

# Modeling and Quantification of Team Performance in Human Reliability Analysis for Probabilistic Risk Assessment

Jeffrey C. Joe<sup>a\*</sup> and Ronald L. Boring<sup>a</sup>

<sup>a</sup>Idaho National Laboratory, Idaho Falls, USA

---

**Abstract:** Probabilistic Risk Assessment (PRA) and Human Reliability Analysis (HRA) are important technical contributions to the United States (U.S.) Nuclear Regulatory Commission's (NRC) risk-informed and performance based approach to regulating U.S. commercial nuclear activities. Furthermore, all currently operating commercial nuclear power plants (NPPs) in the U.S. are required by federal regulation to be staffed with crews of operators. Yet, aspects of team performance are underspecified in most HRA methods that are widely used in the nuclear industry. Furthermore, there are a variety of "emergent" team cognition and teamwork errors (e.g., communication errors) that are 1) distinct from individual human errors, and 2) important to understand from a PRA perspective. The lack of robust models or quantification of team performance is an issue that affects the accuracy and validity of HRA methods and models, leading to significant uncertainty in estimating human error probabilities (HEPs). This paper describes research designed to model and quantify team dynamics and teamwork within NPP control room crews for risk informed applications, thereby improving the technical basis of HRA, which improves the risk-informed approach the NRC uses to regulate the U.S. commercial nuclear industry.

**Keywords:** HRA, PRA, Teams, Operating Crews.

---

## 1. INTRODUCTION

All currently operating commercial NPPs in the U.S. are required by the Code of Federal Regulations [10 CFR 50.54(m)] to be staffed with crews of operators. There are also a variety of "emergent" team cognition and teamwork errors (e.g., communication errors) that are 1) distinct from individual human errors, and 2) important to understand from a PRA perspective. That is, failures at the team level, such as Groupthink [1] and other failures in team cognition, are an emergent phenomenon (i.e., these errors cannot be made by an individual working alone; they can only occur when teams are working together), and can be significant contributors to plant risk. Team errors have been documented as contributing factors for a number of major industrial accidents. Both the Three Mile Island and Chernobyl NPP accidents had team errors (e.g., lack of team situation awareness, groupthink during problem solving and decision-making, and failure to do independent verifications) as causal factors. Similarly, Gladwell [2] attributes the crash of Korean Air flight 801 to the first officer and navigator being unwilling to challenge an error the captain made (i.e., the 'power distance' gap between the leader and subordinates was too large, leading to a break down in communication). Had these teams recognized how dysfunctional team dynamics can impact individual, team, and overall system performance, and implemented an approach to mitigate their effects, the severity of these accidents would have likely been attenuated, and could have possibly been avoided altogether.

Issues with teamwork, and especially accidents caused by failures in teamwork, have prompted a considerable amount of human factors research. One of the earliest efforts was Crew Resource Management [3], though a number of other researchers have since made significant contributions to the field [4, 5]. A number of additional researchers have also studied nuclear power plant operating crews and the challenges they encounter [6, 7, 8, 9, 10, 11], but none of this research has been done within the specific context of informing HRA and PRA. Some HRA methods do consider team cognition and teamwork [12, 13], but are not widely used, in part due to the fact that they are relatively new and complex methods. Most current HRA models focus on performance shaping factors (PSFs)

---

\* Corresponding Author: [Jeffrey.Joe@inl.gov](mailto:Jeffrey.Joe@inl.gov)

that affect the individual's cognition (e.g., how stress, procedures, and fitness for duty affect diagnosis and action, or alternatively, detection, sensemaking, decision-making, and action). Little effort has focused on team cognition and teamwork (i.e., the thinking and actions of the team), or the PSFs that affect team cognition and teamwork (i.e., quality of leadership, leadership style, awareness of what others on the team are thinking and doing, social pressure to conform, etc.). Given that crews operate commercial NPPs, HRAs examining individual cognition and errors may be, depending on what needs to be modeled and understood, at the wrong 'level of analysis'.

