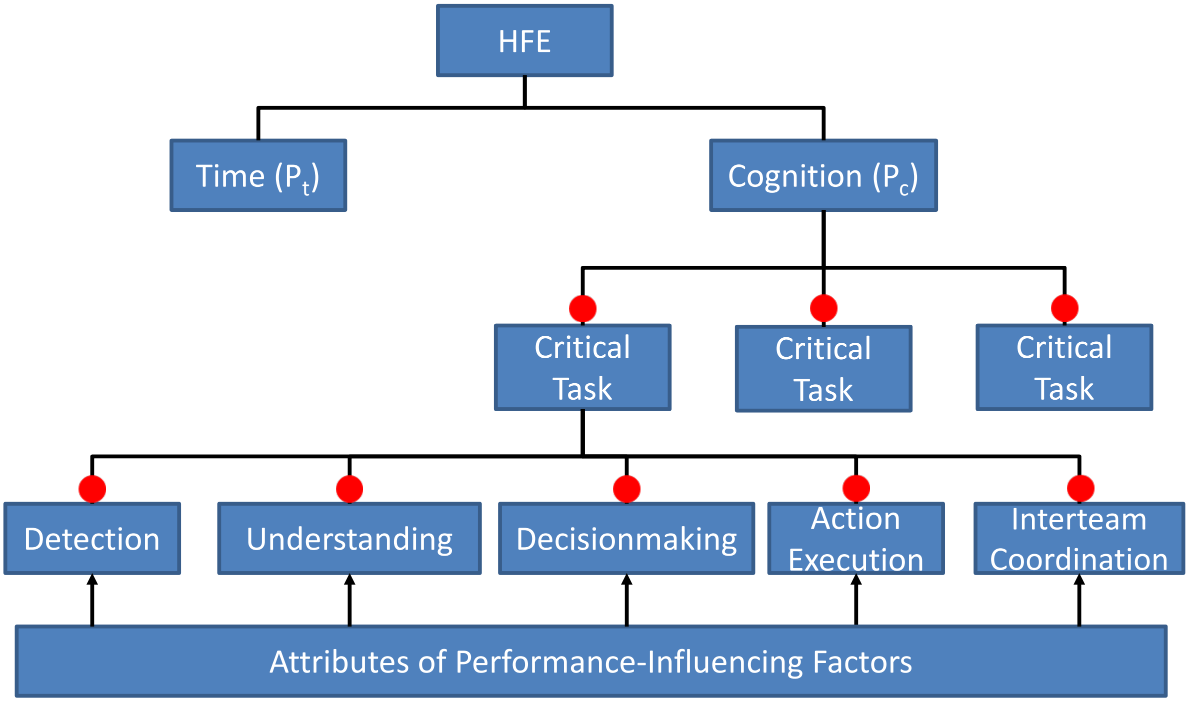
The purpose of the IDHEAS-ECA software is to facilitate the implementation of Steps 4 – 8 above with the goal of calculating the HEP.

Before using the software, HRA analysts should perform Steps 1 – 3 and document the results in Appendix A. The results of Steps 1 – 3 include the following:

- operational narrative, scenario context, and list of HFEs
- HFE definition, task diagrams, and list of critical tasks
- task characterization and applicable CFMs

Once the Steps 1 – 3 have been performed, analysts use the software to calculate the HEP of an HFE. Figure D-1 shows the structure implemented in the software to calculate the HEP. On the top of the structure is the HFE of which the HEP is to be calculated. The HEP of an HFE is the probabilistic sum of two parts, P_t (time) and P_c (cognition), as shown in the level below the HFE. P_t is the HEP attributed to the uncertainty in time available and time required to complete the action. P_c is the HEP attributed to cognitive failures assuming that the time available for performing the human action of the HFE is adequate. P_c of an HFE is the probabilistic sum of the HEPs of the critical tasks in the HFE. Figure D-1 shows the critical tasks one level below P_c.

The HEP of a critical task is the probabilistic sum of the CFMs applicable to the critical task. The five CFMs in IDHEAS-ECA are shown in Figure D-1, one level below the critical tasks. The CFMs are the failures of five macrocognitive functions, namely *detection*, *understanding*, *decisionmaking*, *action execution*, and *interteam coordination*. Finally, the PIF attributes applicable to the CFM determine the HEP of a CFM.



● A switch that the users can open and close

Figure D-1 Structure of Calculating a Human Failure Event's Probability in the IDHEAS-ECA Software

The software is used to calculate the HEP of an HFE and to document the calculation. An analysis includes three main functions: calculating P_c, calculating P_t, and documentation. The analysis begins with an HFE and generates P_c, P_t, and the overall HEP of the HFE as the outputs. For each HFE analysis, the software provides the following three functions:

(1) Calculating P_c: The analyst specifies the critical tasks and their applicable CFMs, then selects applicable PIFs and PIF attributes for every CFM to calculate P_c.

(2) Calculating P_t: The analyst enters the parameters of the distributions of time available and time required of the HFE for the software to calculate P_t.

(3) Documentation: All parameters that the analyst entered to calculate P_c and P_t and the other relevant information are documented in a rich text file to be integrated in the overall analysis document.

These three functions are discussed in detail below.

Calculate P_c

P_c is a function of the PIF attributes, CFMs, and critical tasks applicable to the HFE being analyzed. Twenty PIFs are used to group the PIF attributes. The PIFs and their PIF attributes differ between the CFMs. The analyst's responsibilities in calculating P_c include specifying critical tasks, the applicable CFMs for each identified critical task, and the PIF attributes applicable to the analysis for each specified CFM. The software provides a graphical user interface for the analyst to perform these tasks. The PIF (and PIF attributes) have two different types of impacts on HEPs: base HEP and PIF weights. In the software, the PIF attributes affecting the base HEP are displayed in red text; and the PIF attributes contributing to the PIF weights are displayed in black text.

In IDHEAS-ECA, the status of most PIF attributes is modeled as a binary state (i.e., present or not present). For these PIF attributes, the analyst checks or unchecks a PIF attribute to represent the present or not present state of the PIF attribute, respectively. Some PIF attribute statuses cover a wide spectrum. The impact on the HEP between the two ends of the spectrum is significant. IDHEAS-ECA uses multiple discrete states to represent the possible statuses. The software provides an attribute scale between 1 and 10 for the analysts to specify the appropriate status. The software also provides anchor values with corresponding status to assist the analyst in determining the appropriate status of the PIF attribute.

To calculate P_c, the analyst first needs to specify the number of critical tasks and the applicable CFMs for each. The software interface provides checkboxes so that the analyst can include and exclude CFMs by checking and unchecking the corresponding boxes. Next, the analyst identifies the applicable PIFs and their attributes for each CFM of the critical task being analyzed. The software provides a set of five radio buttons for the analyst to switch to different sets of PIFs and attributes relevant to each of the five CFMs (*detection*, *understanding*, *decisionmaking*, *action execution*, and *interteam coordination*). The PIFs and attributes are presented using a tree structure (PIF tree) with two levels. The first level shows all PIFs relevant to a CFM, and the second level shows the PIF attributes relevant to the CFM. Each PIF attribute has a checkbox for the analyst to assign its presence or absence with respect to its impact on the HEP of the CFM. Every time a PIF attribute is checked or unchecked, the software immediately recalculates the resulting HEPs and updates the displays accordingly. The software updates displays for the following:

- the PIF attribute's checkbox
- the list of PIF attributes checked (by the analysts)
- the checked PIF attributes shown in the CFM panels
- the HEPs of the CFM, the critical task, the P_c (sum of all critical task HEPs), and the HFE

Table D-1 summarizes the analyst's operation, software responses to the analyst's operation, and software displays (graphical user interfaces) to implement the analyst's operation to calculate P_c.

Table D-1 Operation, Calculation, and Display for Calculation of P_c

Analyst Operation	Software Responses	Display
1.1 Enter a critical task. 1.2 Select an applicable CFM. 1.3 Select an applicable PIF. 1.4 Check all the applicable attributes of the PIF. 1.5 Assess and select the scale of every multiscale attribute.	1.4 and 1.5 Responding to the analyst's selection of the applicable PIF attributes, the software calculates all relevant HEPs and updates their displays.	The software displays the following to implement the analyst's operation: 1.1 Three critical tasks and checkboxes to include and exclude the critical tasks 1.2 Five CFMs for each critical task, and checkboxes to include and exclude the CFMs 1.3 Radio buttons to select PIFs applicable to a CFM and a PIF tree to display the PIFs 1.4 The PIF tree (in 1.3 above) shows the PIFs and their attributes. Each attribute has a checkbox to include or exclude a PIF attribute in the analysis. 1.5 A popup window with a numeric up/down control allows the analyst to specify the PIF attribute's status on a scale from 1 to 10. The anchor values and corresponding status descriptions are provided.
Repeat 1.3 for all the applicable PIFs. Repeat 1.2 for all the CFMs of a critical task Repeat 1.1 for all the critical tasks.	Every time the analyst's actions affect HEP, all relevant HEPs are recalculated and displays are updated.	

