QUALITATIVE PRA INSIGHTS FROM SEISMIC EVENTS

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ABSTRACT

Probabilistic risk assessment (PRA) oriented reviews of historical operational events can help identify potential gaps where improved approaches can increase analysis realism. This report documents the results of an exploratory project reviewing seismic events affecting nuclear power plant (NPP) operations through the full range of induced hazards (e.g., ground motion, displacement, fires, floods). Observations regarding human and organizational factors, seismic/fire interactions, and reactivity effects reinforce the importance of an integrated, multidisciplinary approach to seismic PRA.

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ABBREVIATIONS AND ACRONYMS

AC	alternating current
ACRS	Advisory Committee on Reactor Safeguards (NRC)
ADAMS	Agencywide Documents and Management System (NRC)
AFW	auxiliary feedwater
ANS	American Nuclear Society
AOT	Allowed Outage Time
ASME	American Society of Mechanical Engineers
ATWS	anticipated transient without scram
BWR	boiling water reactor
CCDP	conditional core damage probability
CCW	component cooling water
CDF	core damage frequency
CETC	core exit thermocouple
CEUS	central and eastern United States
CFM	cognitive failure mode
CRDM	control rod drive mechanism
CSNI	Committee for the Safety of Nuclear Installations (OECD/NEA committee)
CST	condensate storage tank
DBE	Design Basis Earthquake
DC	direct current
DG	diesel generator
E-W	East-West (when referring to accelerations)
EAL	Emergency Action Level
ECCS	emergency core cooling system
EDG	emergency diesel generator
EOP	emergency operating procedure
EPRI	Electric Power Research Institute
EQ	earthquake
ESF	engineered safety feature
ETH	Eidgenössische Technische Hochschule (Swiss university)
FLEX	diverse and flexible mitigation strategies
FME	foreign material exclusion
FWST	fire water storage tank
GL	Generic Letter (NRC)
GSU	generator step-up
H	horizontal (when referring to accelerations)
HEAF	high energy arc fault
HFE	human failure event
HPSI	high-pressure safety injection
HRA	human reliability analysis
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
IDHEAS	Integrated Human Event Analysis System
ICES	INPO Consolidated Event System (proprietary)
IDAC	Information-Detection-Action-Crew
IEEE	Institute of Electrical and Electronics Engineers
IN	Information Notice (NRC)
INPO	Institute of Nuclear Power Operations

IPEEE	Individual Plant Examination of External Events
IPSSS	Indian Point Probabilistic Safety Study
IRS	Incident Reporting System (IAEA, proprietary)
ISFSI	Independent Spent Fuel Storage Installation
ITIC	International Tsunami Information Center
KE	knowledge engineering
LER	Licensee Event Report
LERF	large early release frequency
LFD	local fire department
LLNL	Lawrence Livermore National Laboratory
LLW	low-level waste
LOCA	loss of coolant accident
LOOP	loss of offsite power
LPI	low pressure injection
LPSI	low pressure safety injection
MCR	main control room
MDAFW	motor-driven auxiliary feedwater
MFW	main feedwater
MR	master relay
M_w	moment magnitude (indication of earthquake magnitude)
N-S	North-South (when referring to accelerations)
NAPS	North Anna Power Station
NEA	Nuclear Energy Agency (OECD)
NEI	Nuclear Energy Institute
NIS	nuclear instrumentation system
NISA	Nuclear and Industrial Safety Agency (Japan)
NM	New Mexico
NOAA	National Oceanic and Atmospheric Administration
NOUE	Notice of Unusual Event
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NSC	Nuclear Safety Commission (Japan)
NUREG	designation for publications prepared by NRC staff
NUREG/CR	designation for publications prepared by NRC contractors
OBE	Operating Basis Earthquake
OECD	Organization for Economic Cooperation and Development
OpE	operational experience
OL	Operating License
ONI	Off-Normal Instruction
PDA	primary disconnect assembly
PGA	peak ground acceleration
PIF	performance influencing factor
PM	preventive maintenance
PRA	probabilistic risk assessment
PSA	probabilistic safety assessment
	Probabilistic Safety Assessment (ANS conference)
PSAM	Probabilistic Safety Assessment and Management (conference)
RCP	reactor coolant pump
RCS	reactor coolant system
RES	NRC Office of Nuclear Regulatory Research
RIDM	risk-informed decision making

