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A Formalized Approach for the Collection of HRA Data from Nuclear Power Plant Simulators

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NOTICE

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ABSTRACT

Data from nuclear power plant (NPP) simulator environments reflect important aspects of human performance and potentially the causes of human error. However, the information collected is constrained by the uniqueness of each particular plant and design of each particular simulator study. Thus, the ability to apply the findings of a given simulator study to other studies of human performance at NPPs is often limited. A well-defined approach to experimental design, a common language or measurement technique for describing and classifying errors and human actions, and an associated theoretical underpinning for the design and resulting statistical analyses are required to allow extrapolation of the results of simulator studies across plant designs, crew make-ups, and scenarios.

The purpose of this report is: to propose an approach for collecting human performance data from NPP simulators and employing the reliability engineering (RE) concept of limit state, to describe the process for collecting data, and to present illustrative examples of data analyses. This approach borrows from techniques applied in traditional RE while using experimental techniques derived from the behavioral sciences.

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Data from nuclear power plant (NPP) simulator environments reflect important aspects of human performance and potentially the causes of human error. However, the information collected is constrained by the uniqueness of each particular plant and design of each particular simulator study. Thus, the ability to apply the findings of a given simulator study to other studies of human performance at NPPs is often limited. A well-defined approach to experimental design, a common language or measurement technique for describing and classifying errors and human actions, and an associated theoretical underpinning for the design and resulting statistical analyses are required to allow extrapolation of the results of simulator studies across plant designs, crew make-ups, and scenarios.

The purpose of this report is: to propose an approach for collecting human performance data from NPP simulators and employing the reliability engineering (RE) concept of limit state, to describe the process for collecting data, and to present illustrative examples of data analyses. This approach borrows from techniques applied in traditional RE while using experimental techniques derived from the behavioral sciences.

The ultimate aim of the proposed approach is to achieve greater consensus, consistency and convergence of human reliability analysis (HRA) methods by stimulating simulator data exchange, greater communication, and review within the HRA research and practitioner community. The overall objective of this work is in accordance with SRM-M090204B.

HRA exists at a nexus between three distinct disciplines: (1) the behavioral sciences (i.e., human factors, ergonomics, cognitive sciences, and psychology); (2) reliability engineering; and (3) probabilistic risk assessment (PRA). Each discipline has a tradition of scientific development and theoretical underpinnings that reflect the formal requirements for, and use of information (e.g., data, knowledge, etc.) to address issues to which the discipline is applied. This tradition includes the use of formal experimental design, protocols for data collection, methods for the analysis and interpretation of data, development of models to integrate results, and development of codes and standards.

This presents challenges to the HRA discipline because, in several important ways, the methodological approaches of these disciplines are quite different. In principle, RE analysis assesses the performance of discrete system elements, having well-characterized governing dynamics (e.g., mechanical, electrical, chemical, etc.), interacting with other discrete elements under well-described conditions. The interactions among components in a mechanical system are straightforward to characterize. Mechanical system interactions are observable, measurable, quantifiable, and predictable.

Human performance is difficult to subject to the same form of reliability analysis that is applied to electro-mechanical systems. The body of behavioral sciences literature and knowledge is not as easy to employ in studies of human reliability analysis as engineered system characteristics are in the analysis of systems reliability. Human capabilities are not as easily understood as the capabilities of electro-mechanical devices. Because of the complexity of the human systems, our state of knowledge of human cognition and behavior is not as mature as it is for mechanical systems. Therefore, developing functional models, as well as testing and refining theories, about these human related processes is difficult.

One of the hallmark characteristics of the RE discipline is the ability to “test to failure” by creating system failure conditions which can be observed and to collect data that can be used to establish failure rates for various failure types. Validated models using such data can describe the physics of failure of electro-mechanical devices or structural systems, including nuclear energy systems.

Studies of humans that enable observations of failure are needed to develop and validate models for human reliability. Failures in human performance that would be of interest to HRA are unlikely to be observed. The HFEs modeled in a PRA, are events that result from unique combinations of failures (i.e., initiating events) and plant conditions and are very plant specific. Few studies of human failures designed to manifest these conditions in nuclear power plant control rooms have been conducted and reported such that the ability to draw general insights about failure rates and types is limited.

As postulated above, the ability to collect data on the reliability of human performance in complex environments is much more difficult than it is to collect data for many of electro-mechanical devices employed in nuclear energy production and other industrial systems. What is needed are opportunities to collect data about human performance in which success and failure are defined and measured and theories of human performance and human reliability that are sufficiently mature to support HRA model and method development.

The approach proposed in this report could be used to provide a common language for human failures (limit state) and human performance within HRA studies that would allow data from one HRA context to be extrapolated to a new context.

Collecting simulator data to support HRA requires robust experimental design and process. This report describes five essential experimental design characteristics based on paradigms from the behavioral sciences that should be considered for robust experimental design when preparing to collect data for application in HRA. The five experimental design characteristics are:

- Performance Measures Should Relate to Success and Failure as Defined in the PRA
- Simulator Contexts should be Representative of PRA Events
- Data Collection Should Include the Opportunity to Observe Human Failure Events of Interest
- Data Collection should include Objective Human Performance Measures of Success or Failure
- Data Collected Should Describe Relevant Aspects of Performance and the Factors that Effect that Performance

HRA methods consider conditions that may be found in NPP contexts to predict the kinds of errors (e.g., slips, lapses, or mistakes) and the likelihood of those errors that can occur. There is substantial experimental and experiential evidence about the many factors that may be “drivers” of human reliability. These include factors such as stress, workload, human-system interface technologies, training and experience, crew resource management, intra-team dynamics, and others. An analysis of crew performance data should permit a determination regarding success of the crew and to minimize the potential for subjectivity in evaluating crew performance.

The report describes in detail the specific process steps for performing an experiment following a robust design that focuses on collecting HRA relevant data from an NPP simulator running risk-significant events. The process of conducting an HRA simulator data collection effort can be described in four main phases: preparation, data collection, data analysis, and reporting. These four phases are further defined by 19 sub-steps. Some of the sub-steps are discussed in detail. For example, in the preparation section, legal contractual mechanisms are discussed, as well as important items to consider when designing and validating the scenarios to be used in the data collection effort. This includes the determination of success and failure criteria and human performance measures. The data collection section presents different methods to be used for data collection and also describes how to structure the collection effort. In the data analysis section, examples of how to develop synopses and how to document deviations and errors are provided. There is also a description of how to analyze performance drivers in this section. This report discusses in detail the concept of limit state as a generic approach to define success and failure criteria so that the data can be used across HRA methods. Limit state from an RE and systems safety perspective denotes a region of performance that distinguishes between performance success and failure.

Two important approaches for analyzing the quality of crew response include (1) analyzing the distribution of crew performance on the criteria related to the limit state and (2) analyzing the variability in crew response relative to the limit state. The performance criteria for human actions are specific to the event sequence and scenario. Even though the same human actions are required in different event sequences, the specific criteria that define success for the human action is scenario specific. Identifying the criteria in each scenario context is the first step of establishing the measure of success and failure for the critical human action. Using observed crew performance during the simulator runs of the scenario and the defined threshold for performance, the data show the response of individual crews against the maximum available response range. This method of analysis produces a distribution of crew performance relative to the limit state and is an indicator of how near the crew was to failing to meet the performance criteria for the scenario.

The second analysis approach uses crew performance data to characterize the variability in crew response. Variability in crew performance reflects intercrew differences in task execution, procedure use, and decision making, all of which are interrelated. It also reflects uncertainty in the results of crew performance that may have implications for the reliability and consistency in crew response to the initiating event(s).

Performing these analyses results in normalization of the raw performance measurement in terms of the limit state. This means that the raw performance measures are adjusted using their relationship to the limit state on a notionally common scale. This permits insights to be drawn regarding three properties related to performance reliability:

- Whether the actions meet the success criteria for the defined HFE
- The amount of margin available between their performance and the limit state for the action as defined by the HFE
- Variability among crews in performing the action(s)

The process of normalization whether using raw data or transformed data relates observed performance to the system limit state and provides a reference that can be used to show performance relative to success and failure criteria alone. There may be many differences between success and failure criteria for accident sequence criteria among different plants and plant types. Normalization and appropriate transformations are ways that data collected from different facilities may be treated and analyzed to permit comparison and potentially aggregation across data collection sites.

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ABBREVIATIONS

AFW	auxiliary feedwater
CCW	component cooling water
CSNI	Committee on the Safety of Nuclear Installations
EDG	emergency diesel generator
EOP	emergency operating procedures
ESF	engineering safety feature
F&B	feed and bleed gpm
	gallons per minute
HFE	human failure event
HHP	head safety injection pump
HRA	human reliability analysis
IDHEAS	A Method of the Integrated Human Event Analysis System
LER	license event report
LOCA	loss-of-coolant accident
LOFW	loss of feedwater
MFW	main feedwater
MSIV	main steam isolation valve
NEA	Nuclear Energy Agency
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
OECD	Organization for Economic Cooperation and Development
PORV	power-operated relief valve
PRA	probabilistic risk assessment
PSF	performance shaping factor
PZR	pressurizer
RCP	reactor coolant pump
RCS	reactor coolant system
RE	reliability engineering
RO	reactor operator
Rx	reactor
S/G	steam generator
SGTR	steam generator tube rupture
SI	safety injection
SM	shift manager
SSC	structure, system, or component
STA	shift technical advisor
US	unit supervisor
WGRISK	Working Group on Risk

1. INTRODUCTION

1.1 Background and Technical Basis

Data from nuclear power plant (NPP) simulator environments reflect important aspects of human performance and potentially the reasons for and causes of human error. However, the information collected is constrained by the uniqueness of each particular plant and design of each particular simulator study. Thus, the ability to apply the findings of a given simulator study to other studies of human performance at NPPs is often limited. A well-defined approach to experimental design, a common language or measurement technique for describing and classifying errors and human actions, and an associated theoretical underpinning for the design and resulting statistical analyses are required to allow extrapolation of the results of simulator studies across plant designs, crew make-ups, and scenarios.

In addition to the NRC research efforts, the need for HRA data has been part of international cooperative activities sponsored by the Organization for Economic Co-Operation and Development (OECD), Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI) which has been pursuing simulator studies at the Halden Reactor Project. (Bye et al. 2012, Forester et al. 2012, Hendrickson et al. 2012, & Marble et al. 2012).

Report NEA/CSNI/R(2008)9 proposes a standardized HRA data collection approach, focusing on data generated in plant training simulators. Specifically, the report describes a pilot study that was conducted with the objective of establishing a framework for collection and exchange of human performance data from training and research simulators, including the establishment of good practices for performing these activities.

Since its inception, the research activity described in the current report was informed by these other efforts to promote the possibility of standardizing the method for use by other organizations. Adding to the complexity of the study of human performance in nuclear power is that many of the causes for human error cannot be observed because they occur in the realm of human cognition. This is one of the reasons why data from human failures have not been used to derive failure estimates for human reliability assessment (HRA) in the same way that equipment failures and unavailability are used to estimate hardware failure parameters for probabilistic risk assessment (PRA). Further, the underlying theoretical treatment of the human as another component of the NPP system that can fail predictably if all the critical parameters can be defined is difficult at best to achieve. Estimating failure probabilities from counts of human error alone ignores relevant aspects of the performance context and overlooks the interdependency between cognition and context. This interdependency is critical given that context is well understood to be a driver for cognition (Sternberg 1996, Wickens 1984, Wickens 2008). The ability to empirically test and verify aspects of operational demand and crew capacity as they relate to success and failure and to develop systematic insights about human reliability would be valuable to predict error, as well as to better estimate the likelihood of its occurrence.

One of the hallmark characteristics of the reliability engineering discipline is the ability to “test to failure” by creating system failure conditions which can be observed and used to collect data to establish failure rates for various failure types. For example, subjecting structures and structural materials to various design loads, including those design loads that could produce structural failures, is one method used to qualify new building materials and construction methods, as well as to establish engineering codes and standards. Validated models using such data can describe the physics of failure of electro-mechanical devices or structural systems. Such models also can be developed for new SSCs employed in safety critical applications, such as those that ensure the safety or integrity of nuclear energy systems are observable, measurable, quantifiable, and predictable.

Human performance cannot yet be subjected to a form of reliability analysis comparable to that of mechanical and electrical systems. Although the behavioral sciences are comprised of an extensive body of literature and knowledge, some believe that this knowledge is not as easy to employ in HRA as is performance data obtained from engineered systems for traditional RE applications. This belief is perhaps supported by the view that human capabilities are far more extensive, complex, and interconnected and therefore, not understood as well as the capabilities of electro-mechanical devices. The notion that our state of knowledge of the functioning of human cognition and behavior is not as advanced as for mechanical systems, has potentially inhibited direct adaptation of reliability engineering (RE) concepts in HRA, although HRA is part of the reliability discipline. Furthermore, until lately, there was little focus in the behavioral science on developing empirical basis for HRA whose objective is to analyze human performance dealing with rather extreme situations. However, developing functional models, as well as testing and refining theories, about human related processes involved in accident conditions has been recognized as vital to shaping our knowledge and expectations about human reliability (Williams 1992).

Failures in human performance that would be of interest to HRA are rare in opportunity and, thus, unlikely to be observed except by design. In the real world, the expected plant conditions to which plant staff would have to respond rarely occur – and occur even more seldom for PRA events and their precursors. The HFEs modeled in a PRA are events that result from unique combinations of failures (i.e., initiating events) and plant conditions. Reports of human failures in behavioral science studies in non-nuclear domains have shown how humans fail in complex environments (Vicente and Tanabe 1993). However, analysis of reported failures cannot always distinguish between failures due to variability in human response (e.g., a simple 'slip' in activating a control device) and failures due to systemic, underlying causes such as real limits in human capabilities (e.g., an overload of mental attention that interferes with an operator's activation of a control device). This underscores the need for more directly relevant sources of data about human performance that can be used to derive information about the limits of operator performance or capabilities in NPPs. In this report the concepts discussed above are being used to develop an approach for using simulators to produce human performance data suitable to HRA. The approach is using some fundamental features of RE engineering allowing the mining and dissemination of the data in an efficient manner reducing the amount of effort needed to be documented, analyzed and shared. A particular emphasis of the proposed approach is the sharing of such data across organizations.

A key aspect of the proposed approach is the use of a standardized measurement technique that could be used by anyone conducting a simulator-based study. The proposed measurement technique employs the notion of comparing crew objective performance with the limiting condition for success as used in the plant PRA, which we characterize as the limit state. The intention of suggesting this particular standardized measure is to support inferences about crew performance and the reliability (or unreliability) of that performance in simulated exercises built around PRA contexts. Other purposes of the proposed approach are to minimize the efforts needed to interpret human performance data collected and to provide an objective measure of human performance that can be directly related to success in the PRA context.

1.2 Purpose

The purpose of this report is to propose a formalized approach for collecting human performance data employing the concept of a limit state, to describe the process for collecting data, and to present illustrative examples. This approach borrows from techniques applied in traditional reliability engineering (RE) while using experimental techniques derived from the behavioral sciences.

The ultimate aim of the proposed approach is to achieve greater consensus, consistency and convergence of HRA methods by stimulating simulator data exchange, greater communication, and review within the HRA research and practitioner community. The proposed approach is intended to yield data that strengthens the technical bases for HRA methods and their applications.

To obtain such data when dealing with human performance requires consideration of the principles of experimental design derived from behavioral and psychological research. This research proposes an approach that can be employed in a standardized manner to consistently collect data that measures aspects of human performance relevant to human reliability analysis. To do so, principles of reliability engineering were investigated, particularly the principle of demand and capacity and the associated notion of a limit state. This latter notion is central to this effort. A limit state is a formally identified region of performance that distinguishes successful from unsuccessful performance. In this effort, the notion of a limit state was applied to human performance in order to define success and failure of actions performed by operators in response to a PRA design basis event.

The approach to design scenarios and measure human performance is derived using a robust experimental design. As such it should ensure consistency of results, and application of the findings from PRA scenarios to address general issues of human reliability as well as support the eventual goal of exchanging data among organizations that collect such data. The characteristics of such a robust experimental design include:

1. Objective performance measures for operating crew performance in PRA scenarios.
2. Plant parameters that correspond directly to operator actions related to human failure events (HFEs) of interest in PRA.
3. Summaries and descriptions of crew performance that account for crew decision making and performance related to the human actions of interest for each PRA scenario.
4. Structured measurement of performance drivers that can be related to operator and crew performance.
5. Crew feedback using structured debriefings to collect retrospective observations from crewmembers that provide insights about the factors that influenced their performance.

Ultimately, HRA practitioners may wish to develop probability estimates from the empirical data collected. However, this is beyond the scope of the current effort. This effort is not intended to serve as an end-to-end method for generating probability estimates of human reliability. The current research is intended to identify and describe some of the research characteristics that can ensure that studies of human performance produce data that are directly related to human reliability issues, as used in PRA. Further, the results of the research can support the eventual exchange of information or data about human performance among organizations that collect and use such data.

1.3 A Framework for Human Reliability Analysis Data Collection

Because of its relationship with other disciplines, an HRA data generation approach must reflect critical aspects of the underlying scientific and methodological requirements of the scientific disciplines upon which it is based (Hallbert et al. 2007). HRA exists at a nexus between three distinct disciplines: (1) the behavioral sciences (i.e., human factors, ergonomics, cognitive sciences, and psychology); (2) RE; and (3) PRA. Each discipline has a tradition of scientific development and theoretical underpinnings that reflect the formal requirements for, and use of information (e.g., data, knowledge, etc.) to address issues to which the discipline is applied. This is seen in efforts that generate data to support HRA to either develop and validate HRA models or to the use performance data to predict human reliability parameters (Hallbert et al. 2011, Groth 2009).

The nature of HRA is interdisciplinary. Behavioral sciences draw from the disciplines of psychology, cognitive science, human factors and offer a variety of theoretical models to model human performance dealing with unexpected conditions. As a result several HRA methods are currently available, each handling human performance differently. An issue dealt with in the last few years is the variability of results in HRA; i.e., recognition that analysis of a given human action may produce different results (estimations and insights) using different methods as well as different analysts using same method. Addressing this issue has been the focus of the HRA community. This led recently to collaborative studies sponsored by OECD (Lois et al, Bye et al, Dang et al.) as well as domestically (Forester et al.). The NRC also undertook the initiative to perform a thorough literature search to update the technical basis for HRA (Whaley et al. 2012 a, Whaley et al. 2012b) as well as to develop a hybrid HRA method called A Method of the Integrated Human Event Analysis System (IDHEAS) (Xing et al). Data that are used to inform (i.e., develop, validate, test aspects of, etc.) modern HRA methods must also be based on solid technical and methodological foundations. This includes approaches to human performance measurement and experimental design based on both behavioral science and reliability engineering.

RE analysis concepts have been developed from an equipment and physical system performance perspective. Accordingly, they are used to assess the performance of discrete system elements, having well-characterized governing dynamics (e.g., mechanical, electrical, chemical, etc.), interacting with other discrete elements under well-described conditions. Hence, the interactions among components in a mechanical system are straightforward to characterize. This includes the manner in which they receive and process inputs from other components, the manner in which they produce outputs, and the specific outputs they produce. The PRA provides a clear structure to identify the tasks needed to be performed as well as the conditions under which the tasks should be performed. From that perspective, PRA analyzes equipment as well as human failures. To assess equipment failures PRA analysts are relying on information and data developed with RE principles, including the test-to-failure principle on the basis of which system capability is characterized for the various conditions assumed to be functioning when needed. Similarly, HRA needs information related to test-to-failure information for the various conditions.

The latest focus of the HRA community is to use simulator experiments to advance HRA. The current effort employs existing capabilities in both behavioral sciences and RE to develop a structured approach for performing experiments focusing on HRA; that is, experiments that produce human performance data which satisfy both the behavioral sciences dealing with human capabilities needed for tasks related to responding to unaccepted events, and associated drivers of performance determined by both external situations (e.g., design of control room, severity of event etc.) as well as cognitive and physical demands. The previously mentioned simulator studies (Lois, Bey, Dang, Forester) for HRA demonstrate the feasibility and practicality to use simulator facilities to improve the robustness of HRA. In fact the NRC has recently undertaken an effort to collect human performance data from the plant's routine training using their plant simulators (Chang & Lois, 2012; Criscione et al, 2012).

Today's field of HRA should benefit from a formalized approach analogous to that used in the behavioral sciences to guide the collection of data that then can be used to develop insights and improve models used for HRA as well as address needs in a reliability engineering domain. For example, collecting data about the performance context of a pump may not be important to estimate a parameter of pump reliability. However, performance context data may be very important for human reliability where performance and context are known to be very interdependent. Also, raw data about operator performance varies from plant to plant, owing to differences in their design and corresponding thermal-hydraulic behavior. The proposed approach attempts to make possible to share human performance data regardless of such differences. Using the PRA concepts of success criteria, it is a formalized approach using performance measures that can be applied to any study regardless of individual plant differences and can relate directly to the matter of human reliability (i.e., the success or failure of human action in PRA contexts).

1.4 Document Organization

The document first describes the theoretical background and technical basis for the proposed standardized HRA simulator data collection approach. Then it describes the five tenets of the data collection approach, followed by a step-by-step process for conducting an HRA simulator data collection study. It is followed by a description and examples from a study where the proposed standardized approach was applied. A conclusion section summarizes the documen

2. PRINCIPLES FOR COLLECTING HRA DATA FROM NUCLEAR POWER PLANT SIMULATORS WITH AN EMPHASIS ON THE LIMIT STATE CONCEPT

2.1 Introduction

Collecting simulator data to support HRA requires robust experimental design and a process. This section describes five essential experimental design characteristics based on paradigms from the behavioral sciences that should be considered when preparing to collect data for application in HRA. The section includes recommendations on categories of information to collect when employing training simulators.