This 'level of analysis' issue can be further exacerbated by the fact that PRA models typically count the success or failure of the human at the team level. If one member of the crew fails at a task, but another member of the crew is able to recover, PRA counts this recovery as a successful human action. Thus, in the context of PRA for commercial NPPs, it may be more appropriate for HRA to model errors committed by humans at the team level. Furthermore, given that both 1) the maturity of conduct of operations in NPPs and 2) training guidelines provided by industry entities, such as the Institute for Nuclear Power Operations (INPO), have provided guidance on how operating crews should work together, there is team performance information available that could be included in HRA. Given the two issues, it is somewhat puzzling that HRA has focused on mitigating individual errors and failures, and seemingly ignored team level issues.

This discrepancy in the 'level of analysis' with respect to how HRA and PRA model human errors is illustrated in Figure 1. The fault tree on the left is a generic model of how human errors are modelled with the SPAR-H method [14]. The fault tree on the right is also based on SPAR-H, but models individual and team performance. This model of individual and team performance is at the same level of analysis that PRA models typically use to model human and/or team success or failure. However, most of the widely used HRA methods do not explicitly model human error within the context of working in teams.

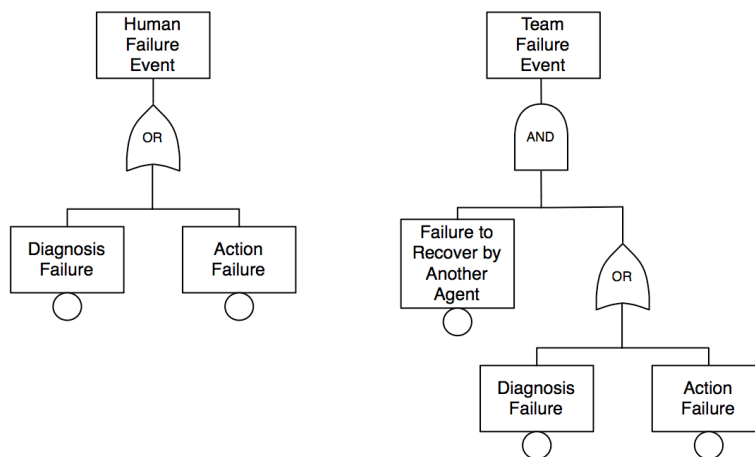


Figure 1. Fault trees showing how the logic changes when modeling individual and team level failures.

Examples of events that involve team performance issues relevant to PRA include:

1. Where an individual error (e.g., slip, lapse, mistake, etc.) manages to propagate through training and the rigorous crew conduct of operations, and ultimately challenges plant safety,
2. Where different members of the crew have all drawn the same erroneous conclusion from the available information, and then collectively commit an error that challenges plant safety,
3. Where different members of the crew have drawn different conclusions from the available information, fail to resolve the discrepancy (leading to outcomes such as incorrect diagnosis), and then collectively commit an error that challenges plant safety,
4. Where the crew is presented with a rare and complex event (e.g., severe accident) that they are initially unable to address because the required diagnoses and subsequent actions are beyond written procedural guidance.

Clearly, all of these examples are more appropriately modeled with the team failure fault tree than the individual human failure fault tree in Figure 1. Moreover, the subsequent success or failure of the crew's diagnoses and actions for these examples, and the safety consequences of their performance, will depend greatly on their ability to work as a team in order to effectively utilize their combined operating experience and training, among other things, to overcome the challenges described in these four examples. Given these issues, it is apparent to us that a technically defensible approach that is also methodologically straightforward is needed in HRA and PRA to address how emergent team performance and team errors contribute to risk.

## 2. RESEARCH ACTIVITIES

Analytical and experimental research is needed to establish the technical basis for modeling and quantifying team performance for inclusion in HRA and PRA. Ideally, the research activities need to be well-grounded in basic human psychology, compatible with current and future PRA frameworks, not be labor-intensive, be resistant to misuse and misapplication, and applicable to all NPP contexts involving teams (e.g., full-power, shutdown, normal operations, severe accidents, etc.). To achieve these ideals, two analytical tasks that could be pursued are 1) the feasibility of modeling and quantifying team performance using standard PRA tools and techniques, and 2) a review of widely used HRA methods, including [14, 15, 16, 17], to determine the suitability of including an HRA at the team performance level in these methods. Follow on experimental research tasks that make use of microworlds, or part-task simulation could then be conducted. These three tasks are described in more detail below.