RPS	reactor protection system
RWST	refueling water storage tank
SBO	station blackout
SECY	designation for NRC staff papers to the Commission
SEL	Seismic Equipment List
SFP	spent fuel pool
SFPE	Society of Fire Protection Engineers
SI	safety injection
SME	subject matter expert
SMiRT	Structural Mechanics in Reactor Technology (conference)
SNSWP	Standby Nuclear Service Water Pond
SS	stainless steel
SSC	systems, structures, and components
SSE	Safe Shutdown Earthquake
SSPS	Solid-State Protection System
TDAFW	turbine-driven auxiliary feedwater
TEPCO	Tokyo Electric Power Company
TSC	technical support center
UAT	unit auxiliary transformer
UE	Unusual Event
UPS	uninterruptable power supply
USGS	U.S. Geological Survey
UTC	Coordinated Universal Time
V	vertical (when referring to accelerations)
WGRISK	Working Group on Risk Assessment (OECD/NEA/CSNI working group)
WNA	World Nuclear Association
WUS	western United States

1. BACKGROUND

As described by SECY-18-0060 [1], the U.S. Nuclear Regulatory Commission (NRC) is seeking to increase its use of risk information in support of regulatory decision making. In support of this initiative, it is important to ensure that supporting probabilistic risk assessment (PRA) studies for nuclear power plants (NPP) provide treatments of the various contributing hazards, including seismic events, that are sufficiently realistic for the decisions at hand. PRA-oriented reviews of historical operational events involving these hazards can help identify and prioritize potential gaps where improved models, methods, tools, and/or data can improve analysis realism. Examples of such reviews are provided by NUREG/CR-6738 [2], which looks at fires, an exploratory study of storms and flooding events [3], and in numerous papers following the March 2011 Fukushima Daiichi reactor accidents (e.g., [4, 5]).

In addition to supporting the improvement of PRA models, operational experience reviews can provide an empirically oriented point of view on key hazards that complements the decomposition-logic view of PRAs. In a risk-informed environment, the broadened perspective from these different points of view can be useful to decision makers as well as analysts. Thus, as the NRC staff changes with personnel knowledgeable of past events leaving the agency, associated knowledge management activities, including "active learning" exercises involving reviews of events and the development of "smart search" tools as well as more conventional activities (e.g., training courses, seminars), are becoming increasingly important. In late 2018, encouraged by the lessons of the previously mentioned study on storms and flooding events [3], staff in the NRC Office of Nuclear Regulatory Research (RES) initiated an exploratory data mining project looking at historical seismic events.

This report documents the results of the project. It is an expansion of a conference paper that presented some of the early project results [76]. Some of the conclusions of this report are based on information from proprietary sources. That information can be found in a proprietary version of this report [80].

2. OBJECTIVES AND SCOPE

The objectives of the project were as follows:

- Identify insights regarding seismic PRA methods, models, tools, and data potentially useful for seismic PRA analysts, reviewers, and/or developers.
- Provide an educational experience for the authors that supports NRC's risk-informed initiatives.
- Identify lessons regarding the mining of seismically related operational experience that might be useful in the development of advanced knowledge engineering (KE) tools.[1]

The project considered the full range of hazards (e.g., ground motion, displacement, fires, floods) induced by seismic events. However, as an exploratory project, the project scope was limited to seismic events affecting NPP operations. In particular:

- The project did not address seismic operational experience involving discoveries of plant conditions (perhaps identified by inspections) that can degrade a plant's response to a seismic event.
- The project did not address seismic effects on non-reactor facilities.
- The seismic engineering community routinely looks at hazard and fragility lessons from seismic events (e.g., [6-16]). The project's focus, therefore, was on the third major element of seismic PRA: plant response analysis.

