Profiles of Human Performance Contributions to Operating Events

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Background

In response to a need to better understand how human performance influences the risk associated with nuclear power plant operations, the U.S. Nuclear Regulatory Commission (NRC) Office of Research (RES) requested work at the Idaho National Engineering and Environmental Laboratory (INEEL) to identify and characterize the influences of human performance in significant operating events. The INEEL used the Accident Sequence Precursor (ASP) program to identify events associated with high-risk sequences and Standardized Plant Analysis Risk (SPAR) models to calculate measures of risk associated with human performance in those sequences.

Risk Analysis Methodology

The ASP program methodology calculates the conditional core damage probability (CCDP) of operating events. Quantification of risk measures is based on event trees developed for each of the nine different design classes of commercial nuclear power plants in the U.S. The INEEL developed SPAR models using the SAPHIRE PRA code. The current version used to support this project is the ASP/SPAR Rev. 2QA models. Only events with a CCDP value equal to or greater than 1.0E-5 were analyzed in this study because they were deemed to be risk significant. In addition to analysis of plant risk, other source materials such as licensee event reports (LERs) are available for all events analyzed. In some instances, augmented inspection team (AIT) reports – a more detailed and thorough description of the event gathered through plant visit(s) by NRC – are also available.

The ASP/SPAR models do not currently cover all plant conditions applicable to some of the events that were analyzed in this study. For such events, qualitative analysis only was performed and important human performance influences noted.

Event Selection and Analysis

Forty-seven operating events were identified for analysis. Eleven events had little or no human performance influence and were not analyzed further. Thirty-six operating events were analyzed in detail. SPAR models exist for 23 of these events; the other 13 operating events have been the subject of qualitative analysis.

The events selected for analysis had relatively high ASP CCDPs, were investigated by NRC, and had human performance as an important contributor. Of the 23 quantitative analyses performed, 6 were for boiling water reactors (BWRs) and 17 were for pressurized water reactors (PWRs). For the other 13 events, two qualitative analyses were performed on events at BWRs; the remaining 11 analyses were performed on events that occurred at PWRs. A team consisting of a plant systems and SPAR analyst, a human factors and human reliability analyst (HRA), and a plant operations subject matter expert (SME) reviewed the events and reached consensus regarding performance influences. Based upon work by Reason (1990), influences were characterized as either latent (i.e., having occurred earlier but influencing the event in some manner) or active (i.e., having functioned as either the initiator or otherwise compromised mitigation or recovery action in some manner). As a result of the analyses, a number of quantitative results and human performance insights were produced. Table 1 summarizes the human performance influences that were observed in operating events.

Table 2 summarizes the results of analyses performed to evaluate the effect of human performance on risk in these operating events. A link was clearly demonstrated quantitatively and qualitatively between human performance and risk. For quantitative analyses, in several operating events the risk factor increase (RFI)[1] did not meet the significance criteria that we established. For the others, the dynamic range for the RFI was from 2.3 to 2.48 E4 demonstrating the significant departures from PRA base cases. The calculated CCDPs ranged from a high of 5.2E-3 to a low of 2.6E-05.

Table 1. Performance failure categories, subcategories, error type and error frequency for significant events (1.0E-5 or greater) (N=37).

Description	**Errors**	
	Latent	Active
Operations		
Command and control issues including crew resource management	5	14
Failure to follow safe practices	1	
Inadequate knowledge or training	14	4
Incorrect operator actions	3	7
Communications	7	2
Continue to Operate During Unstable Conditions	1	2
Design and design change work process		
Design deficiencies	27	
Design change testing	7	
Inadequate engineering evaluation	13	
Ineffective indications for abnormal condition	1	
Configuration management	9	1
Maintenance work process		
Poor work package preparation, QA and use	14	
Inadequate maintenance practices	20	2
Inadequate technical knowledge	4	
Inadequate post-maintenance testing	14	
Procedural design and development process		
Inadequate procedures	19	2
Learning and corrective action program		
Failure to respond to industry and internal notices	11	
Failure to follow industry operating practices	2	
Failure to identify by trending and problem reports	13	
Failure to correct known deficiencies	15	
Management oversight		
Inadequate supervision	12	5
Inadequate knowledge of plant systems and plant requirements	2	1
Organizational structure	1	
Subtotals	215	40

Table 2. Results of SPAR analyses ranked by event importance.