For the modeling and quantification task, the feasibility of using standard fault tree and event tree approaches to model and quantify aspects of team performance, as identified through various sources of information about the conduct of operations in commercial NPPs, should be explored. For example, one source of information on nuclear conduct of operations is through the review of various documents from INPO, such as [18, 19, 20]. The INPO guidance in these documents is well grounded on NPP operational experience from multiple commercial utilities in the U.S. (i.e., “good practices”), and is based on research that is informed by basic human psychology. By overlaying and applying the event and fault tree logic onto the principles for effective team performance formulated by INPO, such as effective communication, independent verification, and other good practices for the conduct of nuclear operations, the research results from this task can effectively model team performance issues that are significant contributors to overall plant risk.

For example, one of INPO’s “good practices” for NPP operators, which is also documented in [21], is to use three-way communication. According to [19]:

The person originating the communication is the sender and is responsible for verifying that the receiver understands the message as intended. The receiver makes sure he or she understands what the sender is saying. First, the sender gets the attention of the receiver and clearly states the message. Second, the receiver repeats the message in a paraphrased form, which helps the sender know if the receiver understands the message. During this exchange, the receiver restates equipment-related information exactly as spoken by the sender. Third, the sender informs the receiver whether the message is properly understood, or corrects the receiver and restates the message. (pg. 17)

This approach to effective communication can be modeled using event and fault trees. Figure 2 shows the three-way communication approach modeled as an event tree, thereby showing the progression of various success and accident sequences. Note, however, that these event trees have been augmented to include more explicitly the team aspects of communication that are implied in three-way communication.