HRA methods consider conditions that may be found in probabilistic safety analysis contexts to predict the kinds of errors (e.g., slips, lapses, or mistakes) and the likelihood of those errors (i.e., probability) that can occur. There is substantial experimental and experiential evidence about the many factors that may be "drivers" of human reliability in PRA contexts. These include factors such as stress, workload, human-system interface technologies, training and experience, crew resource management, intra-team dynamics, and others.

2.2 Principles of the Data Collection Approach

The following are proposed as principles to guide collecting human performance data. They are intended to provide information about the conditions, qualitative aspects of HFE, and data on the occurrence of the HFEs to support their use in HRA research and related applications.

2.2.1 Performance Measures Should Relate to Success and Failure as Defined in the PRA

In all simulator-based activities in which crews of operators demonstrate their performance in PRA-based simulated events, success and failure needs to be clearly defined. The definition of success will differ across PRA events since the required operator actions needed to mitigate the effects of initiating events also differ. It may also differ within a single class of a PRA scenario due to differences in the postulated initial conditions, timing of the initiating event(s), and any additional complications and failures included for training or testing. Notwithstanding such differences, success criteria exist for each PRA context based on plant response and the need to prevent damage to the nuclear fuel and release of radioactive materials.

The measure of success should be capable of characterizing performance on a continuum so as not to limit the ability to draw more useful insights from such a measure. For example, it is possible that all crews in a training sample complete needed actions to mitigate a design basis event. This would indicate one hundred percent success on the critical mitigation action(s). Upon closer inspection, systematic variability may exist indicating that some crews did so with substantial 'margin' to spare while others did not. Employing a continuum permits characterization of performance with greater contextual sensitivity to issues such as available or remaining margin to failure and variability in performance amongst crews. It also permits estimation of measures of central tendency and statistical analysis that can be used in HRA.

For PRA purposes, an absolute, event-specific limit exists for design basis events. Its use should inform data collection efforts, for example, to identify the extent to which it is exceeded or challenged in some other way during simulator based crew performance exercises. Its use would assist in reducing subjectivity when interpreting the results of crew performance.

2.2.2 Simulator Contexts Should be Representative of PRA Events

Scenarios and contexts should be representative of the needs for PRA and the different performance conditions that operating crews may encounter. For purposes of HRA research, this necessitates understanding and incorporating important conditions in data collection situations to ensure the environments sampled are representative of PRA events and performance contexts in PRA events. In particular, differences in scenarios that arise within classes of PRA events should be taken into account. This includes such features as the magnitude of challenge to plant safety, the pace of an event, complications that arise from equipment failures and others, which vary across instances of a class of design basis events. Such features result in differences in the tasks to be performed by the control room crew, available time for crew response, the degree of interpretation and problem solving required, and ancillary demands (e.g., emergency and offsite notifications or use of ex-control room plant staff and coordination of these resources). Human reliability issues may thus arise from differences
in how scenario demands manifest themselves within a class of design basis events.

Characterizing a particular scenario for the purposes of HRA on the basis of the initiating event and event sequence is an important part of describing a representative range of demand conditions. Additional information is also needed to characterize human performance demand features in order to relate observed variability in crew performance or failures back to potential causal demand features. This requires describing, with specificity, the kinds of cognitive and human performance demands present in simulator scenarios that are used for data collection. It also requires that demands be described consistently, following an approach that may be standardized and applying an associated, accepted model of human performance. Characterizing scenario and context demands systematically, according to valid and consistently applied criteria, is an important part of understanding the data. Furthermore, these characterizations may serve as a means of identifying and selecting data for future use and study.

Data collected from well-designed scenarios and run on plant training simulators or research simulators, should be representative of human performance and reliability. This includes the ways that crews are expected to behave and perform in the simulator environment, and the availability of data from plant-specific simulators that can be used to characterize the performance of crews.

2.2.3 Data Collection Should Include the Opportunity to Observe Human Failure Events of Interest

The analysis of a PRA event (i.e., event sequence) encompasses performance conditions and specific needed human actions. The human failure events of interest in an event sequence represent human actions that, if not performed or not performed to a prescribed standard, will result in a functional failure of a system or safety criteria and may lead to degraded plant conditions. Data on these human actions are of primary interest and constitute the main unit of measure. The result is that error information is typically defined in terms of specific plant parameters from an individual plant. Observations based on plant-specific data are not easily generalized to other plants especially where the success criteria for a human action differs across plants.

Observations of failure under varying demand conditions are needed to provide data about one of the most important aspects of HRA methods: the ability to predict performance failure. It is vital to the development of human performance reliability theory and methods that data collection efforts include the opportunity to observe an unrestricted range of human performance, including success and failure. HRA research should be carried out under conditions similar to those modeled in PRAs. It should include those human actions both implicitly and explicitly modeled in PRAs as needed for recovery and mitigation of plant conditions. Limiting the range of demand in data collection to those that minimize opportunities to observe HFEs, errors, or deviations (i.e., partial failures) restricts the ability to formulate or validate theories of human reliability.

Data for performance success and failure are needed for a number of reasons. First, a data collection approach that is capable of yielding a representative range of results from the success and failure regions of interest can form the basis for collaborative research. Because it employs methods and measures that can provide insights about human performance that transcend plant-specific issues, the proposed approach may serve as a means to support the exchange of human performance reliability information across organizations. Collaborative efforts that emphasize the exchange of research methods and results from human reliability studies can be instrumental in overcoming a lack of progress in this area by engaging more organizations in the exchange of human reliability data.

Analogous to electro-mechanical systems reliability assessments, opportunities are needed to gather a substantial record of data from relevant operational contexts to produce baseline human reliability estimates. For HRA, the “system” of interest is the joint human-machine system. Actuarial type data of human reliability from representative PRA contexts could provide a sufficient evidentiary basis to support formulation of insights about a number of relevant issues, including:

- Rank ordering of observed HFEs across event sequences and plant conditions
- Sensitivity of human performance reliability to plant conditions
- Relationships between event sequence instantiations, plant conditions, and PSFs
- Identification of error-likely contexts.

2.2.4 Data Collection Should Include Objective Human Performance Measures of Success and Failure

Performance criteria exist for all aspects of engineered systems and especially so for nuclear energy systems. In the case of PRAs, event sequences characterize the performance of systems using binary diagrams based on the success or failure of systems or functions. The role of operators and criteria for their performance in PRAs is based on needs to carry out actions in response to initiating events and other failures. Human actions are performed to mitigate an event sequence and are essential to plant stabilization and recovery. The task of human reliability analysts is to understand the demands and capabilities of plant staff and estimate the reliability with which it can be done. Translating this into observations that can be made in a simulator environment requires, at a minimum, that criteria exist or can be developed to distinguish between successful and unsuccessful human performance. Beyond this, it is important to characterize contextual features (i.e., plant conditions and performance-shaping factors) that contribute to human performance.

Translating the definition of success or failure to PRA terms is also necessary. For example, for every required human action in an accident sequence context, a thermal hydraulic criterion must be met to prevent more degraded plant conditions. This includes human actions in response to dependent equipment failures that dispose the plant to a more significant damage state. For each human failure event considered, a corresponding consequence that relates explicitly to those modeled in the PRA should be identified.

Taken together, the definition of success (or failure) and the consequence provide the criteria for human performance that also relate directly to the plant PRA and its technical basis. They serve as a single objective measure that, if accomplished according to specified criteria, prevent further degradation of plant conditions. They also signify an action or group of related actions which, if not performed to specifications, imply a functional failure that conditionally worsens plant conditions and leads to possibly more significant plant damage.

2.2.5 Data Collected Should Describe Relevant Aspects of Performance and the Factors that Affect that Performance

In addition to objective performance characteristics, it may be desirable to obtain data that provide insights about crew decisions and behaviors. Objective performance measurement is essential to obtain an unbiased and accurate depiction of crew performance. It describes the “what” and “when” aspects of crew and plant behavior. Though accurate, objective measures may not provide a complete account of crew performance. To do so requires additional and complementary data about the “why” and “how” of performance. Therefore, it is important to gather information about deviations, lesser mistakes, crew tendencies, information processing and decision making, team interactions, and other relevant information that relate to causal mechanisms and influences that account for variation in crew performance.

It is difficult and impractical to anticipate the variability in perceptions, decisions, and actions of crews and crew members as they cope with the many variations of plant challenges that can be played out in a training simulator. It is important to be able to collect data that reflect potential variation in order to subsequently assess its significance for human reliability purposes. This requires that a data collection protocol be designed in advance that is sufficiently flexible to capture both expected and unexpected, emergent crew behavior while at the same time being simple and reliable to employ.

Inter-rater reliability and simplicity of the data collection method are important. The data collection protocol should ensure that the expected user can reliably and efficiently obtain the required data. The data collection protocol should be designed to minimize burden that would arise from the additional tasks expected of plant personnel to produce data.

2.3 Categories of Information

Based on the foregoing considerations, the authors recommend that the following information be collected. It should be noted that all of the categories be tailored according to the scenario and that the scenario could affect which metrics of human performance are most applicable.

1. Objective performance of operators and crews in PRA scenarios.

2. Plant parameters that provide direct evidence of operator actions related to the HFE of interest.

3. Summaries and descriptions of operator performance to account for important differences in crew performance on the critical human actions of interest for each PRA scenario.

4. Structured measurement of PSFs that can be related back to operator and crew performance.

5. Crew feedback using structured debriefings to collect retrospective observations from crew members and trainers or other pertinent plant experts.

To obtain data related to these categories, a combination of sources is needed. This includes data from sources that supply data about the physical behavior of the plant and systems and about the activities of the crew. Typical information about plant systems includes the following:

- Failures and malfunctions inserted into the simulation
- Protection system actuations and automatic actuations of plant systems
- Alarms and notifications through the plant computer
- Plant parameters logged regularly and recorded electronically.

Information about crew performance should include the following (not all may apply):

- Numbers of control room crew members, their qualifications, and when present

- The normal main control room staffing, and any exceptions that applied during the scenario

- Control actions performed correlated in time to plant parameters

- Alarms acknowledged

- Recognitions and communication of key events and plant conditions

- Procedures entered and in effect (i.e., for conditions in which multiple procedures may be opened)

- Information sources consulted other than procedures (e.g., technical and reference information used for decision making or ex-control room advisors such as a technical support center)

- Errors, significant deviations from the expected course of action, consequences, and other noteworthy observations

The next section describes the step-by-step process recommended to collect the data described above.

3. COLLECTING DATA FROM TRAINING SIMULATORS FOR HRA

The process of conducting an HRA simulator data collection effort can be described in four main phases: preparation, data collection, data analysis, and reporting. Table 1 depicts these four phases and their respective sub-steps. Some of the sub-steps are discussed in detail in this section. For example, in the preparation section, legal contractual mechanisms are discussed, as well as important items to consider when designing and validating the scenarios to be used in the data collection effort. This includes the determination of success and failure criteria and human performance measures. The data collection section presents different methods to be used for data collection and also describes how to structure the collection effort, keeping in mind the information in Section 2 of this report. In the data analysis section, examples of how to develop synopses and how to document deviations and errors are provided. There is also a description of how to analyze performance shaping factors in this section.

Table 1 is derived, in part, from the description of integrated system validation in the human factors verification and validation chapter (Chapter 11) of NUREG-0711 (O'Hara et al. 2012). The table provides a high-level description of the different steps in the HRA simulator data collection process.

Table 1 Simulator data collection procedure.

Procedure Step (see Flowchart)		Description
Phase 1: Preparation for Data Collection		
A0	Prepare a formal agreement	A formal agreement must be established with the plant at which the study will take place. The agreement must ensure the anonymity of the plant or utility and that the results of evaluations will not affect individual operators or result in fines.
A1	Assemble the data collection team	All individuals who will be required to design and conduct simulator exercises must be identified at this stage. Ensure that a plant simulator training instructor is available to assist in development of the scenario. Where the exercise is not conducted by onsite personnel, arrangements must be made for plant visits by the data collection team in advance.
A2	Review Human Failure Events from Probabilistic Risk Assessments, Operating Experience Reports, and additional Plant Information	HFEs must be extracted from available information, such as the plant's PRA, event reports, and any other appropriate plant information.
A3	Scenario development	The scenarios selected to be used for the data collection must be representative of the conditions and parameters identified by the team. If possible, obtain input from the plant simulator training instructor.

Procedure Step (see Flowchart)		Description
A4	Review scenarios	The scenarios developed in A3 must be reviewed and finalized for logic and accuracy by the team including a plant simulator instructor. The plant-specific procedures that will be needed to perform each of the scenarios must be identified and made available in the simulated control room.
A5	Conduct walkthrough of scenarios on the simulator	Conduct a walkthrough of the scenario on the simulator to determine plant response times with and without operator intervention. Verify that the procedures that will be used during the study are available and appropriate. Confirm availability of simulator logs to be captured throughout the exercise. If possible, the walkthrough may include operators who were not involved in the scenario development and will not participate in the data collection to obtain independent input on response times and other demands.
A6	Determine plant parameters to be recorded	Select and verify the plant parameters that should be recorded by the simulator for evaluation of the crew and plant performance. Simulator logs must be captured throughout the exercise. This will consist of an electronic record of the plant events and the chronological status of all parameters. Verify that these records will be accurately captured during the exercise. Also verify that the format of the record will be readable and usable for data analysis.
A7	Prepare forms needed for data collection	The forms and other data capture techniques needed for data collection should be identified and developed as needed. Key measures should be defined and incorporated in the data collection forms. Standard, accepted measures of performance should be used, when available.
		Develop and prepare forms for the exercise to include, but not be limited to the following:
		• Consent form
		• Time log
		• Performance measurement forms and records
		• Post scenario, pre-debrief forms and questions
		• Post-scenario debriefing questions.
		More information on principles and methods of performance measurement may be found in NUREG-0711.

Procedure Step (see Flowchart)		Description
A8	Verify crew(s) availability	Ensure through the facility that the crews and crew members identified to assist in data collection will be available as scheduled. As available, conduct informed consent with the crews and crew members prior to actual data collection. Provide informed consent information to plant personnel who serve as the main interface with operating crew members to assist in explaining the informed consent.
A9	Conduct scenario dry run	A dry-run is a rehearsal of the actual data collection and should be performed for each of the simulator scenarios using plant training staff as crew members and evaluators to validate each of the scenarios. This includes the following:
		• Identifying simulator instructor roles
		• Re-verifying scenario event times
		• Verifying procedure usage and operator anticipated actions
		• Establish data collector and observer roles and responsibilities. Identify observer positions in the simulator in order to minimize interference with the crew members.
Phase 2: Data Collection		
B0	Conduct scenario exercises	Each exercise starts with an entrance meeting with the crew members where they are introduced to the data collectors, the purpose of the exercise is explained, how the exercise will be conducted, and the purpose of the post-exercise debriefings. Informed consent must be obtained prior to obtaining data from crews. Before the scenario begins, the plant simulator instructor will give the plant status briefing and turnover. The scenario will be initiated and the data collector(s) will record events and crew actions. The scenario will be run to the identified end point or until a point determined by plant training personnel in conjunction with the data collection team.
B1	Record real-time observation data	Use forms prepared in A7 to collect data from simulator indications and from crew responses to forms and questionnaires. Where possible, use audio/video recordings to capture the entire scenario. These recordings can be used during crew debriefings and will be reviewed during the data analysis phase. They can be used to confirm data recorded manually and to identify any behaviors that went unnoticed during the exercise.
B2	Collect performance driver information	Any immediate debriefing information should be collected following the conclusion of each scenario. This should be done when it is necessary to avoid discussions influencing individual crew members’

Procedure Step (see Flowchart)		Description
		recall or assessment of debriefing subject matter.
B3	Conduct scenario debriefing	A debriefing of the crew occurs following completion of the scenario in the training simulator. This debriefing follows a pre-planned discussion based on a prepared debriefing. The debriefing is conducted using a set of questions developed to guide discussions. Crew discussions are encouraged to facilitate identification of factors that contributed to crew performance and decision making as well as to understand the reasons for any deviations from expected performance, or errors.
Phase 3: Data Analysis		
C0	Analyze results of scenario exercises	Analysis of the results of crew performance includes a detailed review of the electronic record (simulator log). Data reflecting important plant parameters should be selected for all crews. These data will be portrayed on a graphical timeline that shows their evolution over the course of the scenario in response to the initiating event and crew actions. It may be to the analysts' benefit to conduct preliminary analyses onsite, when crew members may still be available for follow-up questions.
C1	Analyze crew performance results	The data analyzed in C0 are used to compile a synopsis of crew performance in each simulated scenario. This consists of a detailed chronological analysis of how each crew responded to the events simulated. The results are integrated with the graphic timeline of plant parameters and equipment actions and emphasizes annotation of the crews' performance. This may include key actions, detections, announcements and notifications, procedural transitions, and other observable behaviors related to management of the simulated event. (See examples in Appendix A).
C2	Performance Driver Analysis	In addition to the analysis of objective performance analyses of performance drivers may be conducted. Analyst(s) should attempt to integrate crew accounts of factors that influenced their performance with their demonstrated performance. In particular, analyses should emphasize the way(s) in which performance drivers contributed to the reliability of crew performance.
C3	Limit State Analyses	The limit state analysis should be conducted to identify the number of successful human actions for each critical action of interest – or HFE represented in the plant PRA. Each synopsis of crew performance in C1 should identify the success or failure of the crew to mitigate the event(s). Analyses may also be performed

Procedure Step (see Flowchart)		Description
		to assess the “margin” between demonstrated crew response and the PRA success criterion.
Phase 4: Reporting		
D0	Produce scenario analysis report	Summaries based upon the data analysis are compiled in a report. The report contains the information and analyses previously described and documents features of the scenarios simulated. The report should be written to highlight key features of the data collection, including: • Purpose and objectives • Scenarios and their relation to the plant PRA • Human actions key to the successful resolution of the event sequence • Data collection method, crew features, sample size • Overview of data collected • Analyses and results • Summary and, conclusions, as appropriate.

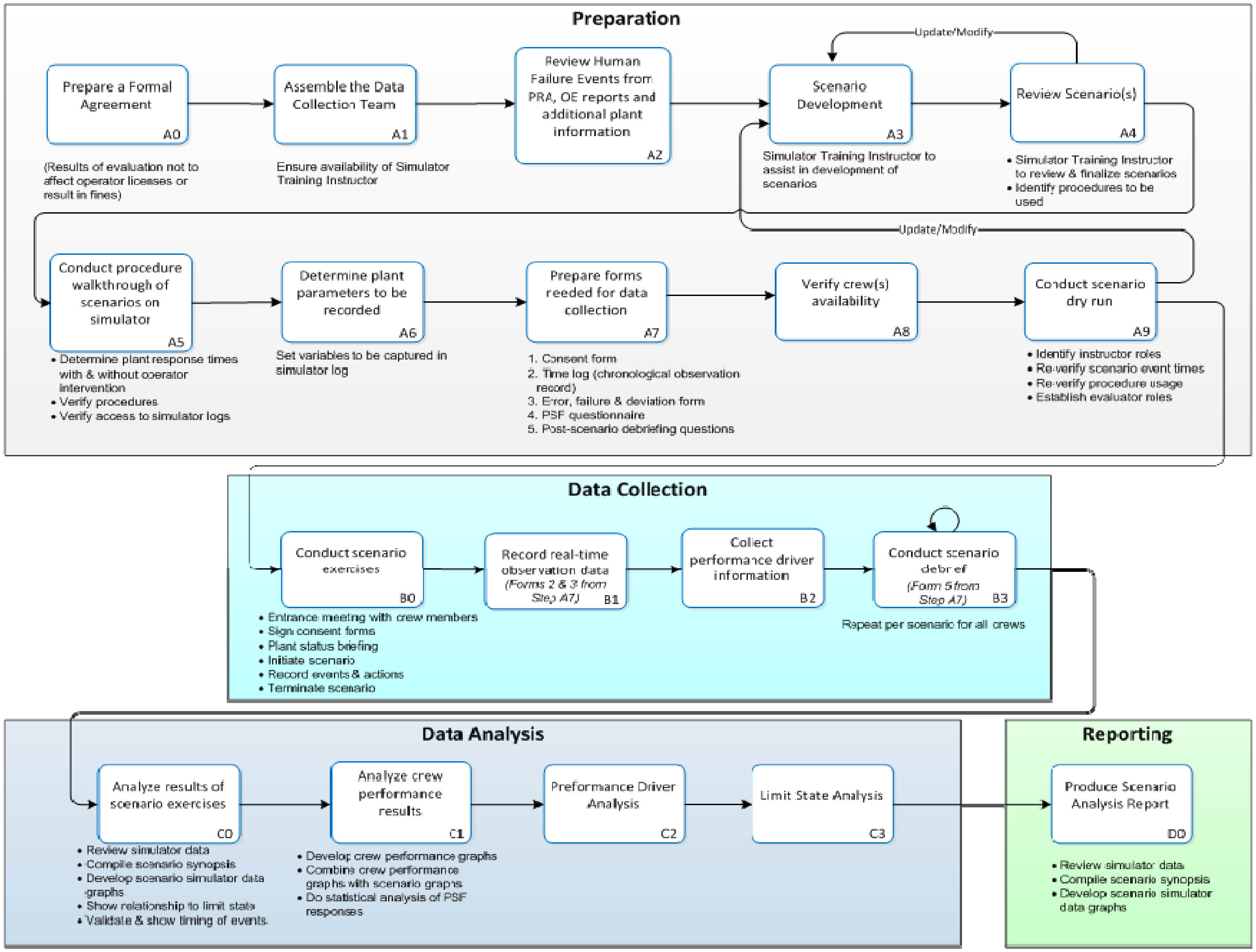

Figure 1 **Recommended human reliability analysis simulator data collection process**

4. PREPARATION FOR DATA COLLECTION

This section provides additional guidance on the steps in the Preparation Phase listed in items A0 through A9 in Table 1.