It should be emphasized that the project was neither an attempt to engage in post-event fault finding nor an exercise to characterize the conditional likelihoods of key failures during postulated earthquakes. The focus was on identifying qualitative lessons for future PRA use and development.

[1] At the start of this project, the original objective was framed in terms of "intelligent search tools." Recognizing that there are many tools that go beyond finding information, we broadened the objective to include "knowledge engineering tools." Advanced knowledge engineering tools include such things as "content analytics" tools, a broad class of software tools that use a variety of approaches (e.g., natural language queries, trends analysis, contextual discovery, and predictive analytics) to identify patterns and trends across an unstructured database (e.g., text). See Chapter 8 for further discussion.

3. APPROACH

The project team started with three members with combined expertise in general PRA methods development and seismic fragility analysis. These team members are quite familiar with seismic PRA (e.g., as reviewers), but do not consider themselves to be experts in the performance of seismic PRA. As the project progressed, the team added staff with expertise in human reliability analysis (HRA) and fire PRA.

The project employed a straightforward two-step process to develop insights. First, the team performed a literature search to identify candidate events for detailed review. This search involved the use of the NRC's Licensee Event Report (LER) search system (https://lersearch.inl.gov/Entry.aspx), the International Atomic Energy Agency's (IAEA) proprietary Incident Reporting System (IRS) (https://irs.iaea.org), the Institute of Nuclear Power Operations (INPO) proprietary INPO Consolidated Event System (ICES) (https://apps.inpo.org/xICES), a publicly accessible event database developed and managed by Eidgenössische Technische Hochschule (ETH) Zürich (http://www.er.ethz.ch/nuclear-energy.html) [17], and various publicly available documents that were identified through typical web search strategies. These latter documents included seismic analysis guidance documents [7, 18] as well as industry trade publications (e.g., [19]). As indicated earlier, the focus was on actual seismic events, as opposed to seismically relevant degraded plant conditions (e.g., as identified during inspections and reported through LERs).

To provide appropriate caveats on the project results, it is important to recognize the following.

- Most of the seismically-induced transients identified in the search were relatively minor events for which little detailed plant response information is readily available. Many of the detailed insights reported in this paper are therefore based on lessons from three well-documented events: the July 16, 2007 Niigataken Chuetsu-oki Earthquake that involved the Kashiwazaki-Kariwa NPP, the March 11, 2011 Great East Japan Earthquake that involved multiple NPPs, and the August 23, 2011 Mineral, Virginia Earthquake that involved the North Anna NPP.[2]

- As a scoping study, we did not attempt to develop a comprehensive event database in the spirit of that described by Ref. 17, nor did we exhaustively review the voluminous literature on Fukushima Daiichi.[3]

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[2] For brevity, the remainder of this report uses "Kashiwazaki-Kariwa" to refer to the events associated with the 2007 Niigataken Chuetsu-oki Earthquake, "3/11" to refer to the 2011 Great Eastern Japan Earthquake, "Fukushima Daiichi" to refer to the 2011 Fukushima Daiichi reactor accidents, and "North Anna" to refer to the events associated with the 2011 Mineral earthquake.

[3] Note that some of the authors have performed more extensive (but still not exhaustive) reviews in support of Refs. 4 and 5.

4. GENERAL OBSERVATIONS

The project's literature search has identified 50 earthquakes that:

- affected power operation (e.g., by triggering a reactor trip);
- could have affected power operation but didn't (e.g., events that might have triggered a reactor trip but didn't because the plant was not yet operating or was already shutdown for other reasons);
- were large but were documented as having little or no actual effect on NPPs in the general region.

The last category of events was included in case there was useful information to be gleaned.