### Three-way Communication

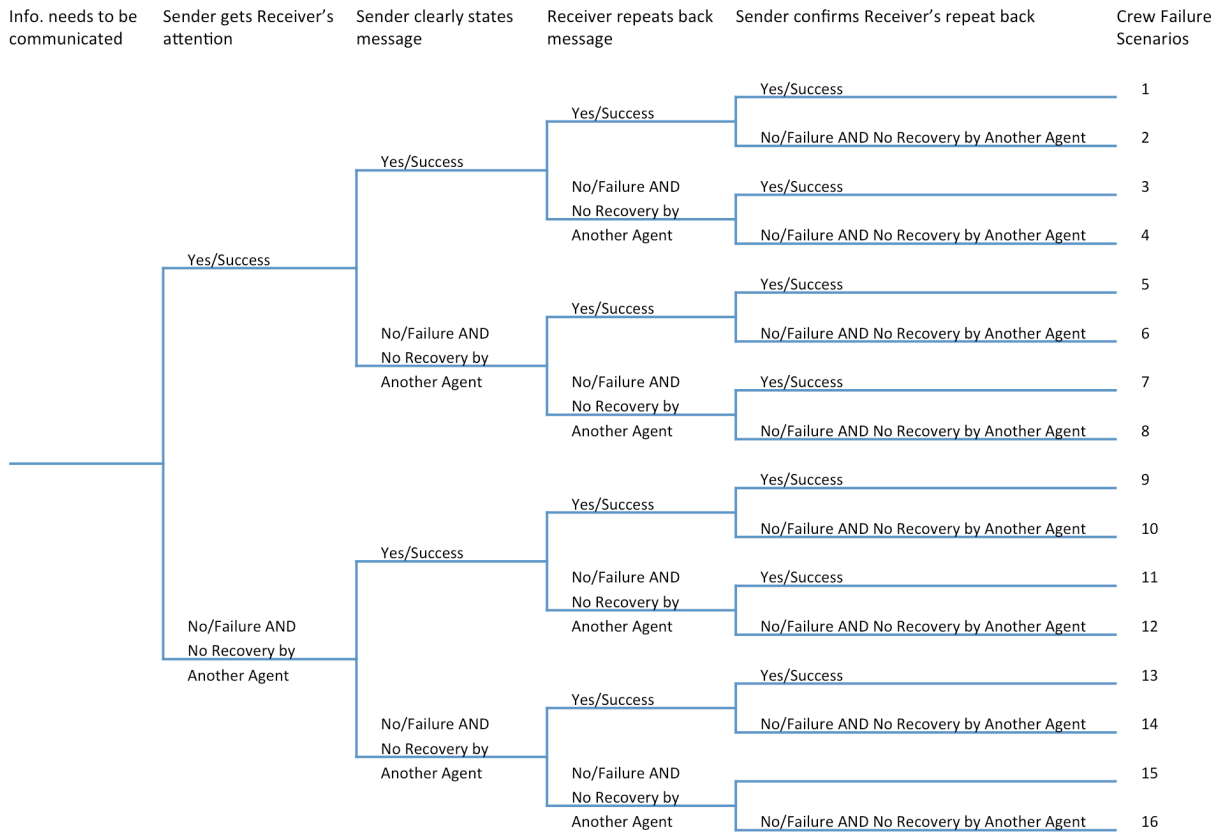


Figure 2. Event tree for three-way communication

Figures 3a-3d shows example fault trees that model some of the credible events and PSFs, which contribute to three-way communication failures. Note that not all possible events and PSFs are depicted in these fault tree examples.