Analysis No.	ASP Reference and Screening Basis Value	Facility	Event Date	LER and AIT Numbers	SPAR Analysis CCDP	Risk Factor Increase (CCDP/CDP)	Event Importance (CCDP-CDP)	Human Error Percent Contribution to Event Importance
					Risk Importance Measures			
1	2.1E-04	Wolf Creek 1	01/30/96	482-96-001	5.2E-03	24,857.0	5.2E-03	100
2	2.1E-04	Oconee 2	10/19/92	270-92-004	3.2E-03	86.5	3.2E-03	100
3	1.2E-04	Perry 1	04/19/93	440-93-011	2.1E-03	242.1	2.1E-03	100
4	2.2E-04	Oconee 2	04/21/97	270-97-001	7.1E-04	2.5	4.3E-04	100
5	NA	Hatch	01/26/00	2000-002	4.1E-03	400.0	4.1E-03	100
6	1.3E-05	Limerick 1	09/11/95	352-95-008	4.8E-04	9.8	4.3E-04	100
7a	2.0E-04 b	Indian Point 2	08/31/99	AIT 50-246/99-08	3.5E-04	25.0	3.4E-04	100
8	9.3E-05	McGuire 2	12/27/93	370-93-008	4.6E-03	2.4	2.7E-04	82
9	2.1E-04	Robinson 2	07/08/92	261-92-013, 261-92-017, and 261-92-018	2.3E-04	4.2	1.8E-04	100
10	6.5E-05	Haddam Neck	06/24/93	213-93-006, 213-93-007; AIT 213/93-80	2.0E-04	4.3	1.5E-04	48
11	1.8E-05	River Bend 1	09/08/94	458-94-023	1.2E-04	2.5	1.2E-04	100
12	3.2E-05	Oconee 1, 2, and 3	12/02/92	269-92-018	1.5E-04	125.0	1.5E-04	100
13	1.8E-04	Sequoyah 1 and 2	12/31/92	327-92-027	1.1E-04	14,103.0	1.1E-04 c	100
14	5.5E-05	Beaver Valley 1	10/12/93	334-93-013	6.2E-05	10,690.0	6.2E-05 c	100
15	NA 4	Dresden 3	05/15/96	249-96-004	2.6E-05	15.3	2.4E-05	100
16	1.1E-04	St. Lucie 1	10/27/97	335-95-005	3.8E-05	2.9	2.5E-05	100
17	4.6E-05	Seabrook 1	05/21/96	443-96-003	3.E-05	2.3	2.5E-05	100
18	6.5E-05 e	Comanche Peak 1	06/11/95	445-95-003 and 445-95-004	1.9E-05	146.2	1.9E-05 c	10
19	6.0E-05	Arkansas Nuclear One Unit 2	07/19/95	368-95-001	1.4E-05	73.7	1.4E-05	100
20	5.6E-04 f	Arkansas Nuclear One Unit 1	05/16/96	313-96-005	9.6E-06	50.5	9.4E-06	100
21	3.7E-05	D. C. Cook 1	09/12/95	315-95-011	3.3E-05	1.2	4.9E-06	80
22	1.3E-04	LaSalle 1	09/14/93	373-93-015	4.5E-05	1.07	3.0E-06	100
23	7.7E-05	Millstone 2	01/25/95	336-95-002	2.6E-05	1.04	1.0E-06	100

Event Profile Analysis

Analyses were also conducted to determine whether there were common groupings of human failures present during events. Statistical cluster analysis identified four groupings that accounted for 55% of the events reviewed in this study. Table 3 identifies the events associated with the four profile groups.