Calculate P_t

An HFE has one and only one P_t (i.e., P_t is performed for the whole HFE). The analyst estimates the probabilistic distributions of time required and time available for performing the HFE. The software calculates P_t by the convolution of the two distributions. The software offers six options for the distribution of time available: lognormal distribution, normal distribution, gamma distribution, Weibull distribution, five-point estimation, and constant (single-point). The software offers the first five options for both the time available and for the time required distributions. The software excludes the constant option for time required, because the time required should never be a single point. With both distributions specified, the software calculates the P_t and displays the time available and time required distributions after the analyst clicks the "Plot and Update Pt" button in the software. The HEP of the HFE is also updated along with the update of P_t. The software provides options for specifying the time unit used in the analysis, including seconds, minutes, hours, and days.

The software uses Monte Carlo sampling techniques to calculate P_t. Monte Carlo sampling is used to calculate P_t of all other combinations. The sampling size for time required and time available is one million each. Every time an analyst clicks the "Plot and Update Pt" button, Monte Carlo sampling is executed. For certain distribution combinations, one million samples may produce slightly different P_t results each time. The differences are considered to have negligible effects on the HEP.

Table D-2 summarizes the analyst's operation, software responses to the analyst's operation, and relevant software displays to implement the analyst's operation to calculate P_t.

Table D-2 Operation, Calculation, and Display for Calculation of P_t

Analyst Operation	Software Responses	Display
2.1 Select the option for the time-available distribution 2.2 Estimate and enter the parameters for the distribution 2.3 Select an option for the time-required distribution 2.4 Estimate and enter the parameters for the distribution 2.5 Click the "Plot and Update Pt" button	2.5 The software plots the two distributions, calculates P_t, and updates the corresponding displays.	The software displays the distribution options and fields to enter parameters for time-available and time-required.

Documentation

The documentation tab supports the documentation of the HRA analysis and results. After the analyst completes the HEP calculation for an HFE, the software provides two options for documentation. The first option is to generate a document in rich text format that has all parameters specified to calculate the HFE's HEP, the HEPs (i.e., HEPs of CFM, critical tasks, P_c, P_t, and HFE), and the other relevant information (e.g., HEP impact of each PIF attribute). This option provides a convenient way for the analyst to integrate the information into the final analysis report. The second option is to save the analysis in a file that can be used to reanalyze the event at a later time or be shared with other analysts. The software allows for the analyst to retrieve a saved analysis from a file and to have all the parameters and displays identical to the saved analysis.

APPENDIX E
EXAMPLE 1: OPERATORS FAIL TO INITIATE FEED AND BLEED COOLING

Human failure event (HFE) name: HPI-XHE-XM-FAB

HFE description: Operators fail to initiate feed and bleed cooling

Summary of HFE Analysis

Table E-1 Summary of HPI-XHE-XM-FAB Analysis

HFE	HPI-XHE-XM-FAB
Critical Task	Operators fail to initiate feed and bleed cooling
CFMs and PIFs	Detection (CFM1) • Scenario familiarity – No impact • Task complexity – **C1, "Detection with multiple competing signals"** • Modification PIFs – No impact Understanding (CFM2) • Scenario familiarity – No impact • Information availability and reliability – No impact • Task complexity – No impact • Modification PIFs – No impact Decisionmaking (CFM3) • Scenario familiarity – No impact • Information availability and reliability – No impact • Task complexity – No impact • Modification PIFs – **MF8, "Emotional stress (e.g., anxiety and frustration)"** Action execution (CFM4) • Scenario familiarity – No impact • Task complexity – **C31, "Straightforward procedure execution with many steps"** • Modification PIFs – **MF2, "Time pressure due to perceived time urgency"** Interteam coordination (CFM5) – CFM5 does not apply • Task complexity – N/A • Modification PIFs – N/A
Recovery	No credit for recovery is provided in this HFE.
P_c	8.2×10^{-3}
Timing	Time available $\mu_{T_{avail}} = 2.99$, $\sigma_{T_{avail}} = 0.15$ Time required $\mu_{T_{reqd}} = 2.24$, $\sigma_{T_{reqd}} = 0.12$
P_t	4.8×10^{-5}
HEP	8.2×10^{-3}

Step 1 – Scenario Analysis

Step 1.1 Develop the Operational Narrative

The operational narrative describes the scenario and is based on the probabilistic risk assessment (i.e., the event tree where the HFE is being credited). See Section 3.1.1 for more details about the operational narrative.

The reactor is at-power with nominal staffing and assuming (unknown to operators) that the auxiliary feedwater (AFW) system is unavailable. Given a postulated reactor trip (with no anticipated transient without scram) due to the initiating event (e.g., general transient, small loss-of-coolant accident (LOCA), loss of direct current bus 111, loss of main feedwater), operators enter procedure E-0, “Reactor Trip or Safety Injection.” Main feedwater (MFW) is isolated automatically due to the reactor trip with low reactor coolant system (RCS) average temperature (T_{ave}). If no safety injection (SI) occurred and none is required, operators transition to procedure ES-0.1, “Reactor Trip Response.” If SI occurred or is required operators stay in procedure E-0. Both of these procedures direct operators to verify adequate AFW flow to the steam generators (SGs). In addition, operators will be monitoring the Critical Safety Function Status Trees. If operators are unable to restore AFW or MFW, operators transition to procedure FR-H.1, “Response to Loss of Secondary Heat Sink,” based on low AFW system flow and low level in all SGs (e.g., narrow range level less than {10} percent).[1] The condition of low AFW system flow and low level in all SGs can be reached between 2 minutes to 20 minutes after the loss of MFW flow [35]. In procedure FR-H.1, operators are directed to compare the pressures in the RCS and SG, check RCS temperature and SG levels, and attempt to restore AFW or MFW. Based on low SG levels (e.g., wide range level less than {27} percent) or high pressurizer (PZR) pressure (e.g., greater than {2335} pounds per square inch gauge (psig)), operators verify the feed path to the RCS (i.e., centrifugal charging pump(s), SI pump(s), and valve alignment) and establish and verify the bleed path from the RCS (i.e., PZR power-operated relief valves (PORVs) and PZR PORV block/isolation valves). The standardized plant analysis risk (SPAR) model assumes core damage if operators fail to initiate feed and bleed cooling for applicable scenarios.

Step 1.2 Identify the Human Failure Events

Section 3.1.2 provides details about the identification of the HFEs.

In this case, the HFE is identified in the SPAR model. The HFE is named “HPI-XHE-XM-FAB” and its description is “Operators fail to initiate feed and bleed cooling.”

Step 1.3 Identify the Scenario/Event Context

The scenario/event context describes the conditions that challenge or facilitate the performance of the operator actions. The scenario/event context is documented in the four categories listed below along with the answers to the probing questions and considerations for each context category identified in Section 3.1.3.

---

[1] Throughout this document, the values in the curly brackets (i.e., “{}”) are plant-specific values and assume that containment conditions are NOT adverse. The values shown are from the procedures of a Westinghouse four-loop plant.

- Environment and situation – The actions related to the HFE being analyzed are performed in the main control room (MCR) assuming no adverse environmental conditions. No adverse environmental conditions means that the MCR has adequate visibility, habitability, and noise levels to perform the actions related to the HFE. Therefore, the PIFs in the environment and situation context category (i.e., work location accessibility and habitability, workplace visibility, noise in workplace and communication pathways, cold/heat/humidity, and resistance to physical movement) are NOT applicable to the HFE.

- System – Given the reactor trip and subsequent plant parameters, several systems are expected to automatically actuate (e.g., SI actuation during a LOCA) and stop working (e.g., MFW trip). For this HFE, the AFW system is assumed to be unavailable, which would be an unexpected behavior of the plant, and operators would be directed to restore or recover the AFW system. Given, the unexpected behavior of the plant, the PIFs in this context category (i.e., system and instrumentation & control (I&C) transparency, human-system interface (HSI), and equipment and tools) are applicable to the HFE.

- Personnel – The MCR operators, composed of a senior reactor operator, reactor operator, balance of plant operator, and shift technical advisor, are performing the actions using the typical conduct of operations and they are adequately trained. These personnel are assumed to be available from the start of the scenario. The PIFs in this context category (i.e., staffing; procedures, guidance, and instructions; training; teamwork and organizational factors; and work processes) apply to the HFE because the command-and-control structure, training, and staffing affect the performance of the actions.

- Task – The MCR operators are following the emergency operating procedures and using the MCR indications. The PIFs in this context category (i.e., information availability and reliability; scenario familiarity; multitasking, interruptions, and distractions; task complexity; mental fatigue; time pressure and stress; and physical demands) are applicable to the HFE because they affect all macrocognitive functions associated with the HFE.

Step 2 – Analyzing Human Failure Events

Step 2.1 Defining the Human Failure Events

The definition of the HFE describes the scope of the analysis using the items listed below (see Section 3.2.1).