A0. Prepare a Formal Agreement

A formal agreement should be established between the data collection organization and the participating asset owner, e.g., nuclear power plant. The purpose of the agreement is to establish the roles and responsibilities and limitations of the data collection and analysis organization and the participating nuclear power plant. The elements in the agreement are to facilitate the free flow of information between the asset owner and its operating crews and the team conducting the data collection. The agreement should ensure that all parties accept the terms and conditions set forth and that data and other proprietary information that may be disclosed for purposes of the study are handled and treated in a manner that protects the participating organization and its staff.

A1. Assemble the Data Collection Team

The team of data collectors should be comprised of several members. One member should be experienced in the HRA process. Other members should be experienced in reactor plant operations and have knowledge of the plant design. This team, in conjunction with the plant simulator training staff, will develop the scenarios to be used for this data collection. A consultant to the team familiar with the plant-specific PRA can provide valuable assistance with scenario design and recommend practical advice to assist in evaluation of data collected. The PRA consultant also should serve as a liaison with the data collection team. Other team members may be needed, depending on the nature of questions that arise in the development of scenarios and data collection. Some or all members of this evaluation team will observe the crews during the simulator scenario exercises, collect data, and analyze the results.

A2. Review Human Failure Events from Probabilistic Risk Assessments, Operating Experience Reports, and Additional Plant Information

The design of the simulator scenario should be developed using the plant-specific PRA. The flow of the events and failures described in the scenario should be as realistic as possible. When developing the script of events in the simulator scenarios, it is recommended to use plant-specific events from past facility events or equipment failures to provide realism. When selecting events from past facility events, they should be related to the plant PRA or the objectives of scenario design (i.e., to manifest plant conditions or context). In addition, operating experience events from plants of similar design that are related to the scenario(s) being developed may prove useful in designing scenarios.

A3. Scenario Development

Scenario development should use plant-specific procedures to establish the expected scenario flow of events. They also serve as a common referent for obtaining input from experienced operations personnel, plant training personnel, and other personnel who may be consulted in development of scenarios. The pace, severity, and complexity of the scenario establish some of the unique demand features on which to focus. Systematic variation of these features to achieve a scenario design objective will allow evaluation of how different aspects (such as crew training, team work, and other capabilities) influence crew response. The scenario should be developed with the expected influence of performance drivers in mind (such as human machine interface, procedural guidance and training, expected workload, and potential deficits in situational awareness induced by the event, etc).

The recommended steps in scenario development are as follows:

1. **Define the purpose, scope, and content of the simulator exercise, as well as the conditions under which the exercise will be conducted**

   It is important that the scenario be focused on the behavior and actions of the control room crew during response to a PRA event.
   The information provided in the scenario description should contain, at a minimum:

   a. Initial plant conditions or the information that will be provided to the crew in a turnover briefing (e.g., reactor at 100% power, list of equipment out of service for testing, and maintenance, time in life, or upcoming evolutions).

   b. The list of planned malfunctions with the appropriate timing for initiation. When timing of malfunctions is crew response-dependent, this should be likewise noted (e.g., a rupture in the steam generator will occur in the steam generator to which the crew reestablishes feedwater, etc).

   c. The list of expected operator actions and procedures expected to be entered. Also, identify contingency actions and needed role play (i.e., by simulator training personnel) to ensure the scenario proceeds as intended.

   d. Identification of the criteria for the crew to successfully perform an action. For example: “To establish auxiliary feedwater (AFW) flow to the steam generators (S/Gs), the crew can dispatch a plant operator to check and close the open recirculation valve (feed S/G B) or cross-connect AFW flow from pump 12 to S/G A, C, or D.”

   e. A summary list of all the pertinent procedures that may be used by the operating crew. This list will be based on the expected flow of events, prior experience and training of plant staff, and reflect best estimates of likely crew response.

   Examples of simulator scenarios are shown in Appendix B.
   It is advisable to develop an extra scenario as a backup in the event that an unforeseen condition will prevent the use of one of the scenarios.

2. **Determine success and failure criteria**

   Using the plant-specific PRA, success and failure criteria can be developed for each planned scenario. Performance criteria for success or failure may be based on engineering reference material, technical reports, procedures, or other sources that establish the performance criteria on which the plant-specific PRA is based. The plant-specific PRAs will define limit states for the described events, thereby aiding in establishing the success and failure criteria. The concept of limit state needs to be operationally defined so that success and failure can be better understood in this context. Limit state from a RE and systems safety perspective denotes a region of performance that distinguishes between performance success and failure. A limit state may be explicit (e.g., establish feed and bleed (F&B) before reaching a certain plant-specific limit) or implicit (e.g., based on an engineering code analysis of thermal-hydraulic behavior).

An example is shown in Figure 2 below. This limit state is based on the required operator action in response to a total loss of feedwater (LOFW) in a pressurized water reactor. The figure is a plot of the time required to manually initiate reactor coolant system (RCS) feed and bleed (i.e., once through core cooling) in response to a total loss of feedwater. Several points on the graph are explicit, based on a MELCOR analysis of fuel behavior for the plant. Other points along the graph are implicit, having been extrapolated from the same MELCOR analysis and estimated based on engineering judgment.

Crew performance below the line denotes success (i.e., initiating RCS feed and bleed in time to prevent fuel damage). Crew performance above the line indicates failure – exceeding the limit state condition for this operator action. This particular graph illustrates an important point regarding objective performance criteria: the criteria used for HRA must be adapted for the particular PRA-based scenario. These performance criteria ought to conform to the notion of the PRA, including recovery criteria and conditions that delineate between successful human performance and an HFE. An analysis of crew performance data should permit a determination to be made regarding success of the crew in terms of the requirements of the PRA. This minimizes the potential for subjectivity in evaluating crew performance.

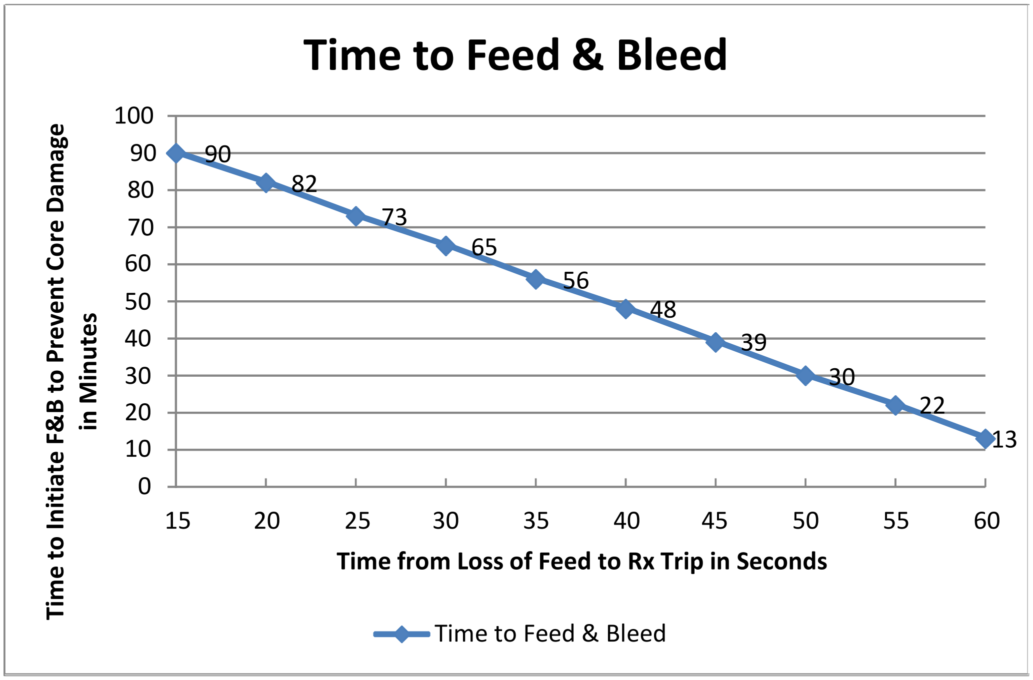

Figure 2 **Performance criteria and limit state for feed and bleed action**

Performance criteria in relation to the plant-specific limit state for the PRA event sequence must be developed for all elements of the scenario that are to be evaluated for their relevance to HRA [e.g., the criteria for re-establishing feedwater to the steam generator (S/G)]. These criteria may be obtained from operating procedure steps or other sources and defined for the plant conditions as they manifest in the scenario. Examples of the success and failure criteria for the scenarios developed in the reference study are found in Appendix C.

3. Define human performance measures

Data collection should sample from the conditions predicted in the PRA to drive performance reliability. Data collection should include human failure events of interest. The data collected should describe objective performance. This includes the physical behavior of the plant and systems, as well as the activities of the crew in the simulated performance context. This will provide a description of what happened and when it occurred.

Performance criteria also must be available or determined for the conditions analyzed. These should be based on the same criteria employed in the PRA, as applied to the particular form of the event sequence run in the simulator. These performance criteria ought to conform to the notion of the limit state as discussed earlier. This means that, in terms of the requirements of the PRA or other relevant portions of the plant safety analysis or design basis of individual systems, a comparison of crew performance data with the performance criteria must allow the analyst to determine whether an individual crew's performance was successful or not.

Information about the crew and its actions should include:

a. Numbers of control room crew members, their qualifications, and when present

b. Control actions performed

c. Alarms acknowledged

d. Recognition of key events and plant conditions and procedures entered and in effect (i.e., for conditions in which multiple procedures may be opened).

The following categories of data are typically recorded during observation of control room crew performance and should be obtained to support subsequent analyses:

a. System performance parameters associated with the scenario event

b. Time available for completing a given task

c. Actual times that crew members took to complete a given task

d. When the crew recognizes the event or announces the parameter change that identifies the event

e. When orders are given and implemented

f. Content of crew briefings

g. Times when procedures are entered and exited

h. When alarms are acknowledged or reset and whether the alarm was identified

To determine the above times, use the simulation run time and record when events occur during the simulation.

These records can be obtained by the evaluation team members who are recording the times, either manually or with recording devices. Where possible, all records should be verified by the simulator parameter recordings.

A4. Review Scenarios

The scenarios should be reviewed for logic and accuracy by the team. Ideally team members who did not develop a particular scenario should perform the review to maintain a level of independence. However a training instructor or another plant staff member familiar with plant operations should be one of the reviewers. As part of the review, the plant operating procedures that will need to be accessed should be used to review the scenario and should be made available for the exercise.

A5. Conduct Walkthrough of Scenarios on the Simulator

To verify that the scenario can be performed as expected, that needed observations can be performed and data can be obtained, and that procedural activities are likely to occur as expected, conduct a walkthrough of the scenario on the simulator to determine plant response times with and without operator intervention. Verify that the procedures that will be used during the study are available and appropriate. Confirm availability of simulator logs to be captured throughout the exercise. If possible, the walkthrough may include operators who were not involved in scenario development and will not participate in the data collection to obtain independent input on response times and other demands.

A6. Determine Plant Parameters to be Recorded

The plant parameters that need to be recorded are those that will be affected by the events of the scenario and that reflect crew management of the plant. It is especially important to collect control signal inputs and plant parameters that reflect crew performance of critical actions. Ideally, this includes a list of predetermined plant parameters that are recorded by the simulator computer.

The specific simulated events, plant systems affected, and crew control actions anticipated and required also will determine the plant parameters that need to be collected. This determination needs to be made for all scenarios that will be performed, alleviating the need for multiple lists and possible omissions of monitored parameters in individual scenarios. Along with recording plant parameters, the simulator computer will produce an event log that consists of the times annunciators alarm and clear, valve and breaker switch positions, and when any control signals are adjusted (i.e., flow controls or pressure controls).

A7. Prepare forms needed for data collection

The data collection team should prepare a set of forms and documents based on the methods of data collection selected prior to collecting data. The purpose of these forms and protocols is to ensure uniformity and consistency in data collection, completeness in the record of information that is generated, and for archival purposes. Five types of forms are described in more detail below: informed consent form, forms for observations, forms for recording deviations and errors, PSF questionnaire, and debriefing form.

a. Informed consent form

Informed consent needs to be obtained to ensure all the participants in data collection activities are well informed about the study in which they will participate and that they are informed about the rights and responsibilities of each party during the study.

Different countries have different requirements for informed consent and information disclosure. Data collectors should check local requirements.

b. Forms for observations of operator and crew actions

For purposes of data collection, forms should be provided to observers to use in documenting observations of crew performance. The types of observations may vary, depending on the scenario and the purposes of data collection. However, it is typical that some form of event log that is time-based is used to record observations, including: (1) key actions performed; (2) alarms and notifications; (3) safety and protection system actuations; (4) crew communications, briefings, internal and external announcements; and (5) decisions and announcements (e.g., use of procedures, diagnosis of an event, etc.). Some of these can be corroborated through event logs from the simulator-based computer and data logging system. The form should contain the crew identifier, the scenario identifier, the date, and observer identifier.

c. Forms for deviations, errors, failures and successes

A form for recording deviations, errors, failures and successes also should be developed. The definitions for each are as follows:

Deviation – a departure from the expected course of action (as proceduralized, trained or directed).

Error – any slip, lapse, or mistake that does not meet the required standard of performance for a task or activity (e.g., failing to transition to the appropriate procedure or overlooking an indicator as directed by procedure).

Failure – failure to meet the performance standard for an action or sequence of actions that result in a functional failure as modeled in the PRA.

Success – performance of a required action or set of actions in a manner conforming to the performance standard established by the plant-specific PRA.

An example of the information that should be captured by this form is as follows:

- Observation (i.e., crew failed to trip all reactor coolant pumps (RCPs) prior to initiation of F&B)

- Classification of the event as a deviation, error, or failure based on the definitions

- Description of crew actions prior to and following the identified deviation, error, or failure

- Recovery actions if any (i.e., the crew tripped the RCPs when the failure to do so per procedural guidance was identified by the unit supervisor)

- Consequences of the identified departure, error, or failure if any.

The documentation of deviations, errors, and failures ought to be sufficiently descriptive so that a knowledgeable reader is able to understand what occurred (or failed to occur) and how it failed to conform to PRA-based requirements or other performance expectations. The taxonomy used for describing noteworthy behavior by the crew ought to be capable of providing useful information about decisions and actions of the crew that relate to the data collection objective(s) and support the development of insights about human reliability.

d. Performance drivers

A form may be developed that identifies the performance drivers that the data collection team wishes to observe or collect data about. A number of different approaches may and have been used to collect this type of data in human performance studies. In cases where performance drivers are operationally defined and manipulated in a controlled manner (i.e. according to a pre-defined plan), then this information should be provided. It is more often the case that performance drivers vary dynamically, especially for scenarios that are delivered as a part of training. This may necessitate observations by subject matter experts that are performed qualitatively. Performance drivers for which metrics exist (such as workload or situation awareness) or for which physiological measures exist, should be used where appropriate to provide an objective measure of the performance driver. An example of such an evaluation form is provided in Appendix D.

e. Debriefing form

A debriefing questionnaire also needs to be developed, covering the different elements of plant operation. **Table 2** describes suggested subject areas with possible questions to be discussed with crewmembers. See the debriefing form in Appendix F for details of potential questions and content.

A8. Verify Crews’ Availability

Working with the facility, develop a schedule that will allow the operating crews to be available for performing the selected scenarios. Ensure that the simulator and the staff are prepared and the scenarios to be run are operational. Ensure that the operating crews are aware of the times that they need to be available for the data collection in advance and receive reminders. Check with the facility to ensure that participation in the data collection does not conflict with working hour limitations.

A9. Conduct Scenario Dry Run

Conduct a rehearsal of the actual data collection for each of the simulator scenarios using plant training staff or other plant staff knowledgeable of plant operations as crew members and evaluators to validate each of the scenarios. This includes the following:

- Identifying simulator instructor roles
- Re-verifying scenario event times
- Re-verifying procedure usage and operator anticipated actions
- Establishing data collector roles and responsibilities and identifying data collector positions in the simulator control room to minimize interference with the crew members

5. DATA COLLECTION

This section provides additional guidance on the preparation steps listed in Items B0 through B4 in Table 1.

B0. Conduct scenario exercises

Prior to the start of the simulator scenario run, the plant operating crew should be introduced to the data collection team who will explain the purpose of the exercise. If this distinction is not made, the mindset of the crew may affect the information that the data collection team will obtain from the crew.

The facility training staff or simulator instructor will perform the crew briefing and provide the crew with all the necessary operational information needed to take the watch. The conduct of the simulator scenario will be controlled by the facility training staff representative(s). During this introductory meeting, any necessary documentation should be completed, such as consent forms can be signed and/or information needed about the crew makeup can be obtained.

The scenario will be initiated and the data collector(s) will record events and actions. The scenario must be allowed to run to the identified end point or until the lead data collector terminates the scenario.

B1. Record Real Time Observation Data

Data collection can be accomplished by several methods. Data may be collected electronically. The simulator computer can collect plant parameters and record their changes over time. The plant parameters that need to be recorded are those that will be affected by the events of the scenario and that reflect crew management of the plant. It is especially important to collect control signal inputs and plant parameters that reflect crew performance of critical actions. Besides the simulator computer recordings, audio and video records also may be available to record operator conversations and actions.

Another set of data that should be collected is direct observation by the data collection team. Direct observations can be accomplished by observers recording events or actions that may or may not be recorded by the simulator computer, such as orders given to operators (e.g., trip reactor coolant pumps), when plant procedures are entered and exited, or crew briefings. The direct observation of crews allows the data collection team to obtain an insight of the crew's interactions, communications, and witness the crew's teamwork. Ideally, three observers would be present: one to observe primary plant operations, one to observe balance of plant operations, and one to monitor the crew supervisors. The shift technical advisor can be observed by any one of the three observers depending on her/his work location.

While observing the crew during the scenario run, the observers should refrain from interactions with any of the crew members or from being an obstruction to crew movement. The observers should select positions in the control room that are unobtrusive but from where crew member actions can be readily observed. A simple form to record the time of the action and a description of the action can be used to record crew responses during the scenario run. An example of a completed log sheet is located in Appendix E.

a. Data structure

Data should be structured in a way that will facilitate completion of predetermined analyses or statistics (i.e., descriptive statistics, correlations, and variance). To begin with, data collectors should recognize the inherent structure of the data imposed by the scope of the data collection in terms of the following typical items:

- Number of scenarios
- Number of tasks per scenario
- Number of crews
- Number of participants per crew
- Crew characteristics
- Specific job positions within the crew (e.g., senior reactor operator, reactor operator, or shift supervisor)
- Scheduling information (times and dates)
- Total run time planned for scenarios
- Success and failure criteria.

Data collection could be designed to be multi-stage or hierarchical and, as a result, data may be aggregated, by scenario, by crew, by crew member, by task, and so on. This is important because the data collection format will affect the ease of analysis for various forms of univariate or multivariate methods. It is recommended that a suitable data management tool be used to collect and manage the data. The data management tool also might provide forms, queries, and reports.

b. Observers and their Tasks

Observers should be limited to those directly involved in the exercise; additional personnel in the simulated control room should be minimized to avoid interference with, obstruction and distraction of the crew. Based on data collection needs, the number of data collectors should be identified. The following disciplines would typically be responsible for the data collection task:

- Qualified simulator training instructor
- Human reliability analyst
- Operations subject matter expert(s)

The tasks of the observers will be influenced to some extent by the methods and tools used to collect data. One primary issue in development of HRA data is that there are different ways to classify performance and differences in the terms that analysts may use. By relying on definitions of human performance measures and using data collection methods that are standardized, variability can be reduced. There is a need to develop tools suitable for the specific adaptation of these methods. This would include recording of the scenario timeline on pre-formatted or free-formatted forms. Also, some observations can be recorded using computer-based tools, while actions of specific members of the crew (e.g., the shift supervisor and shift technical advisor) are recorded by hand. Video cameras and other non-intrusive recording devices also may be used for this purpose.

During information collection, it is necessary to avoid inappropriate interactions among the members of the observation team (e.g., laughing, joking, talking, or any behavior that could influence the validity and independence of data collected by individual observers).

All attempts should be made to avoid any interactions that may significantly influence the performance of the control room crew. Such interactions can influence crew behavior and the reliability of the observation data. All direct interaction with participating crew members should be prevented without exception. Any other action by observers that may influence crew performance and behavior should be avoided. Even eye contact should be avoided. The only acceptable interaction between observers and crew should be intentional communication by a representative of the data collection team with one or more participants at the start of the data collection about specific data collection conditions. Also it will be necessary to interact with the crew members when implementing some of the standardized tools for assessing workload or situation awareness. If possible, observers should observe the crew from a separate control station or observer area without being in the training simulator.

B2 Collect Performance Driver Information

Performance driver information may be collected during the scenario by trained observers and through debriefings and other data collection methods following the simulator scenario. One advantage of obtaining performance driver information directly from individual crew members prior to debriefing is that individual crew members' subjective assessments are less likely to be affected by other crew member comments and information that they learn during the debriefing. Alternatively, a potential benefit to collecting performance driver information during crew debriefing is that the debriefing can refresh their memories of the events that occurred. The questions for this interview should be developed prior to the simulator runs. An example of one type of debriefing is found in Appendix F. The particular debriefing supported by the form in Appendix F is for individual crew member ratings of performance drivers (termed performance shaping factors in the example study) following completion of a scenario and prior to crew debriefing.

Structured discussions are very useful because they provide evidence about how critical mitigation actions are affected by performance drivers that manifest under certain plant conditions. Although feedback from crew members and trainers regarding performance drivers might be subjective, it represents their personal experience and is relevant to drawing conclusions about crew performance reliability.

a. Identification of Performance Drivers

For the purpose of simulator data collections, performance drivers are considered to be factors that, when present at the time a task is performed, change the likelihood of successfully performing a task to a required performance standard. Based on this definition, performance drivers can enhance the likelihood of success or they may hinder it. The performance drivers considered in this way deal with “internal” and “external” influences.