Three of the four profile groups contained concurrent maintenance and design failures. The first event group contained a core of design and maintenance failures (5 events); the second contained a core of design, maintenance, and operations failures (6 events. The third group contained 5 events with additional operations and corrective action program failures and the fourth grouping contained 4 events with additional operations, procedures, and corrective action program failures. In a number of cases, multiple failures were associated with the same system, e.g., the maintenance work package and worker knowledge for industry practices regarding breaker maintenance were both lacking, leading to human errors that caused breaker failures. Potential trends in each event group are discussed.

Group 1.

This group included a core of design and maintenance failures. These failures are summarized below.

Group 1 - Design and Maintenance Failures

- Failures were generally related to design and maintenance on the same equipment, component, or system
- Work package and design problems were a factor in the majority of these events
- Failures were primarily latent
- Failures affected plant equipment outside the control room
- Events occurred at different power modes and at different times of day
- Concurrent failures occurred
- Operations failures did not play a role in these events

Group 2

The second event group contained six significant operating events. This group also contained aspects of maintenance and design failures. What made this group of events unique from the other groups was the inclusion of Operations failures. Design and maintenance failures are discussed in more detail in the Group 1 discussion. The insights from operations failures present in Group 2 events are presented below.

Group 2 - Operations Failure Insights

- There were almost twice as many latent failures as active failures
- Control room knowledge was inadequate regarding activities conducted outside the control room in the majority of events
- Operations-related communications deficiencies existed in most of these events
- All events occurred at power, implicitly making these failures serious
- Active failures primarily involved licensed operators
- Concurrent failures occurred

Group 3

This group also contained aspects of maintenance and design failures. What made this group of events unique from the other groups was the presence in each event of both operations and corrective action program failures. The insights from corrective action program and operations failures are presented below.

Group 3 Insights - Corrective Action Program and Operations

- Failures to correct known deficiencies were present in half of these events
- Failures to trend problems were found in over half of these events
- All involved equipment failures that occurred outside the control room
- All but one event occurred at power
- Operations induced failures had both active and latent effects

Table 3. Event Groupings by Cluster Analysis Methods

Group 1 – Design and Mainenance	**Group 3 - Design, Maintenance, Operations, Corrective Actions**
Catawaba 1996	Arkansas Nuclear 1 1996
Comanche Peak 1995	Dresden 3 1996
Limerick 1 1995	Fort Calhoun 1992
Oconee 1, 2, & 3 1999	Haddem Neck 1993
Robinson 1992	McGuire 2 1993
Group 2 - Design, Maintenance, and Operation	**Group 4 - Operations, Procedures, Corrective Action**
Beaver Vallley 1 1993	Indian Point 2 1999
Calvert Cliffs 2 1994	Oconee 3 1997
Catawba 1993	Salem 1 1994
Oconee 2 1992	Wolf Creek 1994
River Bend 1994	
Wolf Creek 1996	

Group 4

This group contained concurrent operations, procedures and corrective action program failures. There was no discernable pattern regarding human failures in terms of design or maintenance. The insights from the pattern of operations, procedures, and corrective action failures are presented below.

Group 4 Insights - Concurrent operations, procedures and corrective action failures.

- These events occurred while the plant was at different modes of power (e.g., at power, shutdown, and shutting down)
- Control room errors were committed
- Command and control problems were evident for all events in this group
- Inadequate knowledge and training of operations personnel contributed to most events
- Procedural deficiencies were identified in operations, maintenance and emergency activities
- Procedures were either inadequate or non-existent for some activities
- Failures to correct pre-existing, known deficiencies were present in most events

Findings

A number of findings have been drawn regarding the influence of human performance on significant operating events and risk. These are summarized below.

Effect of Human Performance

Human performance was found to be a major contributor to the risk increases in significant operating events. In the samples studied, SPAR models have shown increases ranging from 10% to 100%. The human performance contribution to CCDP was positively skewed with an average of 90%.

Latent Failures

Latent failures from a variety of sources were important and significantly affected events. Latent contributions to events were noted more than active contributions by a factor of five. This is similar to other recent studies (Reason 1998; Gertman *et al*., 1998). Latent failures were noted in all facets of performance studied.