- Success criteria – Operators need to establish a bleed path by opening the appropriate number of PORVs and PORV block valves and provide a feed path to the RCS.[2]
- Consequence – Core damage is assumed given the failure to initiate feed and bleed cooling.

---

[2] Depending on the plant, operators need to open 2-of-2 or 1-of-2 PORVs and their corresponding PORV block valves, and start 1 train (sometimes 2 trains) of high-pressure injection.

- Beginning and ending points – The action begins when the cue about low wide range level in the SGs (e.g., {27} percent) becomes available and ends when operators initiate feed and bleed cooling.
- Relevant procedure guidance – Procedure E-0, "Reactor Trip or Safety Injection;" ES-0.1, "Reactor Trip Response;" E-1, "Loss of Reactor or Secondary Coolant" (given a LOCA); and procedure FR-H.1, "Response to Loss of Secondary Heat Sink."
- Cues and indications for initiating the operator action and timing – Once operators enter procedure FR-H.1, the cue is wide range level less than {27 percent} in any three SGs or PZR pressure greater than {2335} psig. The timing of these cues and indications is judged to be 5 minutes after the criteria to enter procedure FR-H.1 (i.e., between 2 minutes to 20 minutes after the loss of MFW flow [35]), which results in a time delay (T_{delay}) of 7 minutes to 25 minutes.
- Available time to perform the operator action – It is estimated that core damage would be prevented if feed and bleed is initiated within 20 minutes after the feed and bleed cue is generated. Based on the 20-minute estimate, the time available (T_{avail}) is estimated to be between 18 and 22 minutes. This results in a system time window (T_{sw}) of 25 minutes to 47 minutes.
- Time required to perform the operator action – Once the cue to initiate feed and bleed occurs, it is assumed that operators take between 0.5 and 2 minutes to detect the cue, understand it, and decide to take action (T_{cog}) in accordance with procedure FR-H.1. The criterion to initiate feed and bleed is a continuous action step in procedure FR-H.1. Based on the number of steps that need to be executed (i.e., stop all reactor coolant pumps, actuate SI, check emergency core cooling system (ECCS) pumps, check ECCS valve alignment, verify that PZR PORV block valves are energized and open, open the PZR PORVs, and verify the RCS bleed path), the execution time (T_{exe}) is estimated to be between 7 and 9 minutes. The summation of T_{cog} and T_{exe} results in a time required (T_{reqd}) of 8 to 11 minutes. Figure E-1 summarizes the timing information.

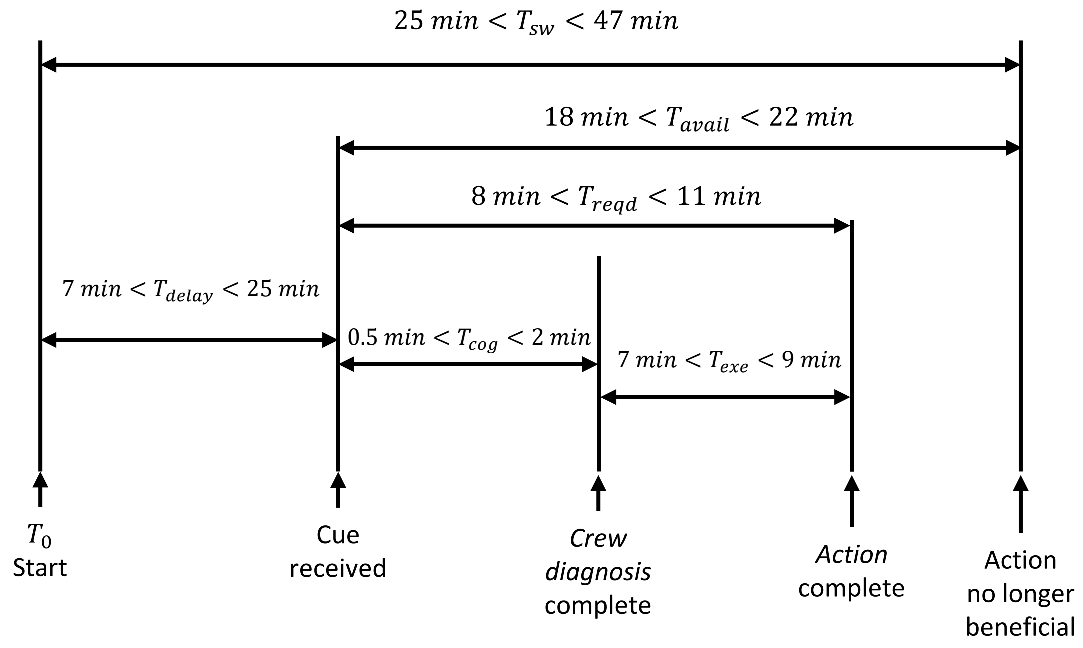


Figure E-1 HPI-XHE-XM-FAB Timeline

Step 2.2 Task Analysis and Identification of Critical Tasks

Section 3.2.2 provides guidance on the task analysis and breaking the HFE into critical tasks.

For simplicity, only one critical task is defined and that is, operators fail to initiate feed-and-bleed cooling. Also, the HFE is modeled as one critical task because the same context applies from the beginning to the end points of the HFE.

Step 3 – Modeling Failure of Critical Tasks

Step 3.1 Characterization of Critical Tasks

The characterization of a critical task specifies the relevant conditions that affect the performance of the critical task. These characteristics are listed below (see Section 3.3.1).

- Critical task goal – Given the unavailability of the AFW and MFW systems, the goal is to cool the reactor using high-pressure injection (i.e., charging pumps or SI pumps) and PORVs.
- Specific requirements – Use the appropriate number of PORVs to establish the bleed path and the appropriate number of high-pressure injection trains to establish the feed path. This should be completed in about 20 minutes after reaching the low wide range level in the SGs.
- Cues and supporting information – Low wide range level in any three SGs or high PZR pressure.
- Procedures – Initially E-0, ES-0.1 (if SI is not required), E-1 (given a LOCA), and transitioning to FR-H.1.

- Personnel – The MCR operators are performing the actions using the typical conduct of operations and they are adequately trained.
- Task support – Procedures (see above) and main control room indications.
- Location – Main control room
- Cognitive activities – See Step 3.2
- Concurrent tasks – Assuming that there are no other tasks.
- Interteam coordination considerations – Multiple teams are not involved in the critical task.
- Additional task characteristics (if any) – None.

Step 3.2 Identification of Applicable Cognitive Failure Modes

The applicable cognitive failure modes (CFMs) are identified by assessing the cognitive activities of the critical task that are associated with each macrocognitive function. Table 3-3 aids in the assessment of the cognitive activities of the critical task. See Section 3.3.2 for more information.

- *Detection* – detect cues and acquire information
  - Operators need to detect indications related to SG levels and PZR pressure.
  - CFM1 – failure of *detection* applies to the critical task
- *Understanding* – maintain situational awareness
  - Operators need to be aware of the AFW flow, SG levels, and PZR pressure. Given a LOCA, in addition to AFW flow and SG levels, operators need to be aware of the level in the refueling water storage tank (RWST) because, initially, it is the water source for charging pump(s) and SI pumps, and the level in the pressurizer because operators are trained to prevent completely filling it with water (i.e., “water solid” condition).
  - CFM2 – failure of *understanding* applies to the critical task
- *Decisionmaking* – make a go/no-go decision for a prespecified action
  - Operators make the decision to initiate the action based on the MCR indications and procedures.
  - CFM3 – failure of *decisionmaking* applies to the critical task
- *Action Execution* – execute cognitively simple actions
  - The actions are “simple” because operators are trained to perform them and require operators to open valves by turning a switch and initiate injection by pushing a button (or turning a switch), which are relatively simple actions. Also, operators need to be aware which valves and pumps they are manipulating.
  - CFM4 – failure of *action execution* applies to the critical task
- *Interteam coordination* – the action is implemented by the MCR operators, which is considered an individual team and *interteam coordination* considers multiple teams.
  - CFM5 – failure of *interteam coordination* DOES NOT apply to the critical task

Step 4 – Assessing Performance Influencing Factor Attributes Applicable to Cognitive Failure Modes

The PIF attributes for *scenario familiarity*, *information availability and reliability*, and *task complexity* and their corresponding base HEPs are located in Table B-1 through Table B-3, respectively. For the remaining (modification) PIFs, the PIF attributes and corresponding PIF weights are in Table B-4 through Table B-15. The guidance for this step is located in Section 3.4.