In addition, the project has reviewed information on a small number of severe earthquakes for which reports provide useful information on earthquake effects but little or no information about NPP impacts.

The full set of events reviewed is provided in Appendix A. It is important to note that the appendix, which draws upon information from multiple documents, is a synthesis and initial compilation of information that we consider adequate for the needs of the project. However, the data have not been peer reviewed and should not considered to be authoritative. Additional verification of the information and associated revision of the notes will be necessary for uses other than those for this project.

Note also that Appendix A includes a number of earthquakes for which we did not find explicit mention of effect (or non-effect) on an NPP. (These earthquakes are not included in the final tally of 50 events.)

Table 1 provides some summary statistics for the 50 earthquakes. It should be emphasized that this table only characterizes the project dataset. Given the exploratory nature of the project, it should not be used as quantitative basis for decision support.

Based on available documentation for the earthquakes in our dataset, we make the following general observations.

- A number of earthquakes have exceeded the NPP's Operating Basis Earthquake (OBE) and/or Safe Shutdown Earthquake (SSE) for at least part of the response spectrum.[4] In a number of cases, this occurred before the plant had started commercial operation. Note that per Refs. 7 and 20 and empirical experience, simple exceedance of the OBE/SSE is not necessarily a good indicator of actual damage. In our project, OBE/SSE exceedance is only an indicator of an event of potential interest for deeper review.

[4] Note that the OBE and the SSE have different regulatory roles. The OBE is used to establish shutdown following an earthquake event and other operational parameters such as fatigue thresholds. The SSE is a design parameter to protect against onset of damage for the SSCs.

Table 1. Summary Statistics for 50 Reviewed Earthquakes (1975-2019)

	Japan	Outside Japan
Earthquakes		
Earthquakes exceeding then-current OBE or SSE	3	7
Earthquakes with large aftershocks ($M_w > 6$)[a]	4	3
Earthquakes felt at multiple sites	7	9
Earthquakes causing at least one reactor trip[b]	8	3
Reactor Effects		
Seismically-induced reactor trips[c]	24	9
Seismically-induced "complicated transients"[d]	12[e]	8

[a] A somewhat arbitrary value chosen solely for illustrative purposes.
[b] Excludes events where trip signals were triggered but the reactor was already shutdown.
[c] Includes trips due to causes other than local ground motion (e.g. seismically-induced tsunamis or offsite grid damage causing loss of offsite power – LOOP).
[d] A subset of seismically-induced reactor trips. For the purposes of this report, a "complicated transient" involves a reactor trip and potentially significant additional failures (e.g., LOOP, challenges to ultimate heat sink, failures requiring significant offsite resources in response).
[e] Eleven of these transients occurred on March 11, 2011.

- The highest peak ground accelerations (PGA) reported were for Kashiwazaki-Kariwa. Per Ref. 21, these were in the free-field and near the foundation levels. Both of these foundation level PGAs were less than 1.0g. (Values around 0.88g were reported from a downhole array in the proximity of the Unit 1 Reactor Building.) At the ground surface, a PGA of about 1.25g was reported in the proximity of Unit 5.

- Some of the larger earthquakes had large (moment magnitude – M_w – greater than 6.0[5]) aftershocks. For one event (3/11), the main shock was preceded by a number of large foreshocks. One event (Kashiwazaki-Kariwa) was followed by an independent, large earthquake (M_w 6.8) some distance away. The potential PRA-significance of multiple shocks is discussed in Section 5.1.

- Earthquakes affecting one unit on a site generally affected other units at the same site. (In some cases where a multi-unit impact is not indicated, it is not clear from the event description if the other units were already shutdown.)