External influences from the immediate task environment include factors such as presence of or quality of operating and emergency procedures, hours worked, breaks between work periods, and the quality and configuration of the work environment (e.g., control room layout, quality of the human-system interaction, or environmental conditions such as heat, noise, vibration, etc).

Internal influences deal primarily with personal attributes (such as skill, ability, attitude, knowledge and training) and perceptual and cognitive factors (such as memory; visual, auditory and kinesthetic perception; emotional state; workload; and situation awareness). Stress has special importance in HRA; it is described in terms of the physiological and psychological tension caused by a mismatch between internal and external influences. For example, if the perceptual requirements of the task environment become too demanding (e.g., due to visual complexity of the human-system interaction or lack of information), task loading will increase and performance will suffer.

Conversely, if task loading is very low resulting in boredom or fatigue, performance also may be degraded because physiological and psychological stress is too low to keep the operator alert (Blackman et al. 2008; Yerks and Dodson 1908).

b. Performance Driver Data

If quantitative data are generated by performance driver assessments (e.g., subjective ratings, evaluations by subject matter experts, etc.), it can be captured into a spreadsheet or a database.

The following items should be captured from the performance driver assessments:

- Identifier for the crew that participated in the study.
- The name or abbreviation of the scenario(s) that was included in the exercise.
- The title (or abbreviation) of the crew member(s) who participated in the exercise.
- The number of tasks that formed part of the scenario (as noted above, scenarios may not have the same number of tasks).
- An example of the type of form used to collect performance driver data in this study is shown in Appendix D.

B3. Conduct Scenario Debriefing

The final set of data to be collected is crew and other plant expert debriefings immediately following the simulator run. Debriefing sessions at the end of each scenario provide useful information about typical crew performance, their perceptions, and tendencies in managing different transients.

Directly following each simulator scenario run, each crew should be debriefed and asked the same predetermined questions regarding their performance. It is advisable to divide the crew into two groups: supervisors and operators. The shift technical advisor (STA), if participating in the exercise can be in either group. Crew discussions are encouraged to facilitate identification of errors or areas of confusion.

Table 2 describes typical debriefing questions used for this portion of the crew evaluation.

Table 2 Typical debriefing questions

Type of Debriefing Question	Examples
Diagnosis of Events and Conditions Based on Signals or Readings	1. What were the events that occurred during this scenario? 2. What information and materials did you use to first recognize and then diagnose the event and conditions? If you did not need materials to recognize the event, how did you know what it was? 3. What did you use to first recognize and then diagnose the event and conditions? 4. What information was communicated with the crew and how was it used? 5. What information did you then communicate to the crew and how was it used? (Was it used properly in your judgment?)
Understanding of Plant and System Responses	1. Were there instances where your indications either helped or hindered you interpretations of plant status and conditions? (Identify the indications and how did they help or hinder?)
Adherence to and Use of Procedures	1. Were there areas in the procedures that were ambiguous or difficult to apply for the conditions you encountered during the event? (Identify the procedure and the area, e.g., Step #.) Were there situations you found challenging to implement procedures as written? (Identify the procedure and the area, e.g., Step #.) 2. In your judgment, were there situations that the correct procedure was not being utilized? (Identify the procedure.)
Control Board Operations	1. Did you find any control actions challenging to execute in this event? (Which ones?) 2. What in your opinion makes these control actions challenging or difficult (such as controls/indications not fine enough?) 3. Did you make any mistakes or are there activities where mistakes are more likely to occur?
Crew Operations	1. Were there any time(s) that you were confused about the decisions or direction being taken during the event? What confused you? 2. How did you contribute to the decisions and directions of the crew's actions?

	3. Were you aware of the procedures and the course of action or goals of the supervisor? (How were you made aware of these?) 4. How were crew resources managed and directed during the event? In your judgment, were crew resources effectively managed or were there any wasted operations?

6. DATA ANALYSIS

This section provides additional guidance on the preparation steps listed in Items C0 through C1 in Table 1. It addresses data collected in the reference study to illustrate and provide examples of applying the tenets and method for collecting human performance data.

C0 Analyze Results of Scenario Exercises

As soon as possible following completion of the scenario run and crew interviews and debriefings, each data collector should develop a synopsis for each scenario run. The synopsis should give a brief description of the crew's performance during the scenario and whether or not the crew was successful in meeting the established mitigation criteria and performance standards for critical actions. The data collector must determine or make a judgment regarding the success or failure by the crew based on the criteria established by the data collection team, not necessarily to training criteria. This is because all crews should have been trained to mitigate all the events. The success criteria should be obtained from the plant's PRA and operating procedures. The purpose of the synopsis is to provide a condensed, comprehensive view of what the data collector observed and include reminders to help evaluate a specific crew's performance.

The data collector gets the time information from the simulator run clock. The success/failure criterion is established before the simulator scenario is run. As stated earlier, the synopsis is just a brief description of what occurred.

Below are two examples of synopses developed for two simulator scenarios:

Example 1 – Simulator Scenario Synopsis

The crew received the loss of main feedwater (MFW) indication at 2:14 into the scenario. The crew tripped the Rx at 2:51 minutes into the scenario or approximately 37 seconds after the loss of feed, which then gave the crew approximately 55 minutes to initiate F&B before core damage. RCS F&B was established 12 minutes and 40 seconds after the loss of feed, thereby satisfying the criterion for this event. The unit supervisor (US) skipped the step to trip the RCP and the shift technical advisor (STA) brought this omission to the attention of the crew and the RCPs were tripped 30 seconds after initiating F&B. Auxiliary feedwater (AFW was re-established to the 'B' S/G at approximately 20 minutes after the trip to the MFW Turbines. At 37:37 minutes into the scenario, 'B' S/G level was at 78% and increasing with feed secured. Adverse containment condition declared at 38:48 minutes and feed was established to all S/Gs at 39:27 minutes. At 42:00 minutes steam generator tube rupture (SGTR) in the 'B' S/G was declared. At 1 hr and 20:20 minutes into the scenario natural circulation had been established with the RCS F&B. The procedure to isolate the S/G with the tube rupture was never entered because of higher priority procedures being executed. The faulted S/G was effectively isolated without the S/G PORV set point being elevated because RCS pressure was maintained less than the PORV setting. This prevented any uncontrolled release of Primary coolant to the atmosphere; therefore, satisfying the criteria for SGTR. All success criteria for this scenario were met by the crew.

Example 2 – Simulator Scenario Synopsis

The loss of MFW occurred at 2:04 minutes and the manual Rx trip was initiated at 2:36 minutes, giving the crew approximately 60 minutes to initiate RCS F&B. At 12:26 minutes, it was reported that all S/G WR indications were <50% (loss of heat sink indication). At 15:23 minutes loss of heat sink red path was declared and FRH1 procedure was entered. RCPs were stopped at 16:50 minutes, safety injection (SI) initiated at 17:00 minutes and the pressurizer (PZR) power-operated relief valves (PORVs) were opened at 18:21 minutes, thereby initiating RCS F&B at 18:21 minutes meeting the F&B criterion. Re-established feed to the 'B' S/G at 20:20 minutes (initiating SGTR in the "B" S/G), and at 26:15 minutes 'B' S/G level were report to be >14% narrow ridge (NR). The crew then commenced the process to secure RCS F&B by establishing a maximum charging pump flow of 200 gallon per minute (gpm) at 30:26 minutes with one charging pump and securing 'C' High Head safety injection Pump (HHP). The crew then started the second charging pump at 34:35 minutes and stopped 'B' HHP at 35:50 minutes. Flow to the 'B' S/G was throttled at 34:50 minutes and secured at 37:11 minutes, with feedwater flow to all four S/Gs being established at 36:45 minutes. The crew then closed the 'B' PZR PORV at 39:00 minutes and the 'A' PZR PORV at 41:10 minutes, stopping RCS F&B. Emergency Operating Procedure: Functional Recovery "H1" Loss of Heat Sink (FRH1) was properly executed until the last high head pump was to be secured, at which time the step was misinterpreted and the RCS PORVs were closed without securing the third HHP. The shift technical advisor (STA) assumed that the step, which stated if any active loop temperature was >405 F, the loop to determine the temperature was the D loop; however, the only active loop at the time was the B loop. The crew may have assumed that an intact S/G on the loop was the same as an active loop. The S/G must have a water level of >14% NR and NC has been established. ('D' loop did not meet this criterion.) It was reported at 41:50 minutes that the 'B' S/G level was still increasing and at 46:54 minutes the 'B' S/G level was >100% NR and at 82.4% WR. At 48:49 minutes the 'B' S/G steam line radiation levels were reported as high and increasing. At 49:19 minutes the Emergency Procedure E30 for isolations of a faulted S/G was entered. At 55:57 minutes the 'B' S/G is isolated. However, at 1 hr and 00:56 minutes the 'B' S/G PORV opens, releasing primary coolant to the atmosphere, the RCS and 'B' S/G are now in a solid pressure condition with the RCS and 'B' S/G pressures cycling. RCS pressure is still at 1,331 psig at 1 hr and 5:38 minutes. A 100 F/hr cool down is started at 1 hr and 16:43 minutes. At 1 hr and 18:57 minutes the 'B' S/G PORV is stuck open and the running HHP has flow of approximately 900 gpm. At 1 hr 25:42 minutes, the 'B' S/G PORV is manually isolated. This crew was successful in initiating the RCS F&B in the time allotted to prevent core damage and was successful in re-establishing feedwater flow to the S/Gs. This crew was not successful in meeting the SGTR criteria because the crew was not able to maintain the RCS pressure less than the S/G PORV setting, thereby allowing primary coolant to escape to the atmosphere.

While developing the synopsis a list of deviations, errors, and failures should be generated. Below are three examples of how to document deviations, errors, and failures.

<table>
<tr><td colspan="5">Observation: Water was allowed to reach the steam lines on the faulted S/G</td></tr>
<tr><td>Deviation</td><td>Error</td><td>Failure</td><td rowspan="2"></td><td rowspan="4">Description: Because of the delay in securing the F&B and subcooling the ‘B’ S/G, the water level reached the steam lines.</td></tr>
<tr><td>X</td><td></td><td></td></tr>
<tr><td colspan="4">Recovery: Following stopping of the F&B, the crew maintained the RCS pressure less than the S/G PORV set point, thereby preventing a release of primary coolant to the atmosphere.</td></tr>
<tr><td colspan="4">Consequence: The water in the steam lines could have damaged the piping and main steam isolation valve (MSIV); if the S/G had gone solid, the PORV set point could have been reached and allowed primary coolant to be released to the atmosphere.</td></tr>
</table>

<table>
<tr><td colspan="5">Observation: Crew failed to stop all 4 RCP prior to initiating F&B.</td></tr>
<tr><td>Deviation</td><td>Error</td><td>Failure</td><td rowspan="2"></td><td rowspan="4">Description: Crew initiated SI and opened PZR PORVs, initiating F&B with the RCPs running. The STA questioned the RCPs running and then the US ordered the RCP tripped. The reactor operator (RO) tripped all 4 RCPs approximately 1 minute after F&B was initiated.</td></tr>
<tr><td></td><td>X</td><td></td></tr>
<tr><td colspan="4">Recovery: Crew tripped all 4 RCPs and continued on with the procedure.</td></tr>
<tr><td colspan="4">Consequence: Missed a procedure step. The RCP running without sufficient subcooling will result in cavitation in the RCP impellers, causing erosion of the pumps and possible damage.</td></tr>
</table>

<table>
<tr><td colspan="5">Observation: Crew did not identify the loss of component cooling water (CCW) pump and charging pumps not running (loss of seal injection/cooling and loss of RCP cooling).</td></tr>
<tr><td>Deviation</td><td>Error</td><td>Failure</td><td rowspan="2"></td><td rowspan="4">Description: The crew did not recognize the loss of RCP seal injection and cooling when the Rx was tripped following the distribution panel fault and the C emergency diesel generator (EDG) did not supply the ‘C’ engineering safety feature (ESF) bus. The reactor operator (RO) reported no charging pumps running and the RCPs were not tripped for another 1:40 minutes. The crew is required by procedure to trip the RCPs within 1 minute following loss of seal cooling/flow and re-establish injection before seal temperatures reach 230°F.</td></tr>
<tr><td></td><td></td><td>X</td></tr>
<tr><td colspan="4">Recovery: No recovery was possible. The crew needed to recognize the loss and initiate seal injection prior to reaching 230°F seal temperature; this did not occur.</td></tr>
<tr><td colspan="4">Consequence: By not identifying and reporting that no CCW pumps or charging pumps were running, the crew was not aware of the loss of cooling to the RCP seal. This failure will result in a possible loss-of-coolant accident (LOCA) if the seals fail. In this scenario the seals were failed when RCP seal temperature exceeded their temperature limit.</td></tr>
</table>

C1 Analyze Crew Performance Results

To understand how the crew managed the simulated event, it is important to plot the pertinent plant parameters that were directly affected by the simulated accident (e.g., core exit temperature for a total LOFW accident, S/G levels and pressures with reactor coolant pressure for a SGTR, etc.). To further understand how the simulated accident was managed, insert time lines for key operator actions (i.e., when reactor coolant pumps were tripped, safety injection pumps were started, etc). To aid the HRA team in their evaluations of crew reliability, plant parameters may be plotted in order to show how close they came to event limits (i.e., S/G and RCS pressures as they relate to the S/G power-operated relief set point for a SGTR).

For purposes of supporting data exchange, standardized templates that graphically depict the key events, plant response, and crew actions should be developed for different classes of design basis events. The graphical format in Figure 3 provides an example of a standard template that could be used to depict the results of data collection. The graph contains both parameters and a key to their interpretation for ease of use. It includes information related to event initiation and plant response, plant parameters that show operator action (e.g., core power showing when the crew tripped the reactor, when F&B was initiated, etc.), and the available margins for crew response. This latter category of information is vital to determining whether the crew's performance met the success criteria established for the scenario. It also shows the margin between crew response (i.e., when F&B initiated, RCS pressure, and temperature) and the limit state. In addition, these data are used to show the relationship between the available margin and the margin used by the crew, and provides a view of the distance of the crew's response from the limit state as required to prevent more significant damage.

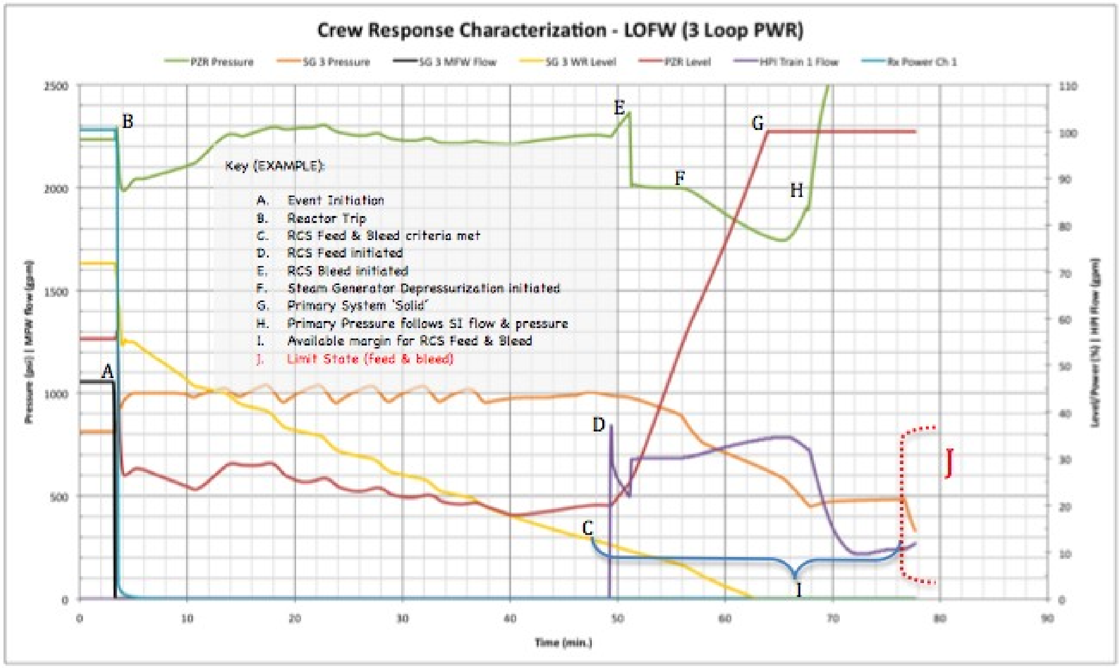

Figure 3 **Example summary of crew response characterization plot**

Refer to Appendix A for examples of other graphical data analyses developed from simulator scenario runs.

C2 Performance Driver Analysis

Unlike crew performance data collected during the scenario run, subjective performance driver data are typically collected after completion of a scenario run.

After the data have been collected, the analysis of responses concerning performance drivers should focus on answering the following questions.

At the crew level:

- Is there evidence of the influence of performance drivers?
- Are the influences of performance drivers observed on all members of a crew or only individual members?
- Are the effects of performance drivers positive or negative in relation to the critical tasks and decisions necessary for successful performance?
- Are the influences of the performance drivers manifest in the observed performance of the crew?

At the scenario level:

- Do performance drivers consistently influence performance of crews?
- Is there evidence of systematic variability that can be related to the influence of the performance drivers?
- Are there differences in outcomes (i.e., success or failure) as an apparent result of some performance drivers?

Figure 4 provides an example of data collected related to performance drivers. In the case of these data, the individual performance drivers were referred to in the original study as performance shaping factors or PSFs, as shown in the title of the graph. An approach to obtain feedback from crew members following each scenario was employed. This entailed crew members rating eight PSFs in terms of their perceived influence on their performance. This was done by anchoring a rating scale with values ranging from 1 to 5 with terms indicating that the PSF hindered their performance or helped them, respectively. The six lines on the graph correspond to six critical mitigation actions (two in each of three separate scenarios). The graphic trends of ratings were used to determine whether crewmembers perceived certain types of performance drivers affecting their performance on important crew actions. These ratings were also used to help focus discussions during crew debriefings and to identify potential issues for exploration during data analysis.

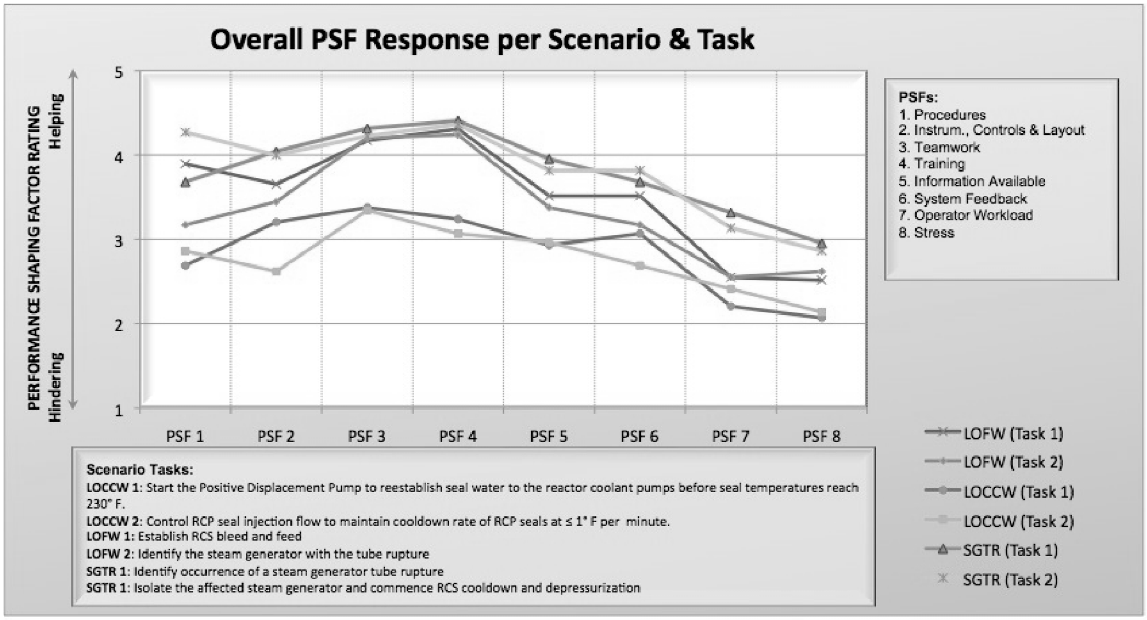

Figure 4 **Example of numerical ratings summary of performance drivers**

C3 Limit State Analyses

Figure 5 shows the performance of crews in reference to a limit state for a prescribed operator action. In the case of this particular action, available time corresponded directly to the limiting plant thermal-hydraulic behavior and was used to define the human performance standard for the PRA event sequence. If a crew used 100% or more of the available time to complete the critical mitigation actions, then crew performance would be considered failure, in terms of the plant-specific PRA. If less time was used than was available, the crew was successful in mitigating the event.

Two important features about this method for measuring the quality of crew response are: 1) the distribution of crew performance on the criteria related to the limit state, and 2) the variability in crew response relative to the limit state. The performance criteria for human actions are specific to the event sequence and scenario. Even though the same human actions are required in different event sequences (e.g., ‘F&B’ core cooling), the specific criterion that define success for the human action is scenario specific. In the case of the F&B actions, the initiating event, initial plant conditions, specific vendor and plant design, core power history, and other factors will determine the response requirements for completing F&B actions in every specific scenario of event sequences containing those human actions. Identifying these requirements in each scenario context is the first step of establishing the measure of success and failure for the critical human action. It establishes the threshold for operator response and specific criteria that must be met (e.g., 4 out of 4 safety injection pumps operating at maximum flow within X minutes of reactor trip). Using observed crew performance during the simulator runs of the scenario and the defined threshold for performance, the data show the response of individual crews against the maximum available response range. This method of measurement produces a distribution of crew performance relative to the limit state that distinguishes between successful and unsuccessful performance.

The distribution of crew response on the critical action reveals the margin between crew response and the limit state. The interpretation of this may be relatively straightforward: the amount of available margin is an indicator of how near the crew was to failing to meet the performance criteria for the scenario.