1. CFM1 – failure of *detection* → $\boldsymbol{P_{CFM1} = 3 \times 10^{-3}}$
   - Scenario familiarity (Table B-1): no impact (**SF0**)
     - Justification – Operators are trained to detect cues related SG levels and PZR pressure.
   - Information availability and reliability (Table B-2): this PIF does not apply to this CFM (see the "NA" under the "D" column of Table B-2)
   - Task complexity (Table B-3): **C1**, "detection with multiple competing signals," "Few (<7)" → $\boldsymbol{3 \times 10^{-3}}$
     - Justification – Procedure FR-H.1 directs operators to detect multiple signals; for example, RCS pressure, RCS temperature, SG levels, PZR pressure, and AFW flow.
   - Modification PIFs – no impact (see summary of PIF attributes assessment (below))

2. CFM2 – failure of *understanding* → $\boldsymbol{P_{CFM2} = 1 \times 10^{-3}}$ because all base PIFs are in their "no impact" states (see 3rd paragraph in Appendix B).
   - Scenario familiarity (Table B-1): no impact (**SF0**)
     - Justification – Operators are trained to understand that low SG levels should lead to initiate feed and bleed cooling.
   - Information availability and reliability (Table B-2): no impact (**Inf0**)
     - Justification – given a successful detection of the MCR indications and understanding (under *scenario familiarity*), this PIF has no impact.
   - Task complexity (Table B-3): no impact (**TC0**)
     - Justification – from the operators' perspective due to their training, the emergency operating procedures should allow straightforward diagnosis.
   - Modification PIFs – no impact (see summary of PIF attributes assessment (below))

3. CFM3 – failure of *decisionmaking* → $\boldsymbol{P_{CFM3} = (1 \times 10^{-3}) \cdot (1 + (1.2 - 1)) = 1.2 \times 10^{-3}}$
   - Scenario familiarity (Table B-1): no impact (**SF0**)
     - Justification – Operators are familiar with making decisions for actions based on procedures.
   - Information availability and reliability (Table B-2): no impact (**Inf0**)
     - Justification – Given that the actions are performed in the MCR based on MCR indications, it is assumed that the information is reliable and complete and has no effect on *decisionmaking*.
   - Task complexity (Table B-3): no impact (**C20)**
     - Justification – Based on the MCR indications and procedure FR-H.1, the operators' decision to initiate feed and bleed is straightforward.
   - Modification PIFs – **MF8** → $w = 1.2$ (see summary of PIF attributes assessment (below))

4. CFM4 – failure of *action execution* → $\boldsymbol{P_{CFM4} = (1 \times 10^{-3}) \cdot (1 + (3 - 1)) = 3 \times 10^{-3}}$

- Scenario familiarity (Table B-1): no impact (**SF0**)
    - Justification – Operators are familiar with MCR-based actions based on procedures.
- Information availability and reliability (Table B-2): this PIF does not apply to this CFM (see the "NA" under the "E" column of Table B-2)
- Task complexity (Table B-3): **C31**, "Straightforward procedure execution with many steps," → $\mathbf{1 \times 10^{-3}}$
    - Justification – From the operators' perspective, due to their training, executing the procedures is straightforward; however, initiating bleed and feed requires going through many steps.
- Modification PIFs – **MF2** → $w = 3$ (see summary of PIF attribute assessment (below))
-

5. CFM5 – failure of *action execution* → As stated in Step 3.2, this CFM is not applicable to this critical task.

Summary of PIF attribute assessment for the remaining (modification) PIFs for all applicable CFMs:

- Environmental PIFs (Table B-4) – As noted in Step 1.3, the PIFs in the environment and situation context do not apply to this HFE. Therefore, for the purpose of quantification, the no impact (**ENV0**) PIF attribute is assigned.
- System and Instrumentation and Control (I&C) Transparency (Table B-5) – No impact (**SIC0**) for all applicable CFMs because the actions are performed in the MCR and the system response and I&C should be transparent to the operators due to their training.
- Human-System Interface (HSI) (Table B-6) – no impact (**HSI0**) for all applicable CFMs because the actions are performed in the MCR and the MCR's design complies with regulatory requirements.
- Equipment and Tools (Table B-7) – no impact (**TP0**) for all applicable CFMs because the equipment and tools that are used to perform the actions (i.e., switches, buttons, etc.) are assumed to be well maintained.
- Staffing (Table B-8) – no impact (**STA0**) for all applicable CFMs because adequate staffing is assumed.
- Procedures, Guidance, and Instructions (Table B-9) – no impact (**PG0**) for all applicable CFMs because operators are following the emergency operating procedures (EOPs) and the EOPs cover the scenario in which this HFE is credited.
- Training (Table B-10) – no impact (**TE0**) for all applicable CFMs because the MCR operators performing the actions are assumed to licensed and have adequate training.
- Teamwork and Organizational Factors (Table B-11) – no impact (**TF0**) for all applicable CFMs because the teamwork and organizational factors are assumed to be adequate.
- Work Processes (Table B-12) – no impact (**WP0**) for all applicable CFMs because the work processes are performed by licensed personnel with assumed good practices.
- Multitasking, Interruption, and Distraction (Table B-13) – no impact (**MT0**) for all applicable CFMs because all attention by the MCR operators is directed at bringing the reactor to a safe and stable condition and it is assumed that there are no other events occurring at the same time.
- Mental Fatigue, and Time Pressure and Stress (Table B-14) –

    - no impact (**MF0**) for CFM1 (failure of *detection*) and CFM2 (failure of *understanding*) because the action is expected to take place relatively early in the scenario.
    - **MF8**, "Emotional stress (e.g., anxiety and frustration)," for CFM3 (failure of *decisionmaking*) due to decision to implement feed and bleed cooling
    - **MF2**, "Time pressure due to perceived time urgency," for CFM4 (failure of *action execution*) because in procedure FR-H.1 there is a note prior to the step to establish the RCS feed path that states: "Steps 13 through 16 must be done QUICKLY to be established RCS heat removal by RCS bleed and feed." Based on the note it is assumed that operators will perceive time urgency to perform the action steps.
  - Physical Demands (Table B-15) – no impact (**PD0**) for CFM4 (failure of *action execution*) because MCR actions are not expected to require extraordinary efforts. Note that the PIF physical demands do not affect CFM1 (failure of *detection*), CFM2 (failure of *understanding*), and CFM3 (failure of *decisionmaking*).

Step 5 – Estimation of Pc – the Sum of Human Error Probabilities of Cognitive Failure Modes

The estimation of P_c relies on the assessment of the PIF attributes performed in Step 4. Since in Step 2.2 we defined the HFE as having only one critical task, P_c is equal to the error probability of the critical task. The error probability of the critical task is estimated using Equation (3.3) as follows:

$$\begin{aligned} P_c = P_{CT1} &= 1 - [(1 - P_{CFM1}) \cdot (1 - P_{CFM2}) \cdot (1 - P_{CFM3}) \cdot (1 - P_{CFM4}) \cdot (1 - P_{CFM5})] \\ &= 1 - [(1 - 3 \times 10^{-3}) \cdot (1 - 1 \times 10^{-3}) \cdot (1 - 1.2 \times 10^{-3}) \cdot (1 - 3 \times 10^{-3})] = 8.2 \times 10^{-3} \end{aligned}$$

This calculation can also be performed using the IDHEAS-ECA software.

Step 6 – Estimation of Pt – the Convolution of the Distribution of Time Available and Time Required

Time available: As discussed in Step 2.1, the time available (T_{avail}) is estimated to be between 18 and 22 minutes. This range of the time available is used to estimate the parameters of an assumed normal distribution. Another assumption is that the estimated T_{avail} range covers 50 percent of the T_{avail} distribution (i.e., confidence level = 0.5) due to the (single) 20-minute estimate mentioned in Step 2.1. In other words, the 18-minute and 22-minute estimates are the 25th ($p_1 = (1 - 0.5)/2 = 0.25$) and 75th ($p_2 = (1 + 0.5)/2 = 0.75$) percentiles of the assumed lognormal distribution, respectively. Based on this information and Equations (C.10) and (C.11), the parameters μ and σ are 2.99 and 0.15, respectively.

Time required: The same process as described above is used to estimate the parameters of the distribution of time required. The range of 8 to 11 minutes is assumed to cover 80 percent of the T_{reqd} distribution (i.e., confidence level = 0.8) due to the decomposition of the tasks (detection, understanding, decisionmaking, and action execution) and procedure use (i.e., the feed and bleed cue monitoring is a continuous step in FR-H.1). In other words, the 8-minute and 11-minute estimates are the 10th ($p_1 = (1 - 0.8)/2 = 0.1$) and 90th ($p_2 = (1 + 0.8)/2 = 0.9$) percentiles, respectively. Based on this information and Equations (C.10) and (C.11), the parameters μ and σ are 2.24 and 0.12, respectively.

Calculation of P_t

Assuming that T_{avail} and T_{reqd} are lognormally distributed with the parameters calculated above and using Matlab (version R2021b), P_t is estimated to be 4.8×10^{-5}.