- Ten earthquakes affected operations (e.g., through the triggering of some alert level) at multiple sites, some of which were separated by significant distances. It appears that only two of these ten events (the 1999 Chi Chi earthquake in Taiwan and the 3/11 event) involved a system response (e.g., reactor trip) at multiple sites. The 3/11 event, which

[5] See Note a for Table 1. Depending on a variety of factors (including NPP distance from the earthquake epicenter), a shock with M_w less than 6.0 can affect the plant. For example, the North Anna main shock was magnitude 5.8. Detailed information on earthquakes (whether) fore-, main, or aftershock, can be found using the U.S. Geological Survey's (USGS) online Earthquake Catalog: https://earthquake.usgs.gov/earthquakes/search/.

affected the Fukushima Daiichi, Fukushima Daini, Onagawa, Tokai, and Higashidori sites – the last two separated by over 500 km – is the only event involving serious challenges across multiple sites.

- None of the earthquakes reviewed appear to have damaged major mitigating systems (e.g., emergency diesel generators – EDG, emergency core cooling systems – ECCS, auxiliary feedwater – AFW) via ground motion. Most onsite equipment losses and other complications (e.g., debris, heavy smoke) during 3/11 were caused by induced hazards, namely seismically-induced tsunamis and fires. Note that per post-3/11 interviews [22]:
    - it is possible that the earthquake damaged air lines needed to operate an air-operated containment vent valve at Fukushima Daiichi;
    - operators had to consider the possibility that the earthquake had damaged fire protection lines inside of buildings that they were trying to use to provide cooling water to the reactors.[6]

- A few earthquakes resulted in very low (0.01 to 0.03g) PGAs at the plant but nevertheless triggered reactor trips or safety system actuations (for shutdown plants).

- In at least two cases (Onagawa 1, 1993; North Anna 1 and 2, 2011), reactor trips were caused by neutron flux readings rather than ground motion detectors.

- Beyond 3/11, other earthquakes causing "complicated transients"[7] are as follows. (See Appendix A for more details.)
    - Chi Chi (Taiwan) Earthquake (1999) – failure of 345 kV transmission line offsite led to grid instability and automatic shutdown of Chinshan 2-3 and Kuosheng 1-3. The onsite PGAs (less than 0.05g) were significantly smaller than the OBE (Chinshan: 0.15g; Kuosheng: 0.20g) [14].
    - Sumatra-Andaman Earthquake (2004) – tsunami flooding and debris failed seawater pumps, complicating shutdown of Madras 2 [31].
    - Kashiwazaki-Kariwa (2007) – an onsite large transformer fire at Kashiwazaki-Kariwa 3 (caused by differential ground subsidence) led to complications in event response. Ground movement also ruptured an underground pipe, leading to some reactor building flooding [78].[8] The maximum onsite PGAs at the foundation levels were around 0.88g in the free field and 0.69g in reactor building basements [23].

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6 Interestingly, based on observations from Kashiwazaki-Kariwa, the plant manager thought such damage was unlikely. However, he knew he had to consider the possibility.

7 See Note c for Table 1.

8 The earthquake damaged an external, buried fire suppression system pipeline. Water soaked into the ground and entered the reactor building through a penetration. Water accumulated in the basement of the radwaste portion of the building, overwhelming the building sump pumps, leading to a water level of 48 cm [79].

- North Anna (2011) – the earthquake induced both reactor trip and LOOP at North Anna 1 and 2. The reactor trips were due to high neutron flux rate; the LOOP was due to actuation of sudden pressure relays for multiple transformers (i.e., due to ground motion but not actual damage). The spectral accelerations exceeded the OBE and design basis earthquake (DBE). However, post-event walkdowns and inspections found no significant physical or functional damage to safety related structures, systems, and components (SSCs) [24]. These appear to be the only seismically-induced commercial NPP reactor trips in the U.S. (Appendix B provides a listing of LERs from the period 1980-2014 that include the search terms “earthquake” and “reactor trip.”)