The second feature that is important from these data is the variability in crew response. This variability reflects inter-crew differences in task execution, procedure use, and decision-making, all of which are inter-related. It also reflects uncertainty in the results of crew performance that may have implications for the reliability and consistency in crew response to the initiating event(s).

An example of a limit state analysis follows. For a Total Loss of Feedwater (LOFW) simulated scenario, crews responded to the loss of heat sink conditions as prescribed by the emergency operating procedures (EOPs). In all cases, crews successfully initiated feed and bleed according to the plant-specific performance standards for the action and the event sequence as carried out in their full scope training simulator.

Using the plant-specific PRA and thermal-hydraulic analyses performed for this simulated event, a maximum allowable time to initiate core cooling using “feed and bleed” techniques was calculated for each crew. The analysis of crew performance in **Figure 5** below plots the proportion of available time used by each crew to accomplish the actions needed to establish feed and bleed core cooling based upon this limit state analysis.

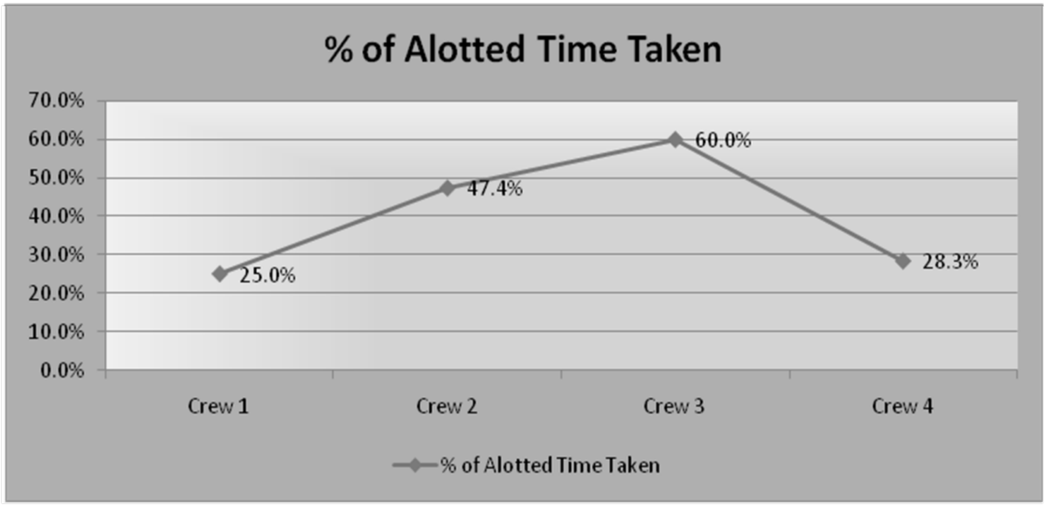

Figure 5 **Distribution of percentage of available time used by crews to initiate feed and bleed**

In addition to showing the number of successful human actions by crews, the results also demonstrate some variability with regard to individual crew performance of the critical action. Three of the crews used less than 50 percent of the available time to initiate RCS F&B while one crew used 60 percent of the available time. This variability may have some meaning in terms of a distribution of success and spare capacity for this action.

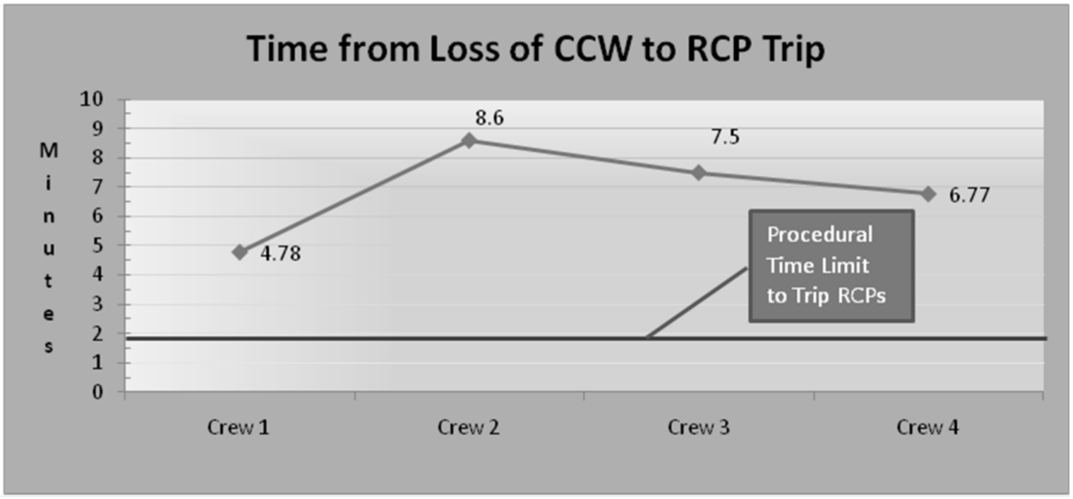

Figure 6 **Crew response times from loss of Component Cooling Water to tripping the Reactor Coolant Pumps**

Figure 6 shows an example of crew actions in which failure to perform an action to the prescribed standard occurred. In this case, a procedural time limit is prescribed to trip the reactor coolant pumps in response to a loss of component cooling water, which supplies cooling water to the seal injection for each of the reactor coolant pumps. None of the four crews who participated carried out the prescribed action within the prescribed time limit, risking damage to the RCP seals and potentially leading to a simulated RCP seal loss of coolant. The design of this particular scenario employed an initiating event which masked the occurrence of the subsequent loss of component cooling water. These results were used to study the effects of “masking” on subsequent event diagnosis and response. This figure shows how comparison of crew performance with a prescribed limit state illustrates the success or failure of operator actions with regard to a reference PRA prescribed action.

In both examples shown here, time served as a suitable surrogate measure of the underlying thermal-hydraulic phenomenon of interest. In many cases, the plant parameter itself may be directly translated as the limit state. For example, many limits in the plant PRA may be based on pressure, temperature, or some other measured parameter. In such cases, crew performance may be transposed on a graph that shows their performance relative to the measured variable or parameter of direct interest.

These types of data analyses or transformations are employed in order to normalize the raw performance measurement in terms of the limit state. This means that the raw performance measures are adjusted using their relationship to the limit state on a notionally common scale. In the case of the data in **Figure 5** the performance data reflect the percent of available time used by each crew for the critical action in reference to the available time defined by the limit state for the human failure event. This permits insights to be drawn regarding three properties related to performance reliability:

- Whether the actions meet the success criteria for the defined HFE

- The amount of margin available between their performance and the limit state for the action as defined by the HFE

- Variability among crews in performing the action(s).

The process of normalization, whether using raw data or transformed data is intended to relate observed performance to the system limit state and provide a reference that can be used to show performance relative to success and failure criteria alone. There may be many differences between success and failure criteria for accident sequence criteria among different plants and plant types. Normalization and appropriate transformations are ways that data collected from different facilities may be treated and analyzed to permit comparison and potentially aggregation across data collection sites

7. REPORTING

Previous sections described the basic data collection and analysis method. Unless the results are documented comprehensively and coherently, much of that effort would be wasted. Following is a brief outline of a typical report that would provide, not only useful information, but would also ensure traceability and repeatability for future studies.

The following essential items should be included in the report:

1. Scenario descriptions. This includes all necessary detail on:
    - PRA basis for the scenario
    - Plant parameters recorded
    - HFEs
    - Data collection (or operational) procedures used
    - Success/failure criteria for the data collection
    - PSFs

2. Crew composition

3. Scenario analysis results, including:
    - Timeline for all scenarios indicated to the nearest second, as appropriate
    - Malfunctions inserted into the simulation, their timing, as well as crew-dependent malfunctions.
    - Crew responses, linked to the timeline of simulated plant performance including procedures entered and noteworthy decisions and procedural transitions
    - Summary of crew performance on critical tasks noting successes, failures, and noteworthy deviations or exceptions to expected performance
    - Limit state analysis
    - Analyses related to the human performance measures collected
    - Performance driver insights and results

4. Summary and Conclusions

8. SUMMARY AND CONCLUSIONS

One of the aims of this research was to develop and describe a systematic approach to data collection involving human performance in PRA-relevant conditions that would provide useful data about human performance reliability, such as it is used in the field of human reliability analysis. An important part of this is to describe the principles of data collection to ensure that key performance aspects of interest related to the PRA are observed and measured with the intent of drawing insights about the reliability and tendencies of human performance with respect to standard criteria based on PRA success and failure criteria. A longer-term goal is to amass a quantity of data that allows more general insights to be drawn about human performance, supporting more formal estimation of reliability-based parameters needed for use in PRA and other risk-informed applications. This may include the distribution of successful and unsuccessful crew performance on similar tasks collected at different plants that have been standardized to ensure their measurement of critical task performance parameters is similar (e.g., success and failure). The use of a limit state approach as demonstrated here may be one way to achieve such data collection and aggregation on human performance criteria of interest to PRA.

The process of normalizing the raw human performance data as demonstrated is a key aspect to achieving this goal. Plant specific differences may preclude aggregation of data, in the raw, due to differences in plant response and the specific requirements to achieve success in crew performance. The normalized measurement of performance around the limit state with sufficient data may permit more direct assessments of human performance reliability. In addition, the measure provides an ability to observe variability by different crews on established criteria for performance. A potential useful activity may be to see whether trends in variability in crew performance may reflect characteristics of performance in different PRA relevant simulated contexts that can be correlated with success and failure or demand parameters of the performance condition that drive performance reliability.

This report recognizes that data from nuclear power plant (NPP) simulator environments reflect important aspects of human performance and potentially causes of human error. However, the information collected is constrained by the uniqueness of each particular plant and design of each particular simulator study. Thus, the ability to apply the findings of a given simulator study to other studies of human performance at NPPs is often limited. The report emphasizes that a well-defined approach to experimental design, a common language or measurement technique for describing and classifying errors and human actions, and an associated theoretical underpinning for the design and resulting statistical analyses are needed to allow extrapolation of the results of simulator studies across plant designs, crew make-ups, and scenarios.

The report goes on to propose an approach for collecting human performance data from NPP simulators employing the reliability engineering concept of limit state, to describe the process for collecting data, and to present illustrative examples of data analyses. The focus of the approach borrows from techniques applied in traditional reliability engineering (RE) while using experimental techniques derived from the behavioral sciences.

The ultimate aim of the proposed approach is to achieve greater consensus, consistency and convergence of human reliability analysis (HRA) methods by stimulating simulator data exchange, greater communication, and review within the HRA research and practitioner community. The proposed approach is intended to yield data that strengthens the technical bases for HRA methods and their applications.

Because of its relationship with other disciplines, an HRA data generation approach must reflect critical aspects of the underlying scientific and methodological requirements of the scientific disciplines upon which it is based. Since HRA exists at a nexus between three distinct disciplines: (1) the behavioral sciences (i.e., human factors, ergonomics, cognitive sciences, and psychology); (2) reliability engineering; and (3) probabilistic risk assessment, it must draw on the tradition of scientific development and theoretical underpinnings that reflect the formal requirements for, and use of information to address issues to which the discipline is applied. This tradition includes the use of formal experimental design, protocols for data collection, methods for the analysis and interpretation of data, development of models to integrate results, development of codes and standards, and so forth. This also applies to the generation of data to support the development and validation of models of human reliability used in systems analyses, and the application of data from experiments, studies, simulation, or other sources to predict human reliability values.

RE analysis assesses the performance of discrete system elements, having well-characterized governing dynamics (e.g., mechanical, electrical, chemical, etc.), interacting with other discrete elements under well-described conditions. The interactions among components in a mechanical system are straightforward to characterize. This includes the manner in which they receive and process inputs from other components, the manner in which they produce outputs, and the specific outputs they produce.

The report discusses how human performance is difficult to subject the same form reliability analysis that is done for electro mechanical systems. Though the behavioral sciences are comprised of an extensive body of literature and knowledge, this knowledge is not as easy to employ in studies of human reliability analysis as engineered system characteristics are in the analysis of systems reliability. Human capabilities are far more extensive, complex, and interconnected; therefore, they are not as completely understood as the capabilities of electro-mechanical devices. Developing functional models as well as testing and refining theories about these human related processes are vital to shaping our knowledge and expectations about human reliability.

The ability to study a structure, system, or component to failure is vital to the study of its reliability and the ability to do this has been perfected in RE. However, the principles of such an approach are not as mature for the field of human reliability. One of the hallmark characteristics of the RE discipline is the ability to ‘test to failure,’ by creating system failure conditions which can be observed and to collect data that can be used to establish failure rates for various failure types. Validated models using such data can describe the physics of failure of electro- mechanical devices or nuclear energy systems.

Studies of humans that enable observations of failure are needed to develop and validate models for human reliability. Unfortunately, failures in human performance that would be of interest to HRA are unlikely to be observed. The HFEs modeled in a PRA, are events that result from unique combinations of failures (i.e., initiating events) and plant conditions and are very plant specific. Few studies of human failures designed to manifest these conditions in nuclear power plant control rooms have been conducted and reported such that the ability to draw general insights about failure rates and types is limited. This underscores the need for more directly relevant sources of data about human performance that can be used to derive information about the limits of operator performance or capabilities in NPPs.

To summarize, the ability to collect data on the reliability of human performance in complex environments is much more difficult than it is to collect data for many of electro-mechanical devices employed in nuclear energy production and other industrial systems. What is needed are:

- Opportunities to collect data about human performance in which success and failure are defined and measured.
- Theories of human performance and human reliability that are sufficiently mature to support HRA model and method development along with sources of data to test and validate the models of human cognition and behavior that are the basis of HRA methods.

The approach proposed in this report could be used to provide a common language for human failures (limit state) and human performance within HRA studies that would allow data from one HRA context to be extrapolated to a new context.

Collecting simulator data to support HRA requires robust experimental design and process. Five essential experimental design characteristics are described that are based on paradigms from the behavioral sciences that should be considered for robust experimental design that should be addressed when preparing to collect data for application in HRA. The section includes recommendations on categories of information to collect when performing simulator studies.

The five experimental design characteristics that are proposed in this report are:

- Performance measures should relate to success and failure as defined in the PRA
- Simulator contexts should be representative of PRA events
- Data collection should include the opportunity to observe human failure events of interest
- Data collection should include objective human performance measures of success and failure
- Data collected should describe relevant aspects of performance and the factors that affect that performance

HRA methods consider conditions that may be found in probabilistic safety analysis contexts to predict the kinds of errors (e.g., slips, lapses, or mistakes) and the likelihood of those errors (i.e., probability) that can occur. There is substantial experimental and experiential evidence about the many factors that may be 'drivers' of human reliability in PRA contexts. These include factors such as stress, workload, human-system interface technologies, training and experience, crew resource management, intra-team dynamics, and others.

The report goes on to describe in detail specific process steps to performing an experiment following a robust design that focuses on collecting HRA relevant data from an NPP simulator using PRA significant events while collecting success and failure data depicted by limit state criteria. The process of conducting an HRA simulator data collection effort can be described in four main phases: preparation, data collection, data analysis, and reporting. These four phases are further defined by 19 sub-steps. The data collection section presents different methods to be used for data collection and also describes how to structure the collection effort. In the data analysis section, examples of how to develop synopses and how to document deviations and errors are provided. There is also a description of how to analyze performance drivers in this section.

The report discusses, in detail, the concept of limit state as a generic approach to define success and failure criteria so that the data can be used across HRA methods. Using the plant-specific PRA, success and failure criteria can be developed for each planned scenario. Limit state from a RE and systems safety perspective denotes a region of performance that distinguishes between performance success and failure. An analysis of crew performance data permits a determination to be made regarding success of the crew in terms of the requirements of the PRA, to minimize the potential for subjectivity in evaluating crew performance.

Two important features about this method for measuring the quality of crew response are: (1) the distribution of crew performance on the criteria related to the limit state, and (2) the variability in crew response relative to the limit state. The performance criteria for human actions are specific to the event sequence and scenario. Even though the same human actions are required in different event sequences, the specific criteria that define success for the human action is scenario specific. Identifying the criteria in each scenario context is the first step of establishing the measure of success and failure for the critical human action. Using observed crew performance during the simulator runs of the scenario and the defined threshold for performance, the data show the response of individual crews against the maximum available response range. This method of measurement produces a distribution of crew performance relative to the limit state and is an indicator of how near the crew was to failing to meet the performance criteria for the scenario.

The second feature that is important from these data is the variability in crew response, which reflects inter-crew differences in task execution, procedure use, and decision-making, all of which are inter-related. It also reflects uncertainty in the results of crew performance that may have implications for the reliability and consistency in crew response to the initiating event(s).

These types of data analyses normalize the raw performance measurement in terms of the limit state. This means that the raw performance measures are adjusted using their relationship to the limit state as a notionally common scale. This permits insights to be drawn regarding three properties related to performance reliability:

- Whether the actions meet the success criteria for the defined HFE

- The amount of margin available between their performance and the limit state for the action as defined by the HFE

- Variability among crews in performing the action(s).

The process of normalization whether using raw data or transformed data relates observed performance to the system limit state and provides a reference that can be used to show performance relative to success and failure criteria alone. There may be many differences between success and failure criteria for accident sequence criteria among different plants and plant types. Normalization and appropriate transformations are ways that data collected from different facilities may be treated and analyzed to permit comparison and potentially aggregation across data collection sites.

In conclusion, this report (1) proposes a standardized approach for collecting human performance data from NPP simulators employing the reliability engineering concept of limit state using experimental techniques derived from the behavioral sciences, (2) describes a process for collecting data, and (3) presents illustrative examples of data analyses.

The report also describes how the approach can achieve greater consensus, consistency and convergence of HRA methods by stimulating simulator data exchange, greater communication, and review within the HRA research and practitioner community through the application of limit state as a means to normalize data collected from different facilities so that the data may be treated and analyzed to permit comparison and potentially aggregation across data collection sites.

The proposed approach is intended to yield data that strengthens the technical bases for HRA methods and their application

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APPENDIX A – SCENARIO DATA ANALYSIS GRAPHS

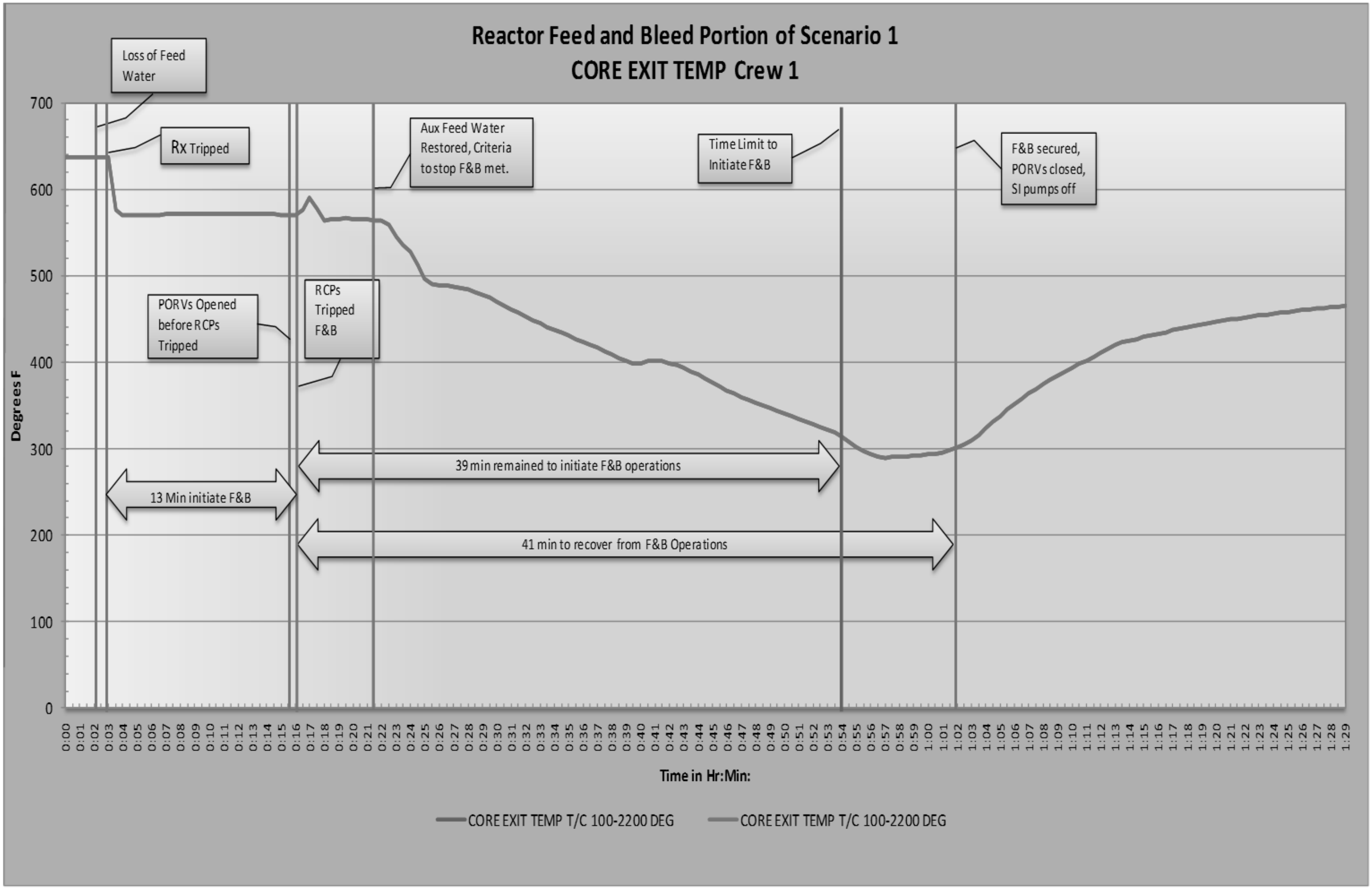

Figure A-1 Example of a reactor feed and bleed analysis with expected crew performance demonstrated