Step 7 – Calculate the Overall Human Error Probability

The overall HEP is calculated using Equation (3.1), which is implemented in the IDHEAS-ECA software, as follows:

$$\text{P(HPI-XHE-XM-FAB)} = 1 - (1 - P_c) \cdot (1 - P_t) = 1 - (1 - 8.2 \times 10^{-3}) \cdot (1 - 4.8 \times 10^{-5})$$

$$= 8.2 \times 10^{-3}$$

Step 8 – Analyze Uncertainties, Perform Sensitivity and Dependency Analyses, and Document the Results

There are a few uncertainties in this analysis, which are as follows:

- Under CFM4 (failure of action execution), the PIF *Task Complexity* may also be assessed as no impact (**C30**) depending on what constitutes “many steps” vs. “a few steps.” If this PIF attribute assessment is made, then $P_{CFM4} = 3 \times 10^{-4}$, which changes P_c to 5.5×10^{-3} and the overall HEP to 5.5×10^{-3}.

- Given that the time available and time required were assumed to be lognormally distributed, Table E-2 provides a sensitivity analysis for P_t, which was calculated using Matlab (R2021b), and the overall HEP. In all the sensitivity analysis cases in Table E-2, the estimated range and confidence are the same as those described in Step 6. The sensitivity analysis shows that P_t ranges from 1.6×10^{-5} to 3.6×10^{-3}, which results in the overall HEP (using $P_c = 8.2 \times 10^{-3}$) ranging from 8.2×10^{-3} to 1.2×10^{-2}. In the case where $P_c = 5.5 \times 10^{-3}$ (see the bulleted item above), the overall HEP ranges from 5.5×10^{-3} to 9.1×10^{-3}. By considering these sensitivity cases, the overall HEP ranges from 5.5×10^{-3} to 1.2×10^{-2}.

- In comparing the result of this analysis to the result obtained using the SPAR-H HRA method, consider the following information from the SPAR model reports:

  “*This human failure event starts from full power operations. Diagnosis of the need for the operator to depressurize the reactor is not modeled since the actions are proceduralized and the need for action is obvious. The action [execution] is modeled. The time available for the action is expected to be barely adequate [$F_{Time\ Available} = 10$] due to the nature of the scenario. The stress level is also expected to be high [$F_{Stress} = 2$] for the same reason. Dependency is not modeled for this action. The geometric mean of ten randomly selected equivalent [industry] PRA events is 1.3E-2.*”

  This information leads to the following calculation: SPAR-H HEP $= 1 \times 10^{-3} \cdot 10 \cdot 2 \cdot 1 \cdot 1 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = 2 \times 10^{-2}$.

Table E-2 Sensitivity Analysis Results for P_t and the Overall HEP for HPI-XHE-XM-FAB

T_{reqd} Distribution Parameters	T_{avail} Distribution Parameters	P_t	HEP
Normal(μ=9.5, σ=1.17)	Normal(μ=20, σ=2.97)	5.0E-4	8.7E-3
Lognormal(μ=2.24, σ=0.12)	Lognormal(μ=2.99, σ=0.15)	4.8E-5	8.2E-3
Weibull(shape=9.69, scale=10.09)	Weibull(shape=7.84, scale=21.10)	2.8E-3	1.1E-2
Gamma(alpha=65.15, beta=0.15)	Gamma(alpha=45.49, beta=0.44)	1.7E-4	8.3E-3
Normal(μ=9.5, σ=1.17)	Lognormal(μ=2.99, σ=0.15)	3.3E-5	8.2E-3
Normal(μ=9.5, σ=1.17)	Weibull(shape=7.84, scale=21.10)	2.8E-3	1.1E-2
Normal(μ=9.5, σ=1.17)	Gamma(alpha=45.49, beta=0.44)	7.9E-5	8.3E-3
Lognormal(μ=2.24, σ=0.12)	Normal(μ=20, σ=2.97)	5.2E-4	8.7E-3
Lognormal(μ=2.24, σ=0.12)	Weibull(shape=7.84, scale=21.10)	2.7E-3	1.1E-2
Lognormal(μ=2.24, σ=0.12)	Gamma(alpha=45.49, beta=0.44)	1.0E-4	8.3E-3
Weibull(shape=9.69, scale=10.09)	Normal(μ=20, σ=2.97)	5.0E-4	8.7E-3
Weibull(shape=9.69, scale=10.09)	Lognormal(μ=2.99, σ=0.15)	1.6E-5	8.2E-3
Weibull(shape=9.69, scale=10.09)	Gamma(alpha=45.49, beta=0.44)	5.6E-5	8.2E-3
Gamma(alpha=65.15, beta=0.15)	Normal(μ=20, σ=2.97)	7.8E-4	8.9E-3
Gamma(alpha=65.15, beta=0.15)	Lognormal(μ=2.99, σ=0.15)	9.3E-5	8.3E-3
Gamma(alpha=65.15, beta=0.15)	Weibull(shape=7.84, scale=21.10)	3.6E-3	1.2E-2

Note – The cited work is in the list of references in Section 5 of this report.

APPENDIX F
EXAMPLE 2: OPERATORS FAIL TO DEPRESSURIZE REACTOR COOLANT SYSTEM/SECONDARY SIDE COOLING

Human failure event (HFE) name: OPR-XHE-XM-DEPRCS (PWR-XHE-XM-DEPRCS)

HFE description: Operator fails to depressurize RCS/Secondary ([secondary side cooling])

Summary of HFE Analysis

Table F-1 Summary of OPR-XHE-XM-DEPRCS Analysis

HFE	OPR-XHE-XM-DEPRCS (PWR-XHE-XM-DEPRCS)
Critical Task	Operators fail to depressurize RCS/Secondary side
CFMs and PIFs	Detection (CFM1) • Scenario familiarity – No impact • Task complexity – No impact • Modification PIFs – No impact Understanding (CFM2) • Scenario familiarity – No impact • Information availability and reliability – No impact • Task complexity – No impact • Modification PIFs – No impact Decisionmaking (CFM3) • Scenario familiarity – No impact • Information availability and reliability – No impact • Task complexity – No impact • Modification PIFs – No impact Action execution (CFM4) • Scenario familiarity – No impact • Task complexity – **C31, “Straightforward Procedure execution with many steps”** • Modification PIFs – No impact Interteam coordination (CFM5) – CFM5 does not apply • Task complexity – N/A • Modification PIFs – N/A
Recovery	Recovery credit is not provided for this HFE.
P_c	3.1×10^{-3}
Timing	Time available $\mu_{T_{avail}} = 5.04$, $\sigma_{T_{avail}} = 0.5$ Time required $\mu_{T_{reqd}} = 2.60$, $\sigma_{T_{reqd}} = 0.06$
P_t	9×10^{-7}
HEP	3.1×10^{-3}

Step 1 – Scenario Analysis

Step 1.1 Develop the Operational Narrative

The operational narrative describes the scenario and is based on the probabilistic risk assessment (i.e., the event tree where the HFE is being credited). See Section 3.1.1 for more details about the operational narrative.

The reactor is operating at 100% power with nominal staffing. Given a postulated reactor trip (with no anticipated transient without scram) due to the initiating event (e.g., small loss-of-coolant accident (LOCA) or stuck-open power-operated relief valve (PORV) that is not isolated), operators enter procedure E-0, “Reactor Trip or Safety Injection.” Main feedwater (MFW) is isolated automatically due to the reactor trip with low reactor coolant system (RCS) average temperature (T_{ave}). Auxiliary feedwater and high-pressure injection are assumed to be available. Based on indications of high containment radiation, high containment pressure, or higher than expected drain sump level, operators transition to procedure E-1, “Loss of Reactor or Secondary Coolant.” Based on a continued decrease in RCS pressure, E-1 directs operators to transition to ES-1.2, “Post-LOCA Cooldown and Depressurization.” Prior to initiating the depressurization/cooldown, ES-1.2 directs operators to recheck that the steam generator (SG) tubes are intact, that the steam dump valves are available, deenergize the pressurizer heaters, and that several permissive blocks (e.g., pressurizer low pressure and steam line isolation) are active. If the steam dumps are unavailable, operators are directed to use the SG atmospheric relief valves (ARVs). Once these steps are completed, operators are directed to initiate the RCS cooldown/depressurization by dumping steam to the condenser from intact SG(s) or via the SG PORVs (i.e., atmospheric dump valves) and using the pressurizer sprays. If normal sprays are unavailable, ES-1.2 directs the operators to use the pressurizer PORVs or auxiliary spray. If these actions fail, the refueling water storage tank (RWST) low-low level will be reached and operators will be directed to initiate cold-leg recirculation via ES-1.3, “Transfer to Cold-Leg Recirculation.”

Step 1.2 Identify the Human Failure Events

Section 3.1.2 provides details about the identification of the HFEs.

In this case, the HFE is identified in the standardized plant analysis risk (SPAR) model. The HFE is named “OPR-XHE-XM-DEPRCS” and its description is “Operators fail to depressurize RCS/Secondary (SSC).”

Step 1.3 Identify the Scenario/Event Context

The scenario/event context describes the conditions that challenge or facilitate the performance of the operator actions. The scenario/event context is documented in the four categories listed below along with the answers to the probing questions and considerations for each context category identified in Section 3.1.3.