- There has been at least one earthquake that, to a non-expert, would appear to have had more damage potential had circumstances (e.g., epicenter location, plant status) been somewhat different. This is the 1993 Hokkaido-Nansei-Oki earthquake (near the Tomari NPP). It appears that there was a 4-5 m tsunami in the vicinity of the plant (per data from Ref. 53) but no effect on plant operations [19]. Per Ref. 53, the tsunami runups were 7-9 m some 45-60 km down the coast. However, recognizing the importance of bathymetry, we do not know if a slightly different epicenter location would have resulted in a significantly larger tsunami at the plant.

5. DETAILED OBSERVATIONS AND INSIGHTS

It is well recognized that, in addition to causing SSC failures by ground motion, earthquakes can influence the progression of an accident scenario by affecting plant operators and/or by causing induced (sometimes called secondary or consequential) hazards such as seismically-induced fires and floods that, in turn, can cause additional SSC failures. Perhaps less well recognized within the NPP PRA community, earthquakes can also cause reactivity excursions that might trigger a class of scenarios (anticipated transients without scram – ATWS).

This section provides some PRA-relevant observations regarding these potential effects based primarily on the descriptions of the Kashiwazaki-Kariwa, 3/11, and North Anna events. Given that these events are several years old and have been extensively studied, some of the observations are not new or unique. Nevertheless, they are useful enough to bear repeating.

5.1 Human and Organizational Factors

In NPP PRAs, the influence of human and organizational factors on accident progression is modelled through human failure events (HFEs), i.e., basic events representing the failure of needed human actions. (In a few cases, inappropriate actions, called errors of commission, are also modelled.) The role of HRA is, as part of an integrated PRA effort, to identify which actions should be included in the PRA model, determine whether these actions are feasible under various conditions specified in the PRA model, and, if so, determine the likelihood of failure. The last step, typically referred to as "quantification," requires a qualitative analysis of the actions (What tasks need to be performed? What are the specific conditions of performance and how might these conditions affect performance?) as well as quantification.

The general principles of NPP HRA are agreed upon by the HRA community (e.g., see NUREG-1792 [25]), but there are many different HRA methods and models, and, consequently, a variety of ways of looking at operational experience. The following observations are organized following the Information-Detection-Action-Crew (IDAC) cognitive framework developed by Mosleh [26] and adapted by the NRC's Integrated Human Event Analysis System – General (IDHEAS-G) methodology [26]. This framework is based on five macrocognitive functions underlying human decision making and action.

As shown in Figure 1, performance of a broad action of interest in the PRA (e.g., depressurizing the reactor coolant system – RCS – to enable low pressure injection – LPI) involves a number of tasks. For each task, needed information must be detected and understood, an appropriate decision must be made, and appropriate action taken. Depending on the task, these macrocognitive functions can be accomplished by a single individual, by a team, by a larger organization, or even multiple organizations, and so coordination is important.

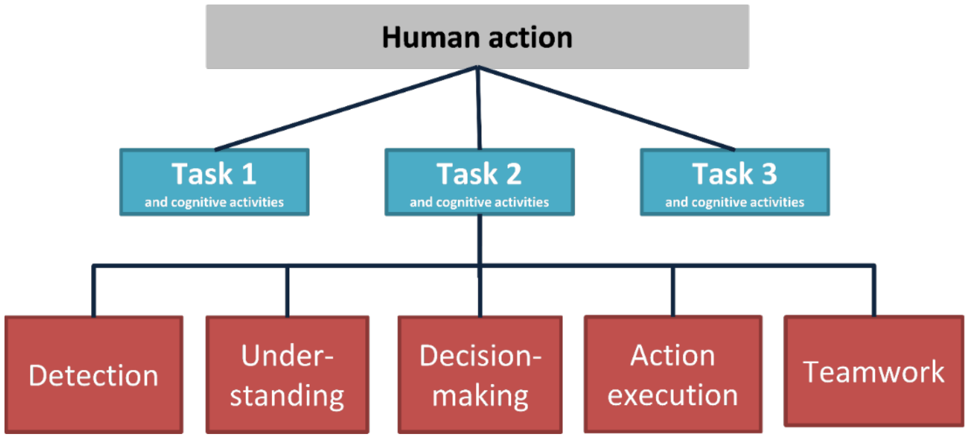

Figure 1. Macrocognitive Functions in IDHEAS-G [27]