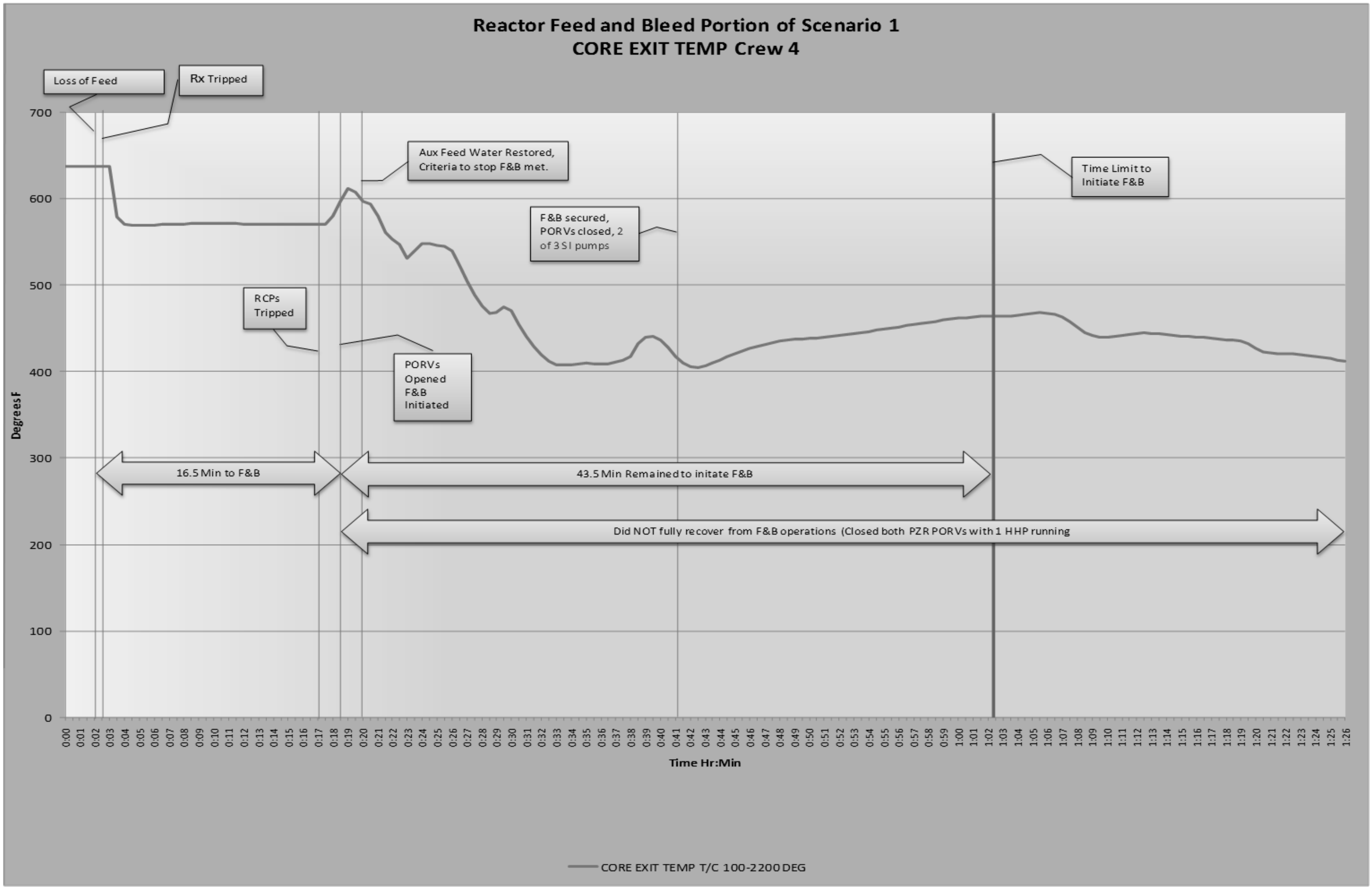

Figure A-2 Example of a reactor feed and bleed analysis with a crew deviation noted

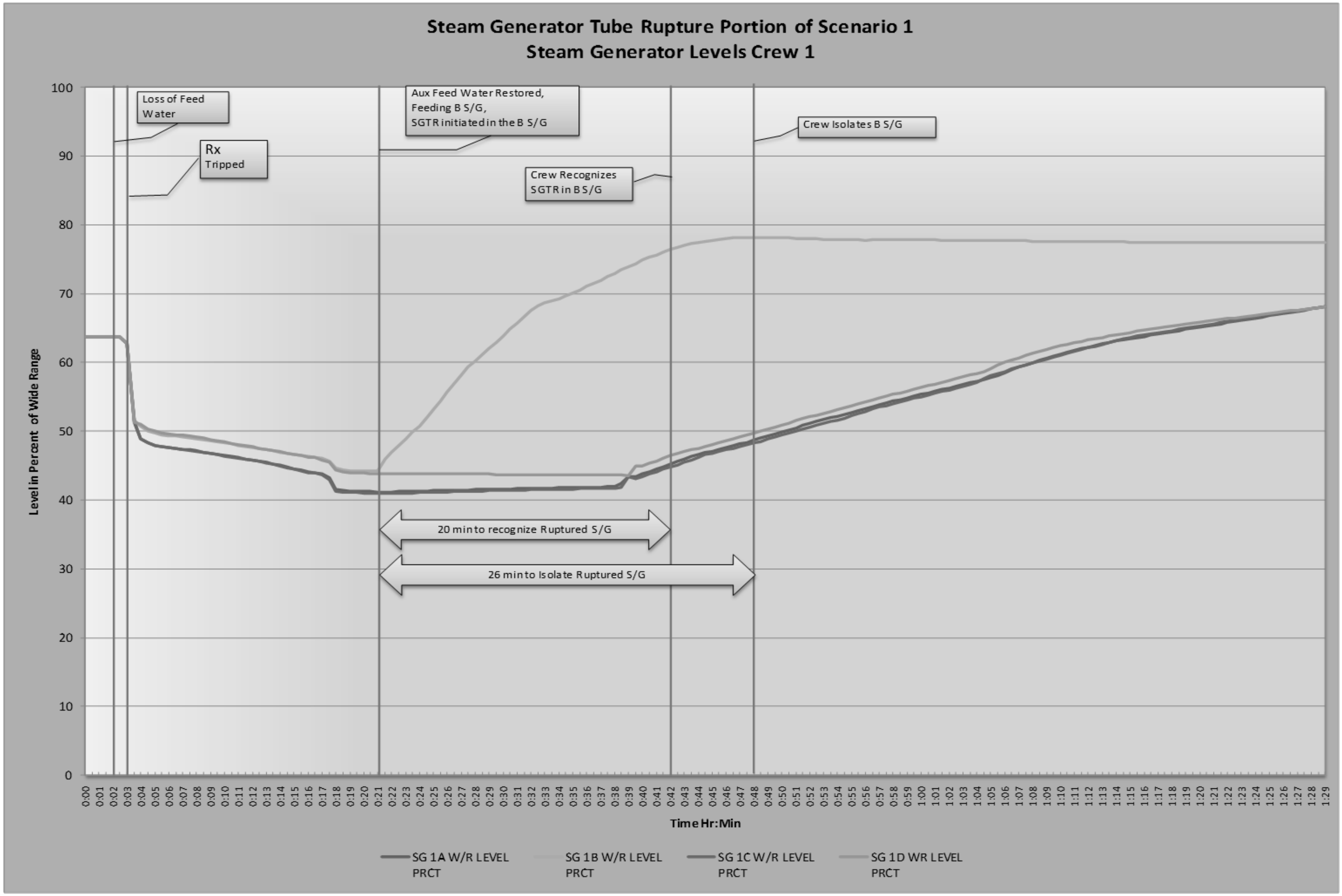

Figure A-3 Example analysis of steam generator tube rupture – expected performance demonstrated

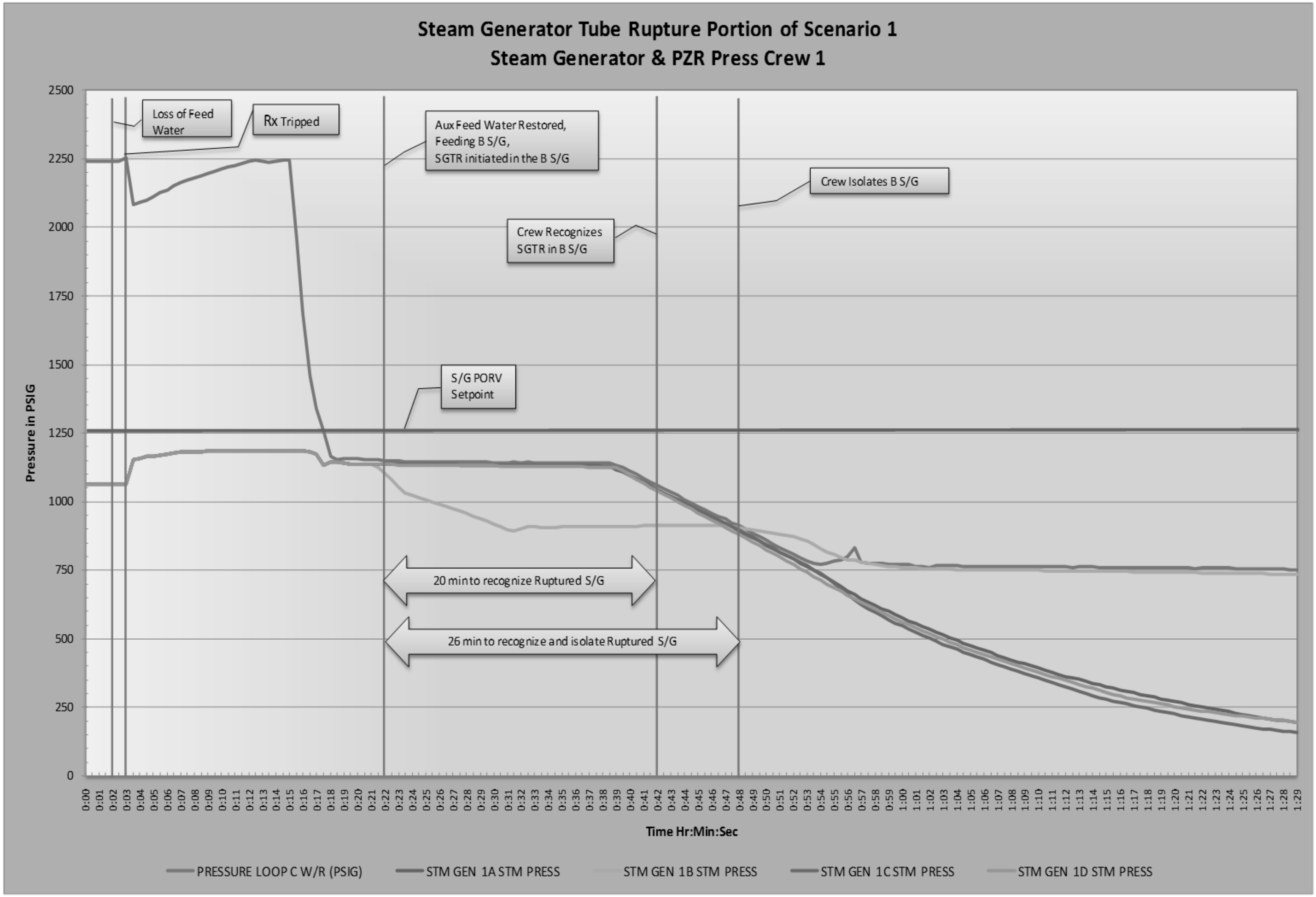

Figure A-4 Example analysis of steam generator tube rupture and pressurizer – expected performance demonstrated

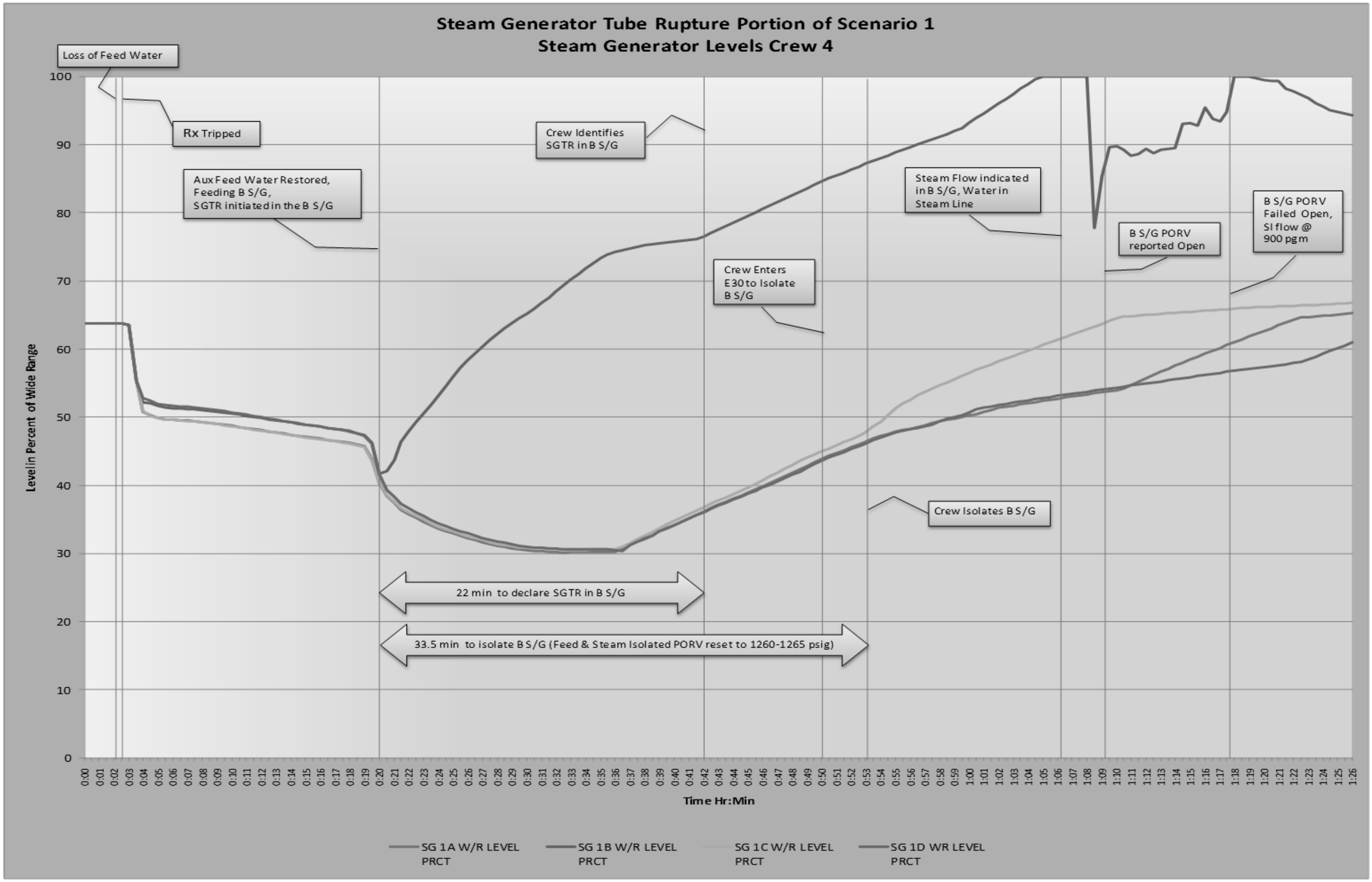

Figure A-5 Example analysis of steam generator tube rupture – performance deviation noted

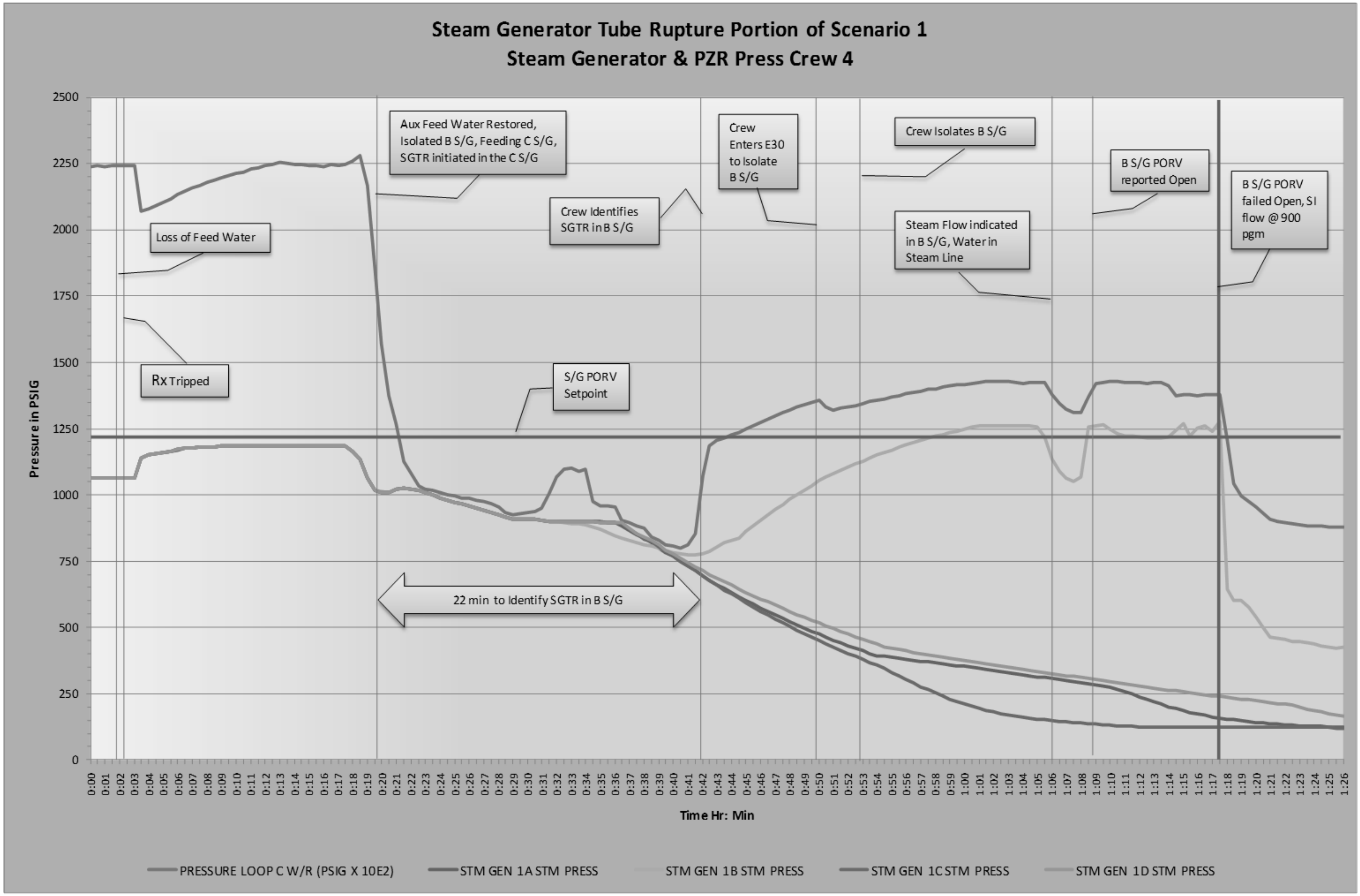

Figure A-6 Example analysis of steam generator tube rupture and pressurizer – performance deviation noted

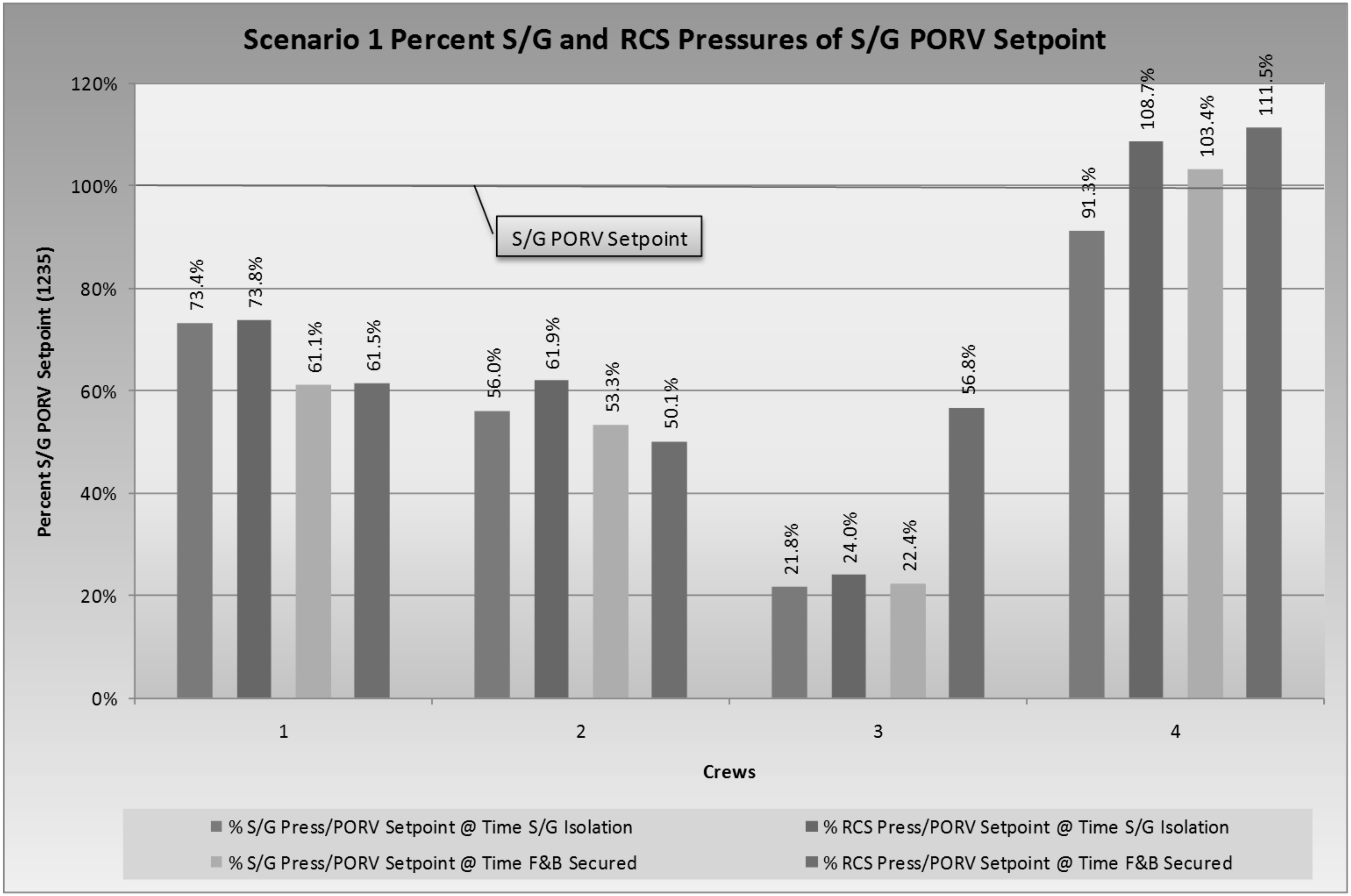

Figure A-7 Example analysis and results of crew performance of pressure management on SGTR with Limit State (S/G PORV Setpoint) superimposed