- Environment and situation – The actions related to the HFE being analyzed are performed in the main control room (MCR) assuming no adverse environmental conditions. No adverse environmental conditions mean that the MCR has adequate visibility, habitability, and noise levels to perform the actions related to the HFE. Therefore, the PIFs in the environment and situation context category (i.e., work location accessibility and habitability, workplace visibility, noise in workplace and communication pathways, cold/heat/humidity, and resistance to physical movement) are NOT applicable to the HFE.

- System – All systems are working as designed. Therefore, the PIFs in this context category (i.e., system and instrumentation & control (I&C) transparency, human-system interface (HSI), and equipment and tools) are NOT applicable to the HFE.
- Personnel – The MCR operators, composed of a senior reactor operator, reactor operator, balance of plant operator, and shift technical advisor, are performing the actions using the typical conduct of operations and they are adequately trained. These personnel are assumed to be available from the start of the scenario. The PIFs in this context category (i.e., staffing; procedures, guidance, and instructions; training; teamwork and organizational factors; and work processes) are applicable to the HFE because the command-and-control structure, training, and staffing affect the performance of the actions.
- Task – The MCR operators are following the emergency operating procedures and using the MCR indications. The PIFs in this context category (i.e., information availability and reliability; scenario familiarity; multitasking, interruptions, and distractions; task complexity; mental fatigue; and time pressure and stress) are applicable to the HFE because they affect all macrocognitive functions associated with the HFE. The PIF physical demands is NOT applicable to this HFE because MCR actions are not expected to require extraordinary efforts.

Step 2 – Analyzing Human Failure Events

Step 2.1 <u>Defining the Human Failure Events</u>

The definition of the HFE describes the scope of the analysis using the items listed below (see Section 3.2.1).

- Success criteria – Operators need to use the steam dump valves (i.e., turbine bypass valves) or SG PORVs (i.e., atmospheric dump valves) AND the normal pressurizer (PZR) spray line or PZR PORVs.
- Consequence – The failure to depressurize/cooldown the RCS will require operators to transition to cold-leg recirculation to maintain core cooling and prevent core damage.
- Beginning and ending points – The HFE begins when operators receive the procedure guidance to initiate RCS cooldown and depressurization in accordance with procedure E-1, and ends when operators complete RCS depressurization per the guidance in procedure ES-1.2.
- Relevant procedure guidance – Procedure E-0, “Reactor Trip or Safety Injection, E-1, “Loss of Reactor and Secondary Coolant” and ES-1.2, “Post LOCA Cooldown and Depressurization”.
- Cues and indications for initiating the operator action and timing – Operators enter procedure E-0 following reactor trip (T_0) and then transition to procedure E-1, Step 1. At the appropriate step of procedure E-1, operators are directed to check if RCS cooldown and depressurization is required. The timing of the cue is judged to between 20 to 25 minutes per the rule of thumb that it takes approximately one minute to perform each procedural step.

- Available time to perform the operator action – the system time window (T_{sw}) is estimated based on when the RWST level drops below the low-low (Lo-2) level. The RWST Lo-2 level is usually defined as 46% but may vary slightly at different plants. The initial volume of water in the RWST is assumed to be the minimum water volume required by the plant technical specifications. In a small LOCA (SLOCA) scenario, safety injection (SI) is required, and operators will use the available emergency core cooling systems (ECCS) pump(s) to inject water into RCS from the RWST. The amount of time to deplete RWST to the Lo-2 level depends on the number of ECCS pumps involved in injection as well as the centrifugal charging pump (CCP) and SI pump flow rates, which depends on the RCS pressure.

  The RWST parameters (the initial volume, minimum water level required by technical specifications and Lo-2 level) and ECCS pumps (CCP and SI pump) flow rates are taken from the SLOCA scenarios, where the residual heat removal (RHR) system does not inject into the RCS, documented in Sections 5.1 and 5.3 of NUREG-2187 [2] and listed in Table F-2. The average CCP and SI pump flow rates are derived using the bounding key events timings (see Table 7 and Table 19 of NUREG-2187). This analysis is based on a ECCS which is comprised of 2 CCPs and 2 SI pumps. As shown in Table F-3, three bounding configurations are considered for ECCS suction from the RWST: (1) one CCP (2) one SI pump (3) two CCPs and two SI pumps. The estimated time for the RWST to reach the Lo-2 level in SLOCA scenarios is between 78 and 434 minutes.

  It should be noted that the parameters listed in Table F-2 are plant-specific values and ECCS pump configurations may also vary at different plants. However, the same methodology can be applied to reproduce the calculation when necessary.

Table F-2 RWST Parameters and ECCS Pump Flow Rates in SLOCA Scenarios from NUREG-2187 [35]

RWST Initial Volume	395,000 gal (89% of RWST instrument span)		395,000 gal from Section 4.1
RWST Lo-2 Level	204,000 gal (46% of RWST instrument span) ($\approx 395,000gal \div 89\% \times 46\%$)		46% from Section 5.1
CCP Flow Rate	Lower Bound	$440gpm\ (\approx \frac{(395000-204000)gal}{434\ min})$	434 min from Case 1a in Table 7
	Upper Bound	$554gpm\ (\approx \frac{(395000-204000)gal}{345\ min})$	345 min from Case 7a in Table 7
SI Pump Flow Rate	Lower Bound	$508gpm\ (\approx \frac{(395000-204000)gal}{376\ min})$	376 min from Case 6 in Table 7
	Upper Bound	$668gpm\ (\approx \frac{(395000-204000)gal}{286\ min})$	286 min from Case 7 in Table 19

Table F-3 Time to Reach RWST Lo-2 Level in SLOCA Scenarios for Three ECCS Pump Configurations

Case	ECCS Pumps Injecting	Time to RWST Lo-2 Level from Initial RWST Level (minutes)	
		Lower Bound	Upper Bound
1	1 CCP	345	434
2	1 SI pump	286	376
3	2 CCPs and 2 SI pumps	78 $\approx \frac{(395000-204000)gal}{\left(2\times 554\ \frac{gal}{min}\right)+\left(2\times 668\ \frac{gal}{min}\right)}$	101 $\approx \frac{(395000-204000)gal}{\left(2\times 440\ \frac{gal}{min}\right)+\left(2\times 508\ \frac{gal}{min}\right)}$

- Time required to perform the operator action – It is assumed that operators take approximately 1 to 2 minutes to assess the plant condition and make a decision (T_{cog}). The operators then go through the steps in procedure ES-1.2 and initiate the action of RCS cooldown to cold shutdown. Based on the number of steps that need to be executed, the execution time (T_{exe}) is estimated to be between 11 and 13 minutes. The summation of T_{cog} and T_{exe} results in a time required (T_{reqd}) of 12 to 15 minutes. All the timing information is summarized in the timeline diagram shown in Figure F-1.

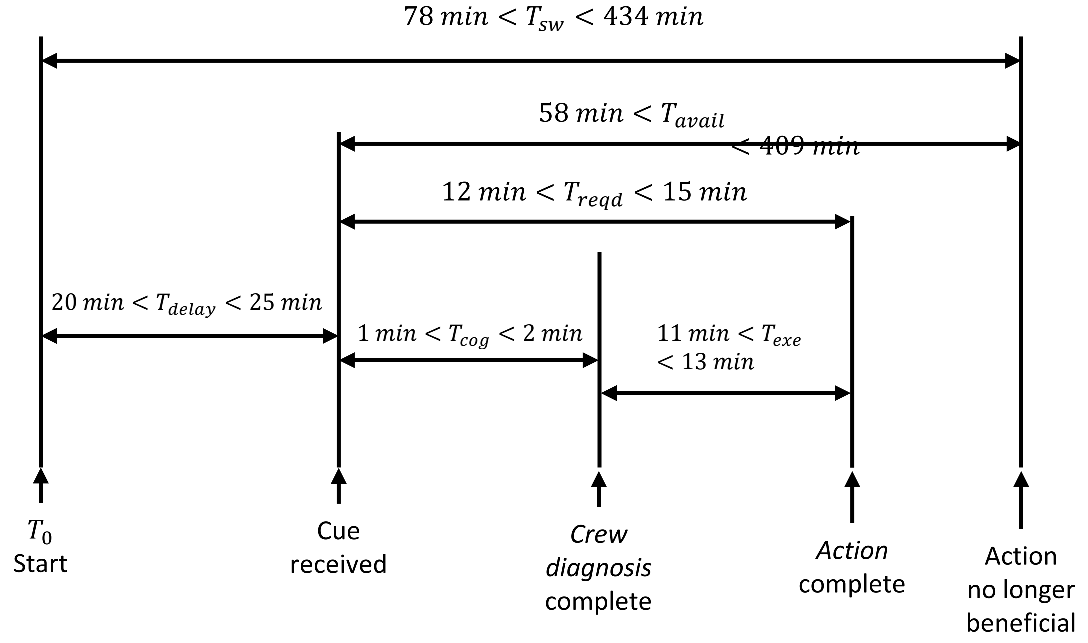


Figure F-1 OPR-XHE-XM-DEPRCS/PWR-XHE-XM-DEPRCS Timeline

Step 2.2 Task Analysis and Identification of Critical Tasks

Section 3.2.2 provides guidance on the task analysis and breaking the HFE into critical tasks.