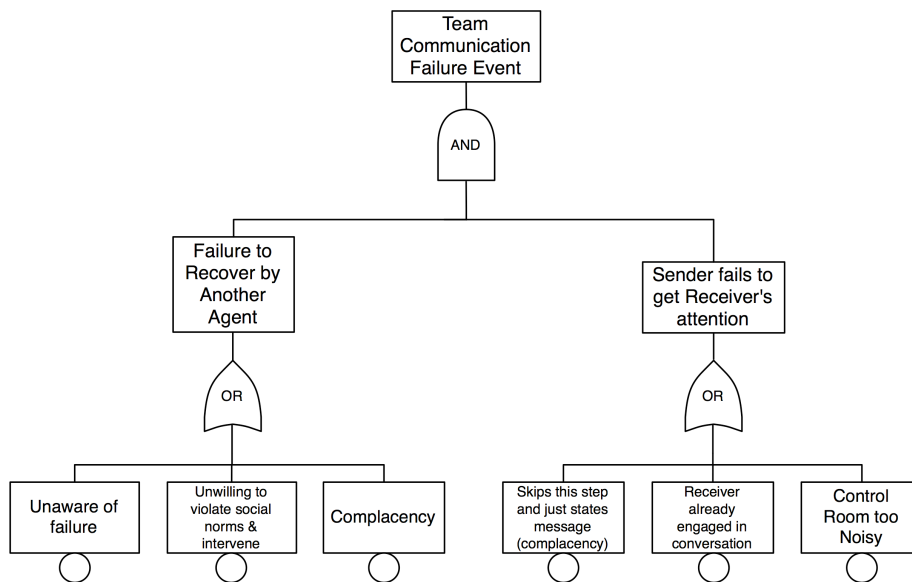


Figure 3a. Fault tree example for sender fails to get receiver's attention

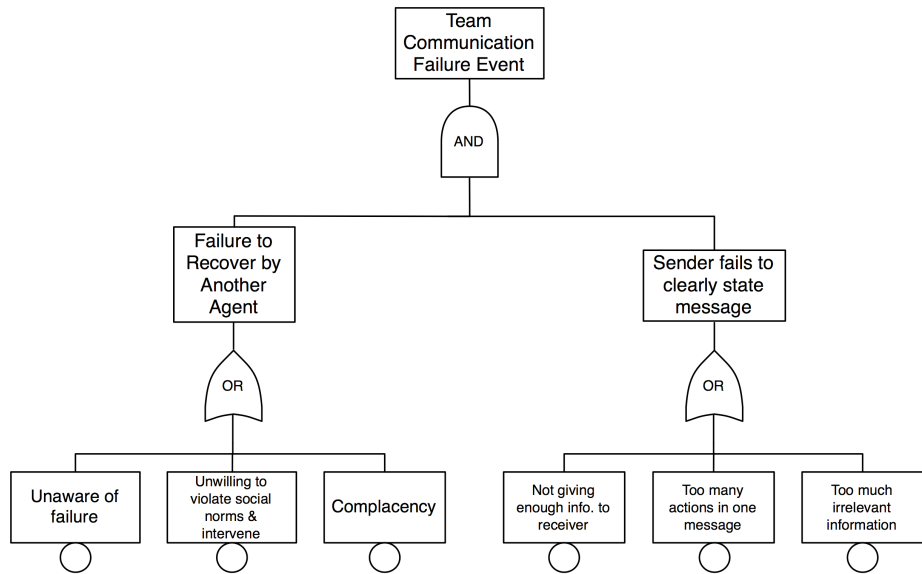


Figure 3b. Fault tree example for sender fails to clearly state message

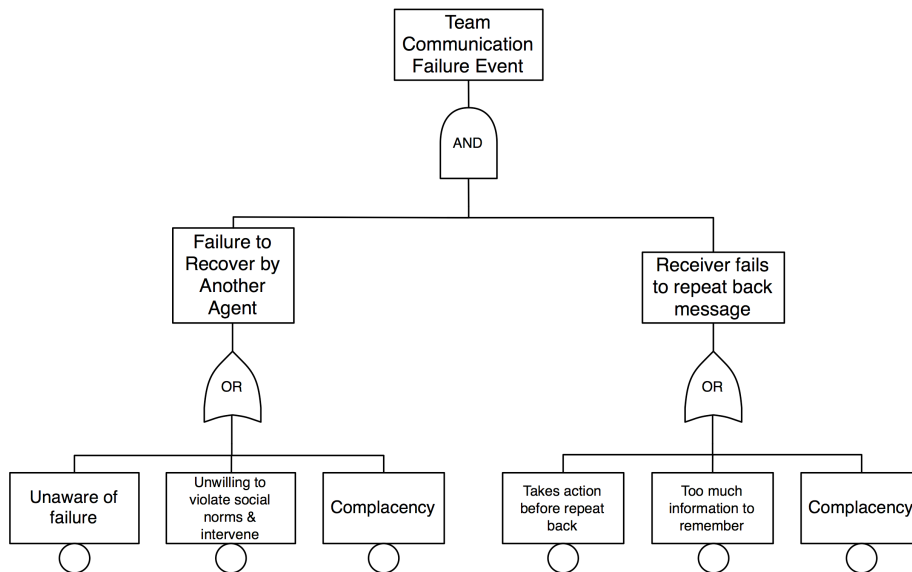


Figure 3c. Fault tree example for receiver fails repeat back

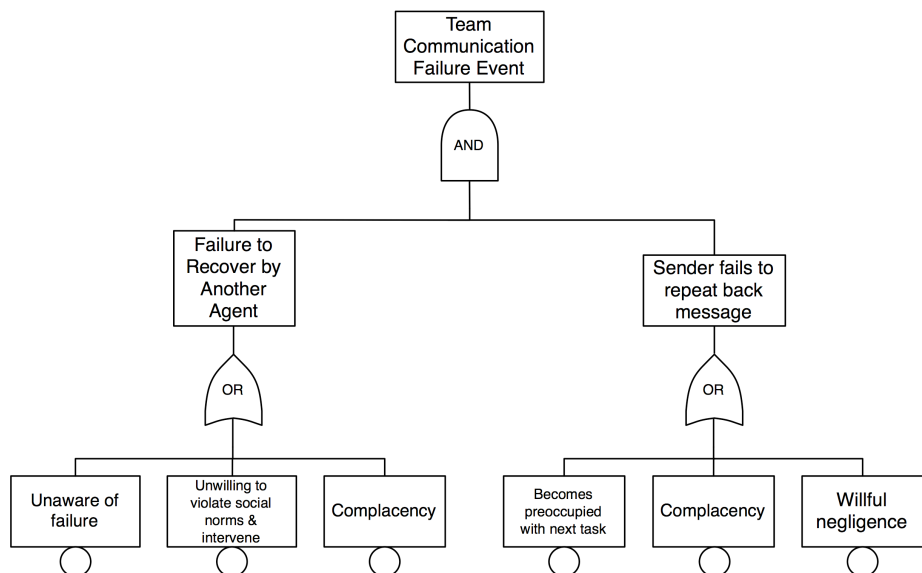


Figure 3d. Fault tree example for sender fails repeat back

Figures 2 and 3 show how it is feasible to model team performance in commercial NPPs in event and fault trees. Given that this is just one example from one information source (e.g., INPO), additional research to model other team aspects of commercial nuclear power's conduct of operations (e.g., independent verification and peer checking) that are obtained from relevant sources of information is needed in order to determine more completely whether team performance can be modeled using standard HRA and PRA tools. Other team errors (e.g., leadership/supervision errors), as described in [22], also need to be investigated for their risk significance across all operating modes in NPPs (e.g., full-power, shutdown, normal ops, severe accidents, etc.).

In order to assess how receptive existing HRA methods are to the inclusion of modeling and quantifying team performance, a literature review of those methods must be conducted. For those methods that can accommodate modeling and quantifying team performance, a technical basis for their inclusion needs to be established. In the event that no existing widely used HRA methods can accommodate team performance modeling and quantification, then work to develop a stand-alone team-level HRA method that will use 'best' practices [23], and tie in the most critical aspects of individual cognition that have a direct bearing on team cognition and teamwork should be performed. An example of such a stand-alone augmentation of existing HRA methods was recent work to address human reliability factors in fires [24]. While it is preferable to work within the framework provided by existing HRA methods, most HRA methods do not allow extension, and it is sometimes necessary to cover unique facets of human and team behavior under separate methods and aggregate them at the PRA level.

The experimental research task could make use of microworlds, or part-task simulation, to conduct proof-of-principle studies to validate the hypotheses that team performance issues are 1) emergent and different from individual performance issues, and 2) measurable contributors to risk. The results of this experimental research would help establish the technical basis that HRA methods can meaningfully model and quantify risk emanating from team performance