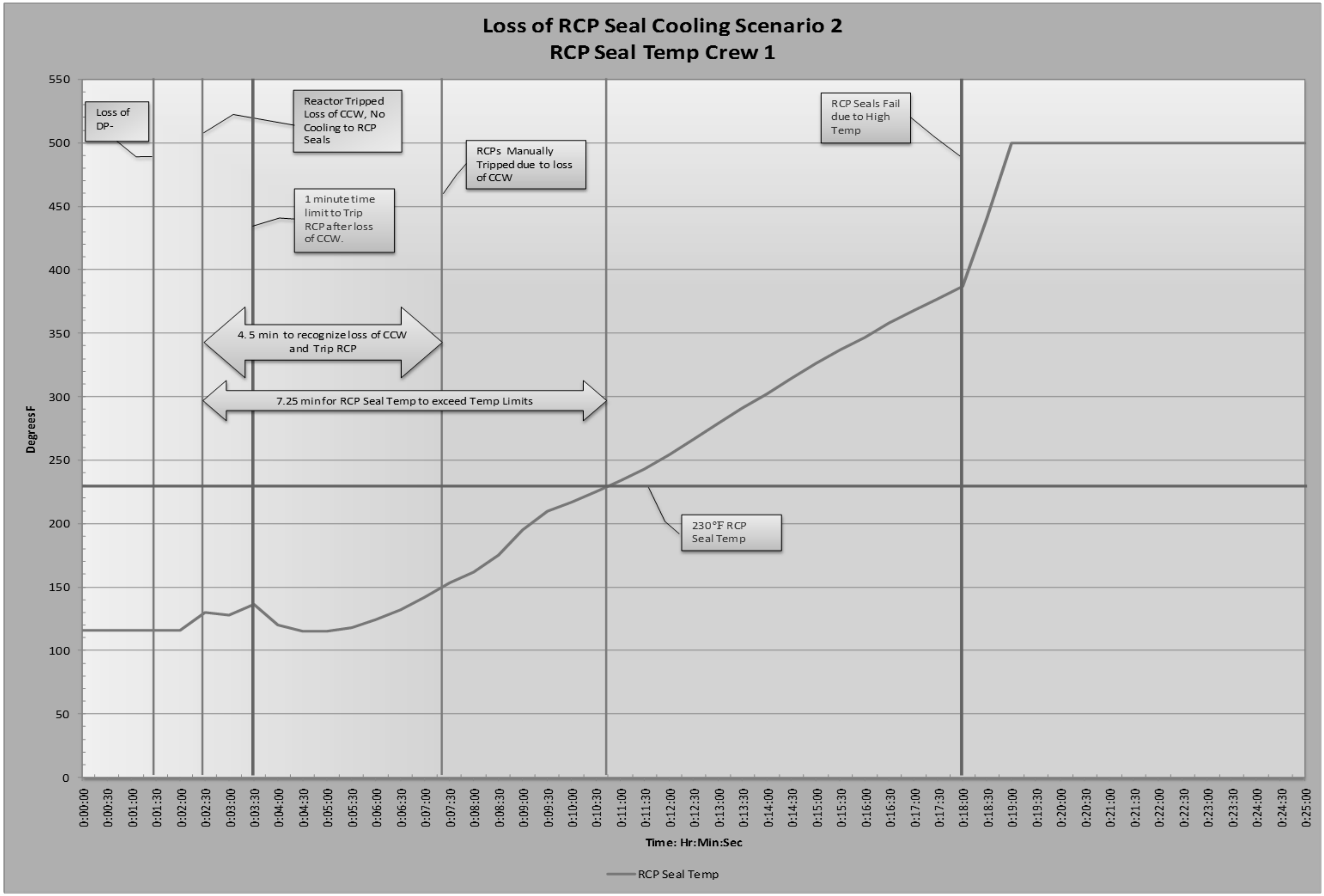

Figure A-8 Example analysis of crew performance – failure noted

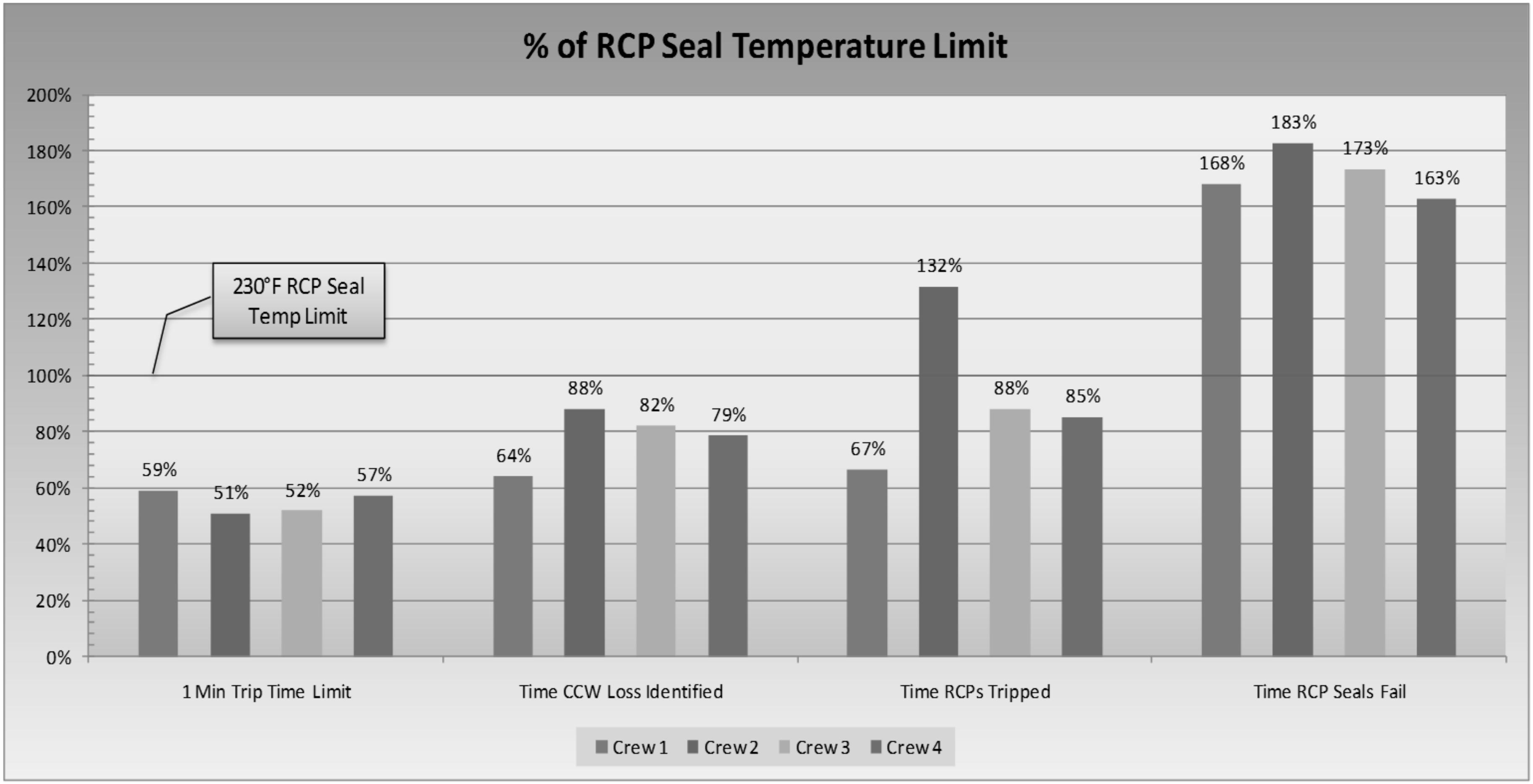

Figure A-10 **Example analysis of crew scenario management reflected in RCP seal temperature with limit state (RCP seal temperature limit) superimposed**

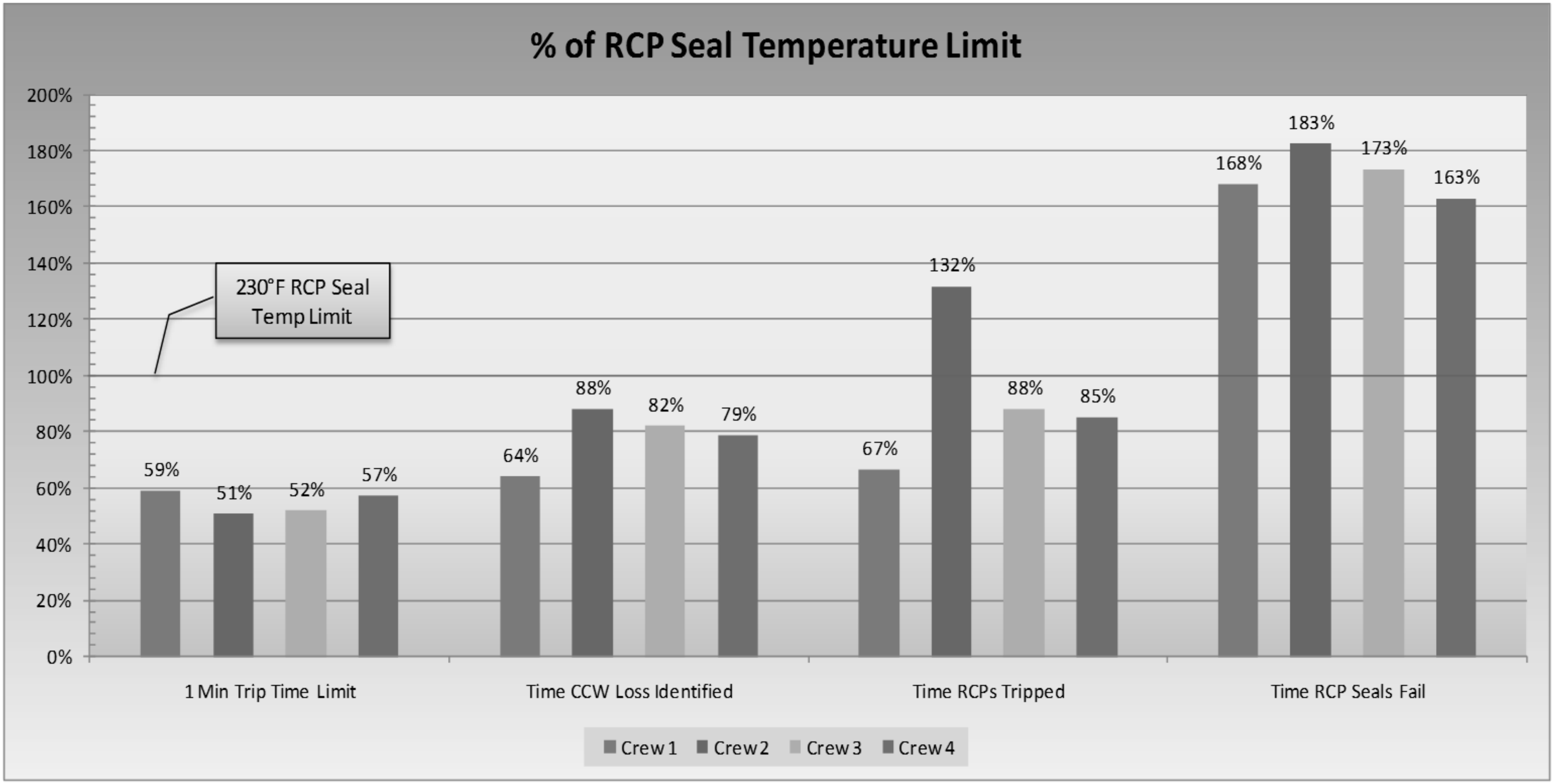

Figure A-11 Example analysis of critical task performance: Time limit to reactor coolant pump trip - all crews with limit state (RCP seal temperature limit) superimposed

APPENDIX B – SIMULATOR SCENARIO DESCRIPTIONS

SLOFW/SGTR scenario

Scenario description

Situation from start

100% Power
S/U feedwater (FW) pump cannot start (not visible)
X-connection valve for auxiliary feed water pump (AFP) B cannot open

1. Total loss of feedwater

Events:

Trip of MFW pumps
S/U FW pump cannot be started
AFWP 11 does not start
AFWP 12 starts and indicates flow, but the recirculation valve is open (does not show in the control room) so the indicated flow does not go to the S/G
AFWP 13 starts but there is no flow (shaft failure)
AFWP 14 starts but trips on over-speed

Consequences:

Level going down in all S/Gs
No flow to any S/G
Indicated flow to S/G B prevent the red entry to FRH1 to be present

Actions:

→ When MFW stops, start FW booster pump and start S/U FW pump (does not start)

→ Manually trip the reactor when there is no feed flow to the S/Gs (anticipate automatic trip)

→ Immediate actions after trip

→ Try to open X-connection valve from AFWP B, cannot be opened.

→ After immediate actions, check if AFW needs to be reduced. Send field operators to check the following:

- Breaker for AFWP1
- X-connection valve on AFWP B
- Check valve line-up, why there is no flow
- Terry turbine, reset over-speed

→ Transfer to ES01 and start monitoring CSF

→ Detect that there is no AFW flow to S/G B (no flow to any S/G). There are trends on S/G WR levels in the back-panels.

→ Decide to transfer to FRH1 procedure based on loss of secondary heat sink (no S/G level and no S/G feed flow). (They will probably make this decision in about 10 minutes according to the training staff.)

→ Start F&B according to procedure FRH1

Procedures:

- 0POP05-E0-E000, “Reactor Trip Or Safety Injection”
- 0POP05-E0-ES01, “Reactor Trip Response”
- 0POP05-E0-FRH10POP05-EO-FRH1, “Response to Loss of Secondary Heat Sink”
- 0POP04-FW-0002, “Steam Generator Feed Pump Trip”

2. Reestablish FW

Event:

X-connection valve from AFWP B becomes available (about 20 minutes into the scenario). We will get the X-connection back as soon as possible after initiating F&B, so that the S/G levels do not drop too much (after they have reset SI and some other actions that they have to do).

Consequence:

It is possible for the crew to establish FW to S/G A, B and C via the X-connection valves

Action:

→ Reestablish FW to S/Gs

Procedure:

- FRH1

3. SGTR

Event:

A tube rupture occurs in the first S/G that is feed via the X-connection valves, one minute after AFW flow is established.

Consequences:

RCS water leaking into the ruptured S/G. The level in the ruptured S/G will rise (but this level rise may be masked by the fact that they are also feeding the S/G to reach)

→ FRH1, stop F&B when NR level in one S/G is <34% (adverse containment condition)

→ Go to ES11 (from FRH1 step 31, may not be possible if RCS pressure is not stable, then you may go to ES1); stop SI (may be done in ECA31, if E1 is used here)

→ Go to FRP1, from the CIP in ES11. The FRP1 will take care of the SGTR, reducing the RCS pressure so that the leak flow to the ruptured S/G stops. (100% NR in about 1h 15 min, WR continue to rise)

→ From FRP1 to ES11; subcooling adequate

→ From ES11 CIP to E3 (1h 20 min). Adjust S/G PORV set point to 1265. Steam line and feed flow already isolated. (Radiation alarm (yellow) at 1h 25 min.

→ ECA31 from E3 step 6, based on S/G pressure (red radiation alarm)

Procedures:

- 0POP04-FW-0002, “Steam Generator Feed Pump Trip”
- 0POP05-E0-E000, “Reactor Trip Or Safety Injection”
- 0POP05-E0-ES01, “Reactor Trip Response”
- 0POP05-E0-F003, “Heat Sink Critical Safety Function Status Tree”
- 0POP05-E0-FRH10POP05-EO-FRH1, “Response to Loss of Secondary Heat Sink”
- 0POP05-E0-ES110POP05-EO-ES11, “SI Termination”
- 0POP05-E0-EO100POP05-EO-EO10, “Loss of Reactor or Secondary Coolant”
- 0POP05-E0-F004, “Critical Safety Function Status Tree”
- 0POP05-E0-FRP10POP05-EO-FRP1, “Response to Imminent Pressurized Thermal Shock Condition”
- 0POP05-E0-EO300POP05-EO-EO30, “Steam Generator Tube Rupture”
- 0POP05-E0-EC31, “SGTR with loss of reactor coolant – subcooled recovery desired”

Human Failure Event

HFE1: Start F&B.

- 13% WR S/G level = hot dry S/G at STP
- 90 minutes (PRA core damage)

HFE2: Identify and isolate ruptured S/G

- top filled S/G
- time? 33 min from SGTR (= 75 minutes total)

HFE3: Stop SI to avoid/ stop S/G PORV release

- top filled S/G
- time? 33 min

The HFEs for SGTR (identify and isolate, and stop SI) can be done in a different order depending on the RCS pressure trend when leaving FRH1 (criteria to stop SI or not).

Procedures

- 0POP04-FW-0002, “Steam Generator Feed Pump Trip”
- 0POP05-E0-E000, “Reactor Trip Or Safety Injection”
- 0POP05-E0-ES01, “Reactor Trip Response”
- 0POP05-E0-FRH10POP05-EO-FRH1, “Response to Loss of Secondary Heat Sink”
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- 0POP05-E0-EO300POP05-EO-EO30, “Steam Generator Tube Rupture”
- 0POP05-E0-EC31, “SGTR with loss of reactor coolant – subcooled recovery desired”

Data collection

Hand out paper copies of the procedure that they use that can be collected after the run. The US writes in the procedure while working.

Remember: In the experimental protocol, decide when the crew will have responses from FOs and chemistry.

RCP Sealwater Scenario

Scenario Description

Situation from start

Facility has a lot of online maintenance. It is not unusual to have a train out of service for maintenance.

100% Power

“B” train out of service from start (condensate cooling pump (CCP) B out of service. CCP B is cooled by CCW)

1. Failure of distribution panel

Event:

Failure of distribution panel DP1201

Consequences:

Failure of controlling channels for A and B S/Gs.

Actions:

- The crew needs to take immediate actions (that they know from training). They don’t have time to take out the procedure in this situation. The US makes sure that the crew establishes control of the situation. (When control is established they may use the procedure, but in this situation they will not gain control, so they probably will not use the procedure.)
  - Charging control valve in manual to control charging flow
  - S/G A and B feed regulation valves in manual to control feedwater flow to S/Gs. (The valve will open fully in automatic.)
  - Control rods in manual to prevent them from stepping in.

Procedures:

0POP04-VA-0001, “Loss of 120 VAC Class Vital Distribution”

2. Reactor trip on high S/G level

Event:

The A MFW control valve cannot be taken in manual, and the valve is fully open, feeding the S/G.

Consequence:

If the crew does not trip manually, there will be an automatic trip on high S/G level.

Actions:

- Trip reactor (because they have lost control of S/G level, and are approaching automatic trip)
- Do immediate actions and start E0
- AFW valves in manual (A and B) to control S/G level (A and B)
- Go to ES01

Procedures:

- 0POP05-E0-E000, “Reactor Trip Or Safety Injection”
- 0POP05-E0-ES01, “Reactor Trip Response”

Comment:

The reactor trip in combination with the failed distribution panel keep the crew busy and may mask the failure of CCW.

3. Loss of CCW and Sealwater

Events (happening at the same time as reactor trip):

- CCW pump 1A (that was the one running) trips
- The busbar E1C is de-energized (failure on busbar, preventing DG from starting)

Consequences:

- Loss of all CCW pumps (B pump out of service, A pump tripped, C pump de-energized)
- Loss of sealwater to RCPs because the running charging pump (CCPA) is powered from E1C. The other charging pump (CCPB) is out of service.

Actions:

- Stop diesel generator 13 (powered from E1C) because it has lost cooling, ECW. E-0 addendum 5 (p40): step 7, verify ECW status, check pumps running, when load sequence is completed start pumps. If cannot be started trip the diesel. (Normally crewmembers don’t wait that long.) The licensed operator has the discretion to take control, protect the diesel, and turn it off.
- Stop RCPs because cooling is lost (within1 minute according to procedure POP4-RC-2 step 3 and CIP)
- Start PDP and establish sealwater (before sealwater inlet or lower sealwater bearing temperatures greater than 230, otherwise establish sealwater slowly)

Procedure:

- OPOP4-RC-0002, “Reactor coolant Pump Off Normal”
- 0POP05-E0-ES01, “Reactor Trip Response” (ES01 step 6 and step 1 and addendum 1 in POP4-RC-2: IF sealwater inlet OR lower sealwater bearing temperatures GREATER THAN OR EQUAL TO 230, THEN DO NOT establish seal injection to that RCP.)