For simplicity, only one critical task is defined and that is, operators fail to depressurize RCS/Secondary side. Also, the HFE is modeled as one critical task because the same context applies from the beginning to the end points of the HFE.

Step 3 – Modeling Failure of Critical Tasks

Step 3.1 Characterization of Critical Tasks

The characterization of a critical task specifies the relevant conditions that affect the performance of the critical task. These characteristics are listed below (see Section 3.3.1).

- Critical task goal – depressurize and cooldown the RCS
- Specific requirements – at least one steam dump valve or several SG PORVs AND the normal PZR spray line or one PZR PORV or auxiliary PZR spray
- Cues and supporting information – procedural cue
- Procedures – Initially E-0, transition to E-1 and then ES-1.2
- Personnel – the MCR operators are performing the actions using the typical conduct of operations and they are adequately trained
- Task support – procedures (see above) and main control room indications
- Location – main control room
- Cognitive activities – see Step 3.2
- Concurrent tasks – assuming that the are no other tasks
- Interteam coordination considerations –multiple teams are not involved in the critical task.
- Additional task characteristics (if any) – none

Step 3.2 Identification of Applicable Cognitive Failure Modes

The applicable cognitive failure modes (CFMs) are identified by assessing the cognitive activities of the critical task that are associated with each macrocognitive function. Table 3-3 aids in the assessment of the cognitive activities of the critical task. See Section 3.3.2 for more information.

- *Detection* – detect cues and gather information
    - Operators need to check the indications related to the RCS pressure
    - CFM1 – failure of *detection* applies to the critical task
- *Understanding* – diagnose problems, maintain situation awareness

    - Operators need to diagnose that RCS pressure is slowly decreasing, but it is higher than the shutoff head of the RHR pumps. In addition to RCS pressure, operators need to be aware of (1) the level in the RWST because, initially, it is the water source for the CCPs and SI pumps, (2) the PZR level, and (3) SG pressures.
    - CFM2 – failure of *understanding* applies to the critical task
- *Decisionmaking* – make a go/no-go decision for a pre-specified action
    - Operators make the decision to initiate the action based on the MCR indications (i.e., RCS pressure, while maintaining awareness of RWST level, PZR level, and SG pressures) and procedures.
    - CFM3 – failure of *decisionmaking* applies to the critical task
- *Action Execution* – execute cognitively simple actions
    - The actions are "simple" because operators are trained to perform them and require operators to open valves by turning a switch, which is relatively simple action. Also, operators need to be aware which valves they are manipulating.
    - CFM4 – failure of *action execution* applies to the critical task
- *Interteam coordination* – the action is implemented by the MCR operators, which is considered an individual team and *interteam coordination* considers multiple teams.
    - CFM5 – failure of *interteam coordination* DOES NOT APPLY to the critical task

Step 4 – Assessing Performance Influencing Factor Attributes Applicable to Cognitive Failure Modes

The PIF attributes for *scenario familiarity*, *information availability and reliability*, and *task complexity* and their corresponding base HEPs are located in Table B-1 through Table B-3, respectively. For the remaining (modification) PIFs, the PIF attributes and corresponding PIF weights are in Table B-4 through Table B-15. The guidance for this step is located in Section 3.4.

1. CFM1 – failure of *detection* → $\boldsymbol{P_{CFM1} = 1 \times 10^{-4}}$ because all base PIFs are in their "no impact" states (see 3rd paragraph in Appendix B).
    - Scenario familiarity (Table B-1): no impact (**SF0**)
        - Justification – Operators are trained to detect cues related to RCS pressure.
    - Information availability and reliability (Table B-2): this PIF does not apply to this CFM (see the "NA" under the "D" column of Table B-2)
    - Task complexity (Table B-3): no impact (**C0**)
        - Justification – Since operators are trained, detecting trends in RCS pressure is not complex.
    - Modification PIFs – no impact (see summary of PIF attributes assessment (below))

2. CFM2 – failure of *understanding* → $\boldsymbol{P_{CFM2} = 1 \times 10^{-3}}$ because all base PIFs are in their "no impact" states (see 3rd paragraph in Appendix B).
    - Scenario familiarity (Table B-1): no impact (**SF0**)

    - Justification – Operators are trained to understand that a slowly decreasing RCS pressure while it is above the shutoff head of the RHR pumps should lead to RCS depressurization.
- Information availability and reliability (Table B-2): no impact (**Inf0**)
    - Justification – The MCR indications are reliable to understand the need for RCS depressurization.
- Task complexity (Table B-3): no impact (**C10**)
    - Justification – The procedures are clear to operators, so they understand the need to depressurize the RCS.
- Modification PIFs – no impact (see summary of PIF attributes assessment (below))

3. CFM3 – failure of *decisionmaking* → $\boldsymbol{P_{CFM3} = 1 \times 10^{-3}}$ because all base PIFs are in their "no impact" states (see 3rd paragraph in Appendix B).
    - Scenario familiarity (Table B-1): no impact (**SF0**)
        - Justification – Operators are trained to decide to depressurize the RCS given the procedures and MCR indications.
    - Information availability and reliability (Table B-2): no impact (**Inf0**)
        - Justification – The procedures and MCR indications are reliable and complete to decide to depressurize the RCS.
    - Task complexity (Table B-3): no impact (**C20**)
        - Justification – The procedure is simple and straightforward. Operators use RCS pressure along with procedures to initiate RCS depressurization. They also need to be aware of other parameters such as SG pressure, PZR level, and RWST level.
    - Modification PIFs – no impact (see summary of PIF attributes assessment (below))

4. CFM4 – failure of *action execution* → $\boldsymbol{P_{CFM4} = 1 \times 10^{-3}}$
    - Scenario familiarity (Table B-1): no impact (**SF0**)
        - Justification – Operators are familiar with MCR-based actions based on procedures.
    - Information availability and reliability (Table B-2): this PIF does not apply to this CFM (see the "NA" under the "E" column of Table B-2)
    - Task complexity (Table B-3): **C31**, "Straightforward Procedure execution with many steps" → $\boldsymbol{1 \times 10^{-3}}$
        - Justification – Once operators enter procedure ES-1.2, the execution of the actions to depressurize the RCS (at a high level) requires resetting SI, resetting containment isolation, verifying that the alternating current power buses are energized by offsite power, checking if the RHR pumps should be stopped, checking the levels in the SGs, checking the PZR pressure, blocking steamline isolation signals, and dumping steam to the condenser. In addition, operators must check the subcooling of the RCS, maintain an appropriate cooldown rate, check the status of the ECCS pumps, deenergize PZR heaters, and refill the PZR to a specific level using normal PZR spray. For operators, these actions are straightforward but are many steps.
    - Modification PIFs – no impact (see summary of PIF attribute assessment (below))

5. CFM5 – failure of *interteam coordination* → As stated in Step 3.2, this CFM is not applicable to this critical task.

Summary of PIF attribute assessment for the remaining (modification) PIFs for all applicable CFMs:

- Environmental PIFs (Table B-4) – As noted in Step 1.3, the PIFs in the environment and situation context do not apply to this HFE. Therefore, for the purpose of quantification, the no impact (**ENV0**) PIF attribute is assigned.
- System and Instrumentation and Control (I&C) Transparency (Table B-5) – No impact (**SIC0**) for all applicable CFMs because the actions are performed in the MCR and the system response and I&C should be transparent to the operators due to their training.
- Human-System Interface (HSI) (Table B-6) – No impact (**HSI0**) for all applicable CFMs because the actions are performed in the MCR and the MCR's design complies with regulatory requirements.
- Equipment and Tools (Table B-7) – No impact (**TP0**) for all applicable CFMs because the equipment and tools that are used to perform the actions (i.e., switches, buttons, etc.) are assumed to be well maintained.
- Staffing (Table B-8) – No impact (**STA0**) for all applicable CFMs because adequate staffing is assumed.
- Procedures, Guidance, and Instructions (Table B-9) – No impact (**PG0**) for all applicable CFMs because operators are following the emergency operating procedures (EOPs) and the EOPs cover the scenario in which this HFE is credited.
- Training (Table B-10) – No impact (**TE0**) for all applicable CFMs because the MCR operators performing the actions are assumed to licensed and have adequate training.
- Teamwork and Organizational Factors (Table B-11) – No impact (**TF0**) for all applicable CFMs because the teamwork and organizational factors are assumed to be adequate.
- Work Processes (Table B-12) – No impact (**WP0**) for all applicable CFMs because the work processes are performed by licensed personnel with assumed good practices.
- Multitasking, Interruption, and Distraction (Table B-13) – No impact (**MT0**) for all applicable CFMs because all attention by the MCR operators is directed at bringing the reactor to a safe and stable condition and it is assumed that there are no other events occurring at the same time.
- Mental Fatigue, and Time Pressure and Stress (Table B-14) – No impact (**MF0**) for all applicable CFMs because, even though the action may last a few hours, operators understand that the cooldown/depressurization of the RCS needs to be carried out in a controlled (not rushed) manner.
- Physical Demands (Table B-15) – As stated in Step 1.3, this PIF is not applicable to this HFE.