Multiple Human Failures

All operating events involved multiple human failures. Events such as loss of offsite power or loss of coolant that challenged the plant contained a concatenation of failures. On average, the 37 events contained four or more human failures in combination with hardware failures. Many events contained between six and eight latent human failures. These failures were diverse, and included factors such as failure to enforce standards, lack of quality assurance during procedure writing, duties and responsibilities not clearly understood during events, failure to trend and address previous problems, and failure to test after equipment malfunctions.

Recurrent Problems

A significant number of events demonstrated evidence of failure to monitor, observe, or otherwise respond to negative trends, industry notices, or design problems. This suggests that weaknesses in licensee corrective action programs may play an important role in influencing operating events.

Relationship to Individual Plant Examination (IPE)

The IPEs (see NUREG-1560) primarily account for the human contribution to plant risk through operator actions in response to upset plant conditions. This is a legitimate source of risk. For example, three common event sequences segments - (1) switch to recirculation, (2) feed and bleed, and (3) depressurization and cooldown - were determined to be important in all PWR analyses. In this study, latent maintenance failures such as maintenance and work process factors were identified as important sources of risk in operating events. The extent to which these latent failures contributed to plant risk is not well documented in IPEs.

Combining of Human Performance Problems

All operating events were the result of multiple contributing factors. The manner in which they contributed to produce events is not well understood by analysts. It would be beneficial to develop an understanding of the common cause mechanisms underlying human–system and human–human dependencies. Failure rate information regarding the concatenation of smaller failures into events is non-existent. It would also be beneficial to determine the linkages between these failures and to generate failure rates for use in HRAs and PRAs. For active contributing failures, the important factors included command and control, correctness of actions, and adequacy of supervision. Latent contributing factors included problems in design, engineering evaluations, work package preparation, maintenance practices, supervision, and failure to correct known deficiencies. Inadequate technical knowledge for maintenance and operations also contributed to events.

Summary

Findings from this work underscore the significant contribution human performance makes to nuclear power plant risk. Most of the ASP events analyzed contained elements that were related to human performance and failures in work processes. These human performance elements, in conjunction with other failures, contributed to significant increases in plant risk over the nominal, base case risk estimates. In nearly all cases, a number of latent failures combined with concurrent hardware failures and active human errors to produce these risk increases. The Individual Plant Examinations do not currently document these kinds of failures well, either in terms of the ways they occur or their extent of occurrence.

A number of insights have been derived from studies of failures that occurred across events that may prove useful to the reactor oversight process. First, deficiencies were identified in design and maintenance work practices in the majority of events. Such failures are almost entirely latent, preceding the operating event in time. Hence, they may also be detectable before an event occurs. Since the core of most operating event profiles involved design and maintenance failures, improvements in inspection processes that improve detection of such failures may be important for reducing certain kinds of events, or at least reducing their severity. Shortcomings in licensee corrective action programs were also observed in many operating events. Such programs are reviewed through the Problem Identification and Resolution Procedure. In some events, the technical knowledge of operators and maintenance personnel was judged to be weak for the systems or evolutions in the plant based on their performance. The NRC has inspection modules in many areas in which deficiencies in performance were identified in this study. The results of this work may serve to inform future revisions of such inspection modules to improve upon their ability to identify such deficiencies before they have the opportunity to contribute to future operating events.

Most of the current generation of Human Reliability Analysis (HRA) methods used in Individual Plant Examinations are not well suited to identifying or modeling the complex latent errors that occurred in these events. As a part of efforts that address future HRA needs, such failures should be considered.

Finally, the profiles of human failures identified through this work suggest a degree of complexity and subtlety that should be addressed to reduce the frequency and severity of future operating events. Events consisted of a number of contributors. The contributors were from diverse sources and combined in ways that were difficult to predict and observe. As a result, plant personnel who were responsible for incident response at the time of the events may not have been aware of the causes of the failures. This, in turn, complicates diagnosis, response planning, and mitigation efforts. Efforts to reduce the effect of human error on plant safety need to consider such factors in order to produce prevention and mitigation strategies that are robust to such effects.

References

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[1] The RFI is the event CCDP divided by the nominal (base) case CDP. The CDPs are SPAR peer-reviewed baseline PRA models, the CCDP is a reflection of the event scenario being evaluated.