issues. Microworlds have traditionally been used to assess individual operator performance, but research should expand on current microworld research platforms such as the one developed at the Idaho National Laboratory and University of Idaho [25] to assess group tasking and team performance. Early phase research could involve developing a crew framework representative of traditional crews (e.g., Reactor operator, Balance-of-plant/Turbine operator, Senior Reactor operator, Shift Technical Advisor), while later research would study crew performance using advanced digital instrumentation and control systems in traditional and nontraditional crew configurations, such as multi-modular reactor operations being proposed by small modular reactor (SMR) vendors. Previous research has suggested operators working on advanced digital workstations may tend to lose sight of the big picture and experience a breakdown in traditional three-way communication protocols (e.g., the keyhole effect documented in [26]). Human operators working as a team with automated agents is also a new concept for the operation of SMRs that will likely have some risk significance [27]. In short, the risk implications of a breakdown in teamwork in advanced control rooms are an important topic of research.

Additionally, as the NRC uses PRA and HRA to inform their risk-informed approach to regulating advanced NPPs, this research could leverage research conducted at places such as the Halden Reactor Project. Halden's simulator research to develop advanced control room instrumentation and control systems (e.g., large overview displays), which are designed to address team performance issues (e.g., team situation awareness) in a manner applicable to HRA and PRA, among other things, and their experience and subject matter expertise in running crews of NPP operators in simulators should provide important insights into team performance challenges in advanced control rooms.

In summary, more HRA related research is needed to address the effect of emergent team performance issues on overall plant risk. This research needs to focus on the modeling and quantification of team errors, which result from the interactions of individual crewmember errors, but also explicitly includes the possible recovery actions by other crewmembers or agents. Furthermore, by using fault and event trees to model and quantify team performance, and by using microworlds to validate the results, the

subsequent team HRA method's products and results should meet the ideals described above, including compatibility with current and future PRA frameworks, and applicability to all NPP contexts involving teams (e.g., full-power, shutdown, normal ops, severe accidents, etc.).