Step 5 – Estimation of Pc – the Sum of Human Error Probabilities of Cognitive Failure Modes

The estimation of P_c relies on the assessment of the PIF attributes performed in Step 4. Since in Step 2.2 we defined the HFE as having only one critical task, P_c is equal to the error probability of the critical task. The error probability of the critical task is estimated using Equation (3.3) as:

$$\begin{aligned} P_c = P_{CT1} &= 1 - [(1 - P_{CFM1}) \cdot (1 - P_{CFM2}) \cdot (1 - P_{CFM3}) \cdot (1 - P_{CFM4})] \\ &= 1 - [(1 - 1 \times 10^{-4}) \cdot (1 - 1 \times 10^{-3}) \cdot (1 - 1 \times 10^{-3}) \cdot (1 - 1 \times 10^{-3})] \\ &= 3.1 \times 10^{-3} \end{aligned}$$

This calculation can also be performed using the IDHEAS-ECA software.

Step 6 – Estimation of Pt – the Convolution of the Distribution of Time Available and Time Required

Time available: The range of the time available is estimated in Step 2.1. The lower and upper bounds of the estimate are assumed to be the 2.5th and 97.5th percentiles of any assumed probability distribution because plant specific ECCS pumps flow rates were used to derive these estimates. Assuming that the time available is lognormally distributed, its parameters are calculated using Equations (C.10) and (C.11) and the results are $\mu_{T_{avail}} = 5.04$ and $\sigma_{T_{avail}} = 0.5$.

Time required: As mentioned in Step 2.1, the time required to perform the action is estimated to be between 12 minutes and 15 minutes. The lower and upper bounds of the estimate are assumed to be the 2.5th and 97.5th percentiles of any assumed probability distribution. Assuming that the time required is also lognormally distributed, its parameters are calculated using Equations (C.10) and (C.11) and the results are $\mu_{T_{reqd}} = 2.6$ and $\sigma_{T_{reqd}} = 0.06$.

Calculation of P_t

Assuming that T_{avail} and T_{reqd} are lognormally distributed with the parameters calculated above and using Matlab (version R2021b), P_t is estimated to be 9×10^{-7}.

Step 7 – Calculate the Overall Human Error Probability

The overall HEP is calculated using Equation (3.1), which is implemented in the IDHEAS-ECA software, as follows:

$$\begin{aligned} \text{P(OPR-XHE-XM-DEPRCS)} &= 1 - (1 - P_c) \cdot (1 - P_t) = 1 - (1 - 3.1 \times 10^{-3}) \times (1 - 9 \times 10^{-7}) \\ &= 3.1 \times 10^{-3} \end{aligned}$$

Step 8 – Analyze Uncertainties, Perform Sensitivity and Dependency Analyses, and Document the Results

There are a few uncertainties in this analysis, which are as follows:

- In Step 4, the PIF attributes C21 “Transfer step procedure – integrating a few cues” may be assigned to CFM3 (failure of decisionmaking), which would result in $P_{CFM3} = 4.5 \times 10^{-3}$. This would result in P_c increasing from 3.1×10^{-3} to 6.6×10^{-3} and the overall HEP increasing from 3.1×10^{-3} to 6.6×10^{-3}.
- Given that the time available and time required were assumed to be lognormally distributed, Table F-4 provides a sensitivity analysis for P_t, which was calculated using Matlab (R2021b), and the overall HEP. In all the sensitivity analysis cases in Table F-4,

the estimated range and percentiles are the same as those described in Step 6. The sensitivity analysis shows that P_t ranges from 2×10^{-7} to 7.1×10^{-3}, which results in the overall HEP (using $P_c = 3.1 \times 10^{-3}$) ranging from 3.1×10^{-3} to 1.0×10^{-2}. In the case where $P_c = 6.6 \times 10^{-3}$ (see the bulleted item above), the overall HEP ranges from 6.6×10^{-3} to 1.4×10^{-2}. By considering these sensitivity cases, the overall HEP ranges from 3.1×10^{-3} to 1.4×10^{-2}.

Table F-4 Sensitivity Analysis Results for P_t and the Overall HEP for OPR-XHE-XM-DEPRCS

T_{reqd} Distribution Parameters	T_{avail} Distribution Parameters	P_t	HEP
Normal(μ=13.5, σ=0.8)	Normal(μ=233.5, σ=89.5)	7.0E-3	1.0E-2
Lognormal(μ=2.6, σ=0.06)	Lognormal(μ=5.04, σ=0.5)	9.0E-7	3.1E-3
Weibull(shape=22.3, scale=14.1)	Weibull(shape=2.6, scale=245.2)	5.6E-4	3.7E-3
Gamma(alpha=309.1, beta=0.04)	Gamma(alpha=4.5, beta=43.03)	9.0E-7	3.2E-3
Normal(μ=13.5, σ=0.8)	Lognormal(μ=5.04, σ=0.5)	6.2E-4	3.1E-3
Normal(μ=13.5, σ=0.8)	Weibull(shape=2.6, scale=245.2)	8.7E-5	3.7E-3
Normal(μ=13.5, σ=0.8)	Gamma(alpha=4.5, beta=43.03)	7.0E-3	3.2E-3
Lognormal(μ=2.6, σ=0.06)	Normal(μ=233.5, σ=89.5)	6.2E-4	1.0E-2
Lognormal(μ=2.6, σ=0.06)	Weibull(shape=2.6, scale=245.2)	8.7E-5	3.7E-3
Lognormal(μ=2.6, σ=0.06)	Gamma(alpha=4.5, beta=43.03)	7.1E-3	3.2E-3
Weibull(shape=22.3, scale=14.1)	Normal(μ=233.5, σ=89.5)	1.1E-6	1.0E-2
Weibull(shape=22.3, scale=14.1)	Lognormal(μ=5.04, σ=0.5)	9.3E-5	3.1E-3
Weibull(shape=22.3, scale=14.1)	Gamma(alpha=4.5, beta=43.03)	6.8E-3	3.2E-3
Gamma(alpha=309.1, beta=0.04)	Normal(μ=233.5, σ=89.5)	2.0E-7	9.9E-3
Gamma(alpha=309.1, beta=0.04)	Lognormal(μ=5.04, σ=0.5)	5.1E-4	3.1E-3
Gamma(alpha=309.1, beta=0.04)	Weibull(shape=2.6, scale=245.2)	5.7E-5	3.6E-3

- In comparing the result of this analysis to the result obtained using the SPAR-H HRA method, consider the following information from the SPAR model reports:

  "*This human failure event starts from full power operation. Diagnosis of the need for the operator to depressurize the reactor is not modeled since the actions are proceduralized and the need for action is obvious. The stress level is expected to be high [$F_{Stress} = 2$] due to the nature of the scenario (typically SLOCA/SGTR). Action complexity is [moderate] [$F_{Complexity} = 2$] due to the various alignments that must occur. All other [performance] shaping factors are assumed nominal. The action [execution] is modeled. Dependency is not modeled for this action. The geometric mean of eight randomly selected equivalent [industry] PRA events is 3.9E-3.*"

  This leads to the following calculation: SPAR-H HEP $= 1 \times 10^{-3} \cdot 1 \cdot 2 \cdot 2 \cdot 1 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = 4 \times 10^{-3}$

Note – The cited work is in the list of references in Section 5 of this report.

NRC FORM 335
(12-2010)
NRCMD 3.7

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG-2256

2. TITLE AND SUBTITLE

INTEGRATED HUMAN EVENT ANALYSIS SYSTEM FOR EVENT AND CONDITION ASSESSMENT (IDHEAS-ECA)

3. DATE REPORT PUBLISHED

MONTH	YEAR
Month	**20xx**

4. FIN OR GRANT NUMBER

5. AUTHOR(S)

J. Xing
Y. J. Chang
J. DeJesus Segarra

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.)

Same as above

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

Copy and paste Abstract here (200 words or less)

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Probabilistic risk assessment
Human reliability analysis
Human error probability
Human performance
Performance influencing factors
Macrocognition

13. AVAILABILITY STATEMENT

unlimited

14. SECURITY CLASSIFICATION

(This Page)

unclassified

(This Report)

unclassified

15. NUMBER OF PAGES

16. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS

@NRCgov

NUREG-2256

INTEGRATED HUMAN EVENT ANALYSIS SYSTEM FOR EVENT AND CONDITION ASSESSMENT
(IDHEAS-ECA)

Month20xx