Human Failure Event

HFE: Start PDP and close the recirculation valve to establish sealwater

- before 230°F
- within 13 minutes

Procedure:

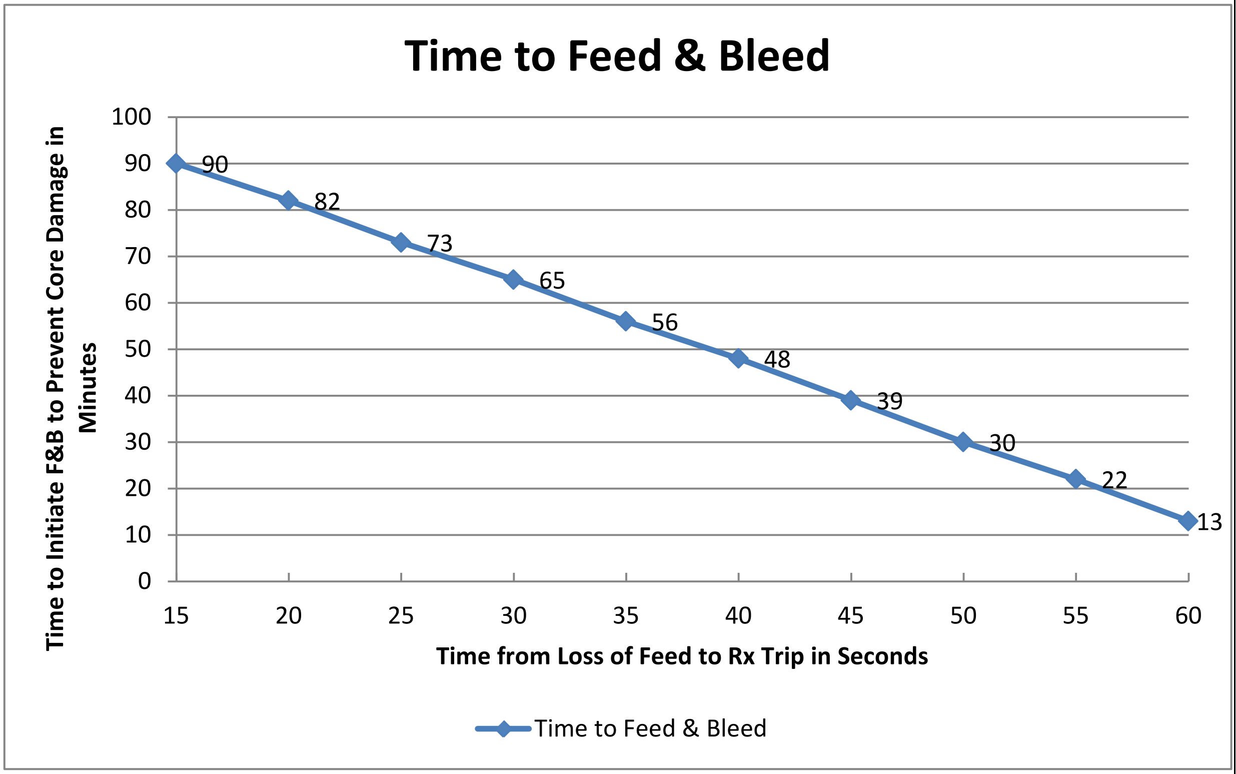
- 0POP04-VA-0001, “Loss Of 120 VAC Class Vital Distribution”
- 0POP04-RC-0002, “Reactor Coolant Pump Off Normal”
- 0POP05-E0-E000, “Reactor Trip Or Safety Injection”
- 0POP05-E0-ES0, “Reactor Trip Response”
- 0POP04-VA-0001, “Loss of 120 VAC Class Vital Distribution”

APPENDIX C – PERFORMANCE CRITERIA

LOFW/SGTR Scenario

1. Total Loss of Feedwater

Pass Criteria for Loss of All Feedwater:



- Time to initiation of F&B must be below the curve. (Depending on the time of the Rx trip following a complete loss of feed to the S/Gs, the crew has between 90 and 13 minutes to initiate RCS F&B. [The sooner the Rx is tripped after the loss of Feed to the S/G the more water inventory (in the S/Gs) to remove decay heat from the Rx, thus giving them more time to initiate Feed and Bleed.]
- Successful RCS F&B is determined when at least one high-head safety injection) pump is running and both PZR PORVs isolation valves and both PZR PORVs are open and flow is verified (into and out of the RCS).
- (If PZR PORVs are not available, then the RX head vent must be open.)
  - (Secondary Criteria) maintain containment pressure (If ≥5 psig, initiate or verify initiation of containment spray)(If ≤6.5 psig, verify containment spray may be stopped or stop containment spray.)

Note: Loss of heat sink is determined by:

S/G wide range level in at least two S/Gs less than 50% [73%] or pressurizer pressure greater than 2,335 psig.

2. Reestablish Feedwater

Pass criteria for reestablishing feedwater:

- Start AFWP ‘B’
- Open X connection to establish flow to S/Gs A, B, and/or C.
- Feed rates are maintained within limits.
  a. FRH1 step 3.e. Check total AFW flow to S/Gs > 576 gpm. [≤675 gpm/pump]
  b. AFW flow to dry S/G.

3. SGTR

Pass criteria for SGTR:

- Identify the faulted S/G
- Isolate faulted (S/G level ≤90% WR)
  - Feedwater isolated (feedwater isolation valve closed)
  - Steam isolated (main steam line isolation valve closed)
  - S/G PORV set point increased to required setting. (1,265 psig)
    - (Secondary criteria) maintain RCS pressure less than S/G PORV setting (1,265 psig)
  - No uncontrolled release of primary coolant through the steam lines

Note: Reestablishing the heat sink with the S/G and then stopping the F&B?

- At least 1 S/G level returned to >14% NR [34%].
- Steam flow from the S/G with level > 14% NR.
- RCS pressure and temperature being maintained (soak) and/or decreasing within the cool down limits.
- PZR PORVs in auto and/or closed.

Loss of RCP Sealwater Scenario

4. Failure of distribution panel

Pass criteria for loss of distribution panel DP1201

- Place rod control in manual (stop rods from stepping in)
- Place S/G A & B feed water regulating valve (FRV) in manual (return feed flow to normal) (B S/G only A S/G FRV will not respond)
- Place charging control valve in manual (maintain PZR level in the operating band)
- Trip reactor prior to reaching S/G water level high Rx trip (87.5% NR S/G level)

5. Reactor Trip on high S/G Level

Pass criteria for reactor trip

- Monitor RCS temperatures (>567 allow cool down, if <567 limit steam loads)
- Verify control rods fully inserted (rod bottom lights lit)
- Verify PZR level and pressure (PZR level in the operating band PZR pressure >1,875 psig)

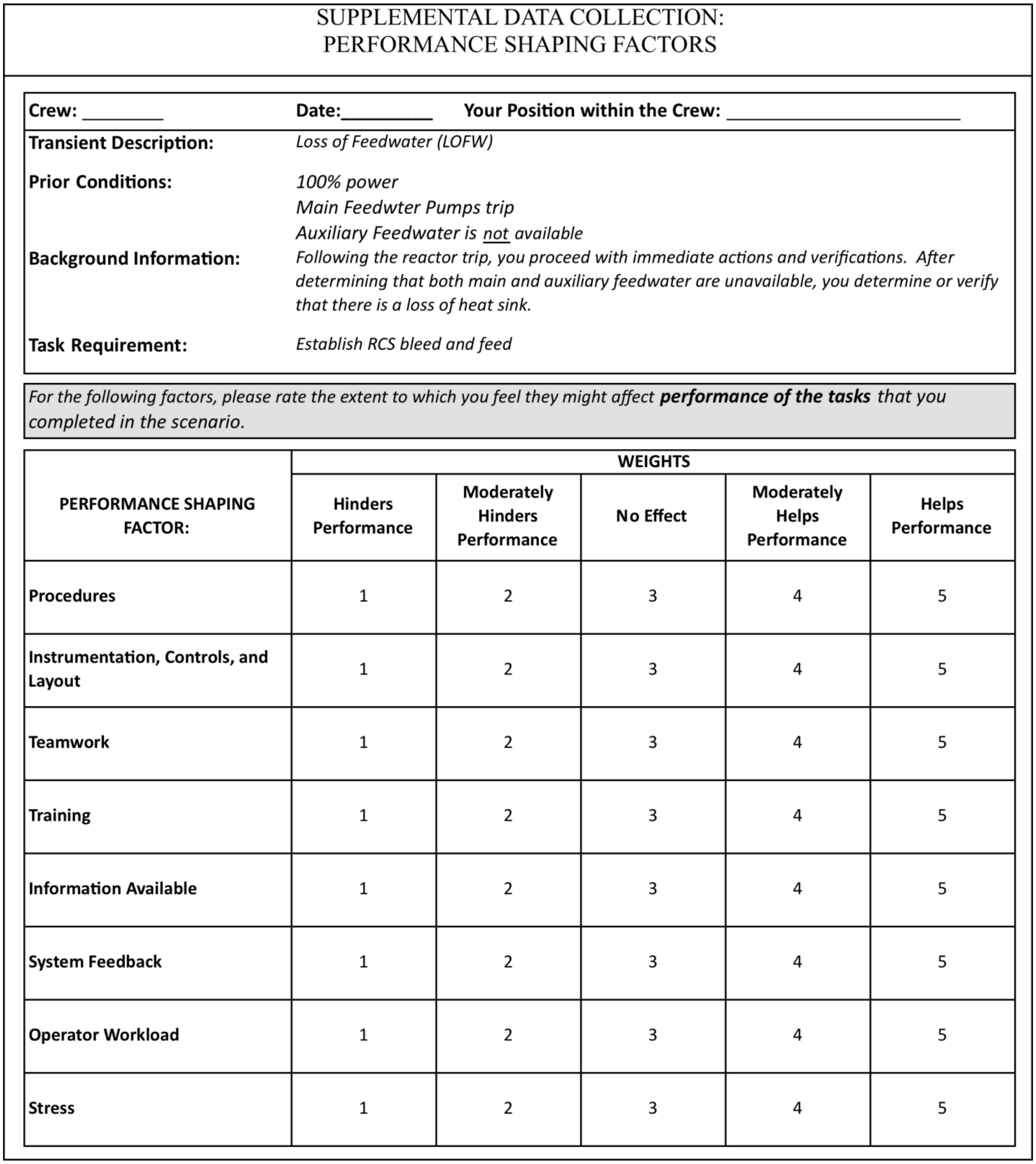
6. Loss of CCW and Sealwater

Pass criteria for loss of CCW and RCP sealwater

- Stop RCPs <1 min following loss of cooling and flow (seal injection flow ≤6 gpm, sealwater injection temp ≥135°F)
- Start PDP before seal temperatures are ≥230°F
- Slowly open RCP sealwater injection flow control valve (cool down seals at ≤1°F/min) **(cool down limit could not be met during scenario validation runs)**
- Continue cooling until RCP seal inlet temps are within 30°F of Sealwater injection temp or seal inlet temps are stable with seal injection established
- If ≥230°F do not start sealwater flow (close seal isolation valves)
- Establish natural circulation cool down
- Cool down within cooldown limits.

APPENDIX D – PERFORMANCE DRIVERS DATA COLLECTION

Below is an example of a data collection questionnaire that was developed to assess a group of performance drivers, termed Performance Shaping Factors drawn from an individual case study. The questionnaire provides a brief description of the task that had been completed for the particular scenario. A similar questionnaire was completed by crewmembers for each task. Note that all scenarios will typically include different tasks.



SUPPLEMENTAL DATA COLLECTION:
PERFORMANCE SHAPING FACTORS

Crew: ________ **Date:**_________ **Your Position within the Crew:** ________________________

Transient Description:	*Loss of Feedwater (LOFW)*
Prior Conditions:	*100% power* *Main Feedwter Pumps trip* *Auxiliary Feedwater is not available*
Background Information:	*Following the reactor trip, you proceed with immediate actions and verifications. After determining that both main and auxiliary feedwater are unavailable, you determine or verify that there is a loss of heat sink.*
Task Requirement:	*Establish RCS bleed and feed*

For the following factors, please rate the extent to which you feel they might affect ***performance of the tasks*** *that you completed in the scenario.*

PERFORMANCE SHAPING FACTOR:	**WEIGHTS**				
	Hinders Performance	**Moderately Hinders Performance**	**No Effect**	**Moderately Helps Performance**	**Helps Performance**
Procedures	1	2	3	4	5
Instrumentation, Controls, and Layout	1	2	3	4	5
Teamwork	1	2	3	4	5
Training	1	2	3	4	5
Information Available	1	2	3	4	5
System Feedback	1	2	3	4	5
Operator Workload	1	2	3	4	5
Stress	1	2	3	4	5

APPENDIX E - EXAMPLE OF LOG SHEET

Scenario # 1 Crew # 1 Date ____

TIME	ACTIONS
2:14	MFP Trip Total loss of FW
2:25	Report auxiliary feed water pump (AFP) did not start
2:51	Rx Trip
3:12	Turbine Trip
4:07	Attempted to start AFP
4:37	Verified good Rx Trip and Main Turbine Trip
4:56	Verified power to all Engineered Safety Feature (ESF) buses
5:22	RO Reports Rx Pressure @ 2121 psig and slowly increasing, SI not required
6:19	AFP running flow indicated to ‘B’ S/G, level not increasing
6:39	RO report there is flow to the ‘B’ S/G
7:34	RO There is no Aux Feed
7:51	Level decreasing in the ‘B’ S/G reported
8:34	US transitions to EOP ES01: “Response to Reactor Trip”
9:02	T_{ave} 570 °F and stable
9:59	MFW verified isolated
10:13	Verified MFPs tripped
11:06	Report AFP 12 & 13 not available
12:00	FRH1 entered assuming no feed to ‘B’ S/G
12:48	Verified RCS pressure > S/G pressure
13:05	Verified RCS T_{hot} > 570 **°F**
13:34	Actuated SI
14:04	Verified 3 HHP running
14:17	Verified HHP valve lineup
14:31	Verified power to PZR PORVs
15:00	Opened both PZR PORVs
15:19	STA questions if RCPs are running
15:39	RO ordered to Trip RCPs
15:50	All 4 RCPs tripped (RCS F&B initiated)
16:08	Site Area Emergency declared
16:22	RCPs tripped reported
17:09	Reset SI signal ordered
17:29	RO attempts to reset SI
18:57	SI reset
19:36	Reset MFW isolation
19:56	PRT rupture disc ruptures
20:45	MFRV demand lowered to zero
21:09	Reset main steam line (MSL) isolation
21:23	Reset Low T_{ave} Isolation
21:31	Reset S/G HiHi level isolation
21:56	AFW 70 valve closed commenced feeding ‘B’ S/G
23:16	Alarms coming in RO not reporting
25:20	Reset S/G HiHi level isolation again
26:30	RO questions opening cross connect valve,
29:34	All FW Isolation to permissive
31:00	‘B’ S/G >40% RO recommends opening cross connect valve
31:47	Opened cross connect valve connecting steam generators

TIME	ACTIONS
32:24	Opened Containment air isolation
32:49	Verified charging pump running
33:30	Closed Charging flow control valve
33:50	RO closes charging flow control valve 205
34:20	RO opens MOV 25
34:49	RO establishes maximum charging flow
36:16	‘A’ S/G MFRV will not close report by RO
37:04	AFW verified to ‘B’ S/G
37:37	‘B’ S/G level 78% and increasing
37:50	RO verifies feed to ‘B’ S/G has been secured
38:16	Rx Head Vent closed verified
38:25	3 HHP and 1 charging pump running verified
38:48	Adverse Containment announced
38:56	178 °F subcooling increasing reported
39:12	PZR Level >100% reported
39:27	AFW to all 4 S/Gs reported
39:39	RO re-verifies feed to ‘B’ S/G is secured
40:06	Stopped 1 HHP ‘A’
40:26	RCS pressure 1100 psig and slowly decreasing
40:52	RO report ‘B’ S/G level still increasing
42:00	US recognizes SGTR and discusses with SM
43:36	Discusses procedure priority
43:50	STA reports slightly elevated Radiation level on ‘B’ S/G
44:21	Determined FRH1 procedure applies
44:41	SM states the ‘B’ S/G needs to be isolated
45:21	Crew briefing on ‘B’ S/G
45:30	AFW isolation to the ‘B’ S/G is closed
45:50	Continue feeding other S/Gs
46:18	Red path report from STA for Functional Recovery Procedure 1 (FRP1)
46:40	RO reports AFW to ‘B’ S/G is closed
47:19	PRC pressure 930 psig and decreasing
47:40	US request T_{cold} status need stable or increasing; RO reports T_{cold} decreasing
48:09	Verified S/G PORV’s closed (‘B’ S/G isolation)
49:28	Verified approximately 50% WR levels on A, C, and D S/Gs
50:09	RO told to continue feeding S/Gs until at least one is >34% NR
50:46	Verified MSIVs closed
51:40	Verified PZR PORVs open
53:35	No subcooling
55:10	Crew Briefing
55:32	RCS pressure 788 psig
56:03	Subcooling @>200 °F
56:02	Stopped ‘B’ HHP and placed in Auto
56:50	RCS pressure reported at 783 psig and decreasing
57:37	Crew Briefing
58:46	RCS pressure 773 psig and stable
59:33	239 °F subcooling reported
1:00:13	T_{hot} >405 **°F**
1:00:39	Stopped ‘C’ HHP

TIME	ACTIONS
1:01:20	RCS pressure 762 psig and steady
1:02:03	US orders the PZR PORVs closed
1:02:20	PZR PORVs are closed
1:02:50	RCS pressure is 767 psig and slowly increasing
1:02:56	Low head pump (LHP)s stopped and place in automatic ordered
1:03:13	LHPs stopped and in automatic
1:03:50	FRH1 completed; Functional Recovery Procedure 1 (FRP)1 entered
1:05:20	Subcooling 195 °F and slowly decreasing
1:06:29	Subcooling 182 °F and slowly decreasing
1:06:53	Verified T_{hot} stable WR = 309 °F and 383 °F
1:07:38	RO ordered to energize Accumulator Isolation Valves
1:08:27	RO ordered to close Accumulator Isolation Valves
1:08:56	RO told to maintain S/G levels
1:09:02	All Accumulator Isolation Valves Closed
1:10:27	PZR level reported >100%
1:11:16	Subcooling 142 °F and decreasing
1:12:09	Makeup pumps isolation valves opened
1:14:08	Crew recognizes ‘B’ S/G acting as the RCS PZR
1:19:00	RCS pressure 761 psig
1:20:39	Letdown flow is established
1:22:56	RCS pressure @ 757 psig
1:24:20	Charging pump suctions shifted to Volume Control Tank
1:24:49	Crew Briefing
1:25:44	PZR heaters energized and auxiliary spray established
1:27:27	Discussion about Reestablishing PZR pressure control
1:27:56	Established Auxiliary PZR spray Backup heaters off
1:28:46	Open 2 S/G PORV slightly to establish secondary Heat sink
1:28:56	Simulator froze

APPENDIX F - EXAMPLE OF POST-SCENARIO DEBRIEFING FORM

Debriefing Team Initials:	Date:	Page
Crew:	Scenario:	

Diagnosis of Events and Conditions Based on Signals or Readings

1. What were the events that occurred during this scenario?

Type Answer Here

2. What information and materials did you use to first recognize and then diagnose the event and conditions?

2a. What did you use to first recognize and then diagnose the event and conditions?

Type Answer Here

3. What information was communicated with the crew and how was it used?

3a. What information did you then communicate to the crew and how was it used? (Was it used properly in your judgment?)

Type Answer Here

Understanding of Plant and System Responses

1. Were there instances where your indications either helped or hindered you interpretations of plant status and conditions? (Identify the indications and how did they help or hinder?)

Type Answer Here

Adherence to and Use of Procedures

1. Were there areas in the procedures that were ambiguous or difficult to apply for the conditions you encountered during the event? (Identify the procedure and the area [e.g. step #].)

Type Answer Here

2. Were there situations where you found it challenging to implement procedures as written? (Identify the procedure and the area [e.g. step #].)

Type Answer Here

3. In your judgment, were there situations that the correct procedure was not being utilized? (Identify the procedure.)

Type Answer Here

Control Board Operations

1. Did you find any control actions challenging to execute in this event? (Which ones?)

Type Answer Here

2. What in your opinion makes these control actions challenging or difficult? (Controls/indications not fine enough?)

Type Answer Here

3. Did you make any mistakes or are there activities where mistakes are more likely to occur?

Type Answer Here

Crew Operations

1. Were there any time(s) that you were confused about the decisions or direction being taken during the event?

Type Answer Here

2. How did you contribute to the decisions and directions of the crew’s actions?

Type Answer Here

3. Were you aware of the procedures and the course of action or goals of the supervisor?

(How were you made aware of these?)

Type Answer Here

4. How were the crew resources managed and directed during the event?

4a. In your judgment were crew resources effectively managed and were there any wasted operations?

Type Answer Here

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NRCMD 3.7

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(See instructions on the reverse)

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11. ABSTRACT (200 words or less)

Data from nuclear power plant (NPP) simulator environments reflect important aspects of human performance and potentially the causes of human error. However, the information collected is constrained by the uniqueness of each particular plant and design of each particular simulator study. Thus, the ability to apply the findings of a given simulator study to other studies of human performance at NPPs is often limited. A well-defined approach to experimental design, a common language or measurement technique for describing and classifying errors and human actions, and an associated theoretical underpinning for the design and resulting statistical analyses are required to allow extrapolation of the results of simulator studies across plant designs, crew make-ups, and scenarios.

The purpose of this report is: to propose an approach for collecting human performance data from NPP simulators and employing the reliability engineering (RE) concept of limit state, to describe the process for collecting data, and to present illustrative examples of data analyses. This approach borrows from techniques applied in traditional RE while using experimental techniques derived from the behavioral sciences.

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