### 3. CONCLUSION

Aspects of team performance are underspecified in most HRA methods that are widely used in the nuclear industry. The lack of robust models or quantification of team performance is an issue that affects the accuracy and validity of HRA methods and models, leading to significant uncertainty in estimating HEPs.

The objective of this research is to model and quantify team dynamics and teamwork (i.e., "team performance") within NPP control room crews for risk informed applications. We believe analytical and experimental research needs to be conducted to establish the technical basis for modeling and quantifying team performance for inclusion in HRA and PRA. Analytical work could begin with modeling and quantifying team performance. Experimental research could make use of microworlds, or part-task simulation, to conduct proof-of-principle studies to validate the hypotheses that team performance issues are 1) emergent and different from individual performance issues, and 2) measurable contributors to risk. In short, this research would establish the technical basis that HRA methods can meaningfully model and quantify risk emerging from team errors such that the epistemic uncertainty associated with their current under-specification would be minimized. The benefits of this research will be the improvement of the state-of-the-practice for HRA and PRA, which in turn supports an effective nuclear regulator that helps assure the safety and reliability of modern nuclear technologies.

### Acknowledgements

INL is a multi-program laboratory operated by Battelle Energy Alliance LLC, for the United States Department of Energy under Contract DE-AC07-05ID14517. This work of authorship was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately-owned rights. The United States Government retains, and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof. The INL issued document number for this paper is: INL/CON-14-31339. The lead author also thanks Allison C. Joe for her help in preparing this article.

### References

- [1] I. Janis, "*Groupthink: Psychological Studies of Policy Decisions and Fiascoes*," Wadsworth Cengage Learning, 1982, Boston.
- [2] M. Gladwell, "*Outliers: The Story of Success*," Brown and Company, 2008, New York.
- [3] B. Kanki, R. Helmreich, and J. Anca, "*Crew Resource Management*," Academic Press/Elsevier, 2010, San Diego.
- [4] E. Salas and S. Fiore, "*Team Cognition: Understanding the Factors that Drive Process and Performance*," American Psychological Association, 2004, Washington, DC.

- [5] C. Bowers, E. Salas, E., and F. Jentsch, *“Creating High-Tech Teams: Practical Guidance on Work Performance and Technology,”* American Psychological Association, 2005, Washington, DC.
- [6] J. Park, W. Jung, and J. Yang, *“Investigating the Effect of Communication Characteristics on Crew Performance Under the Simulated Emergency Condition of Nuclear Power Plants,”* Reliability Engineering and System Safety, 101, 1-13 (2012).
- [7] S. Kim, J. Park, and S. Byun, *“Crew Resource Management Training for Improving Team Performance of Operators in Korean Advanced Nuclear Power Plant,”* In IEEE International Conference on Industrial Engineering and Engineering Management (IEEE IEEM), 2055-2059, (2009).
- [8] Y. Chung, W. Yoon, and D. Min, *“A Model-Based Framework for the Analysis of Team Communication in Nuclear Power Plants,”* Reliability Engineering and System Safety, 94(6), 1030-1040, (2009).
- [9] P. Carvalho, M. Vidal, and E. de Carvalho, *“Nuclear Power Plant Communications in Normative and Actual Practice: A Field Study of Control Room Operators' Communications,”* Human Factors and Ergonomics in Manufacturing, 17(1), 43-78, (2007).
- [10] J. O'Hara and E. Roth, *“Operational Concepts, Teamwork, and Technology in Commercial Nuclear Power Stations,”* In C. Bowers, E. Salas, and F. Jentsch (Eds.) *Creating High-Tech Teams: Practical Guidance on Work Performance and Technology.* American Psychological Association, 2005, Washington, DC.
- [11] E. Roth, R. Mumaw, and P. Lewis, *“An Empirical Investigation of Operator Performance in Cognitively Demanding Simulated Emergencies,”* (NUREG/CR-6208). U.S. Nuclear Regulatory Commission, 1994, Washington, DC.
- [12] Y. J. Chang and A. Mosleh, *“Cognitive Modeling and Dynamic Probabilistic Simulation of Operating Crew Response to Complex System Accidents Part 1: Overview of the IDAC Model,”* Reliability Engineering and System Safety, 92, 997-1013, (2007).
- [13] A. Mosleh and M. Azarkhil, *“Dynamic Behavior of Operating Crew in Complex Systems: An Object-Based Modeling and Simulation Approach,”* University of Maryland Center for Risk and Reliability technical report, (2013).
- [14] D. Gertman, H. Blackman, J. Marble, J. Byers, and C. Smith, *“The SPAR-H Human Reliability Analysis Method,”* (NUREG/CR-6883). U.S. Nuclear Regulatory Commission, 2005, Washington, DC.
- [15] A. Swain and H. Guttman, *“Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications (THERP), Final Report,”* (NUREG/CR-1278). U.S. Nuclear Regulatory Commission, 1983, Washington, DC.
- [16] Electric Power Research Institute, *“An Approach to the Analysis of Operator Actions in Probabilistic Risk Assessment, Final Report,”* (EPRI TR 100259), 1992, Palo Alto, CA.
- [17] S. Cooper, J. Wreathall, C. Thompson, M. Drouin, and D. Bley, *“Knowledge-base for the New Human Reliability Analysis Method: A Technique for Human Error Analysis (ATHEANA),”* (BNL-NUREG-63256). Brookhaven National Lab, 1996, Upton, NY.
- [18] Institute of Nuclear Power Operations, *“Verification Practices: Process Description,”* (INPO AP-931), 2004, Atlanta, GA.



- [19] Institute of Nuclear Power Operations, *“Human Performance Tools for Workers: General Practices for Anticipating, Preventing, and Catching Human Error During the Performance of Work,”* (INPO 06-002), 2006, Atlanta, GA.
- [20] Institute of Nuclear Power Operations, *“Human Performance Reference Manual,”* (INPO 06-003), 2006, Atlanta, GA.
- [21] U.S. Department of Energy, *“Human Performance Improvement Handbook: Human Performance Tools for Individuals, Work Teams and Management,”* (Vol. 2; DOE-HDBK-1028-2009), 2009, Washington, DC.
- [22] A. Whaley, J. Xing, R. Boring, S. Hendrickson, J. Joe, and K. Le Blanc, *“Building a Psychological Foundation for Human Reliability Analysis,”* (NUREG-2114). U.S. Nuclear Regulatory Commission, 2014, Washington, DC.
- [23] A. Kolaczowski, J. Forester, E. Lois, and S. Cooper, *“Good Practices for Implementing Human Reliability Analysis (HRA),”* (NUREG-1792). U.S. Nuclear Regulatory Commission, 2005, Washington, DC.
- [24] S. Lewis and S. Cooper, *“Methodology for Low Power/Shutdown Fire PRA,”* (NUREG-1921). U.S. Nuclear Regulatory Commission, 2012, Washington, DC.
- [25] R. Boring, D. Kelly, C. Smidts, A. Mosleh, and B. Dyre, *“Microworlds, Simulators, and Simulation: Framework for a Benchmark of Human Reliability Data Sources,”* Joint Probabilistic Safety Assessment and Management and European Safety and Reliability Conference, 16B-Tu5-5, (2012).
- [26] D. Woods, E. Roth, W. Stubler, and R. Mumaw, *“Navigating Through Large Display Networks in Dynamic Control Applications,”* Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 34(4), 396-399, (1990).
- [27] J. Joe, J. O’Hara, H. Medema, and J. Oxstrand, *“Identifying Requirements for Effective Human-Automation Teamwork,”* Proceedings of the 12th International Conference on Probabilistic Safety Assessment and Management (PSAM 12, Paper #371), (INL/CON-14-31340), 2014, Honolulu, HI.