The following observations are organized by macrocognitive function. Note that they are focused on impacts particularly relevant to seismic PRA. There are, of course, many more lessons (particularly from 3/11) regarding human and organizational lessons (e.g., [28-32]). HRA-specific lessons are also available in the literature (e.g., [4, 5]).[9]

5.1.1. Detection

The collection of needed information has been directly hampered by earthquake ground motions and/or induced hazards (e.g., flood, fire). The hazard impacts include:

- Unavailability of instrumentation and control (including the seismic event detection system)
- Spurious alarms
- Degraded and dangerous site conditions (e.g., debris, damaged roads, uncovered manholes, onsite flooding[10]) that hampered surveys and, in combination with loss of communication systems, delayed relaying of field information to decision makers

5.1.2. Understanding

The ability of the operating crew to understand plant status and event progression can be affected by a severe seismic event. In addition to the information issues mentioned above,

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9 Most HRA-related observations derived from the events of March 11 emphasize negative aspects. Given our interest identifying areas of potential PRA improvement, this paper has a similar emphasis. However, it should be recognized that, in spite of the enormous challenges facing operators, there were also significant human action successes (e.g., the prevention of damage to other reactor units, including Fukushima Daiichi Units 5 and 6).

10 Note that two workers died at Fukushima Daiichi while performing a field survey [29].

seismic events can raise stress levels and potentially impact cognitive processing. At Fukushima Daiichi, operators were highly stressed not only because of the deteriorating plant conditions but also because of concerns of offsite conditions affecting family, friends, etc. We note that operators were initially confident in their response to the earthquake shock but became increasingly stressed after the second tsunami struck and reactor units lost power.[11] However, at this point, we do not have clear evidence that stress affected operator understanding. Additional discussion is provided in Appendix C.

It should be recognized that such cognitive effects are not mentioned for the other seismic events reviewed in this project. However, in most cases, it can be reasonably assumed that the effects (if any) were minor, due to the minor ground motions at the site. Furthermore, in at least one case involving more severe shaking (North Anna), the effects also appear to have been minor, as evidenced by the Shift Manager's appropriate decision to enter the Emergency Action Level matrix despite the lack of indication from the Seismic Monitoring Instrumentation Panel (which had lost power). It would be interesting to investigate the reactions and performance of the operating crews at the Kashiwazaki-Kariwa plant during the 2007 earthquake, given the significant ground accelerations (greater than those experienced by Fukushima Daiichi on 3/11) and offsite damage caused by that earthquake.

5.1.3. Decisionmaking

Of the events reviewed, naturally the greatest decision-making challenges were posed by the multiple unit accidents at Fukushima Daiichi. Given the lack of preparation and resources for such events, decision makers, particularly the Site Superintendent, had to decide upon and prioritize recovery activities (in a situation where key plant status information was unavailable). We note that tsunami warnings following the main earthquake shock apparently affected the superintendent's accident management plans, focusing concern on the potential loss of the seawater pumps (the plant's ultimate heat sink). This is an illustration of how the anticipation of seismically-induced events (whether or not they actually occur) might need to be considered in an HRA and is related to the topic of aftershocks discussed below.

It is worth noting that post-event interviews (e.g., [22]) indicate the Site Superintendent's lack of confidence in available accident management plans, due to the view that these plans focused on scenarios triggered by internal events and did not cover the ongoing, seismic-/tsunami-triggered conditions:

> *"Yoshida [the Site Superintendent] was asked if he opened up the accident management manual and used it as a reference. He said he never referred to it or even opened it up.*
>
> *He explained how ineffective measures thought up by people beforehand can be. Yoshida also explained that nuclear plants in Japan were designed with priority*

[11] The staff at the Emergency Response Center "was lost for words at the ongoing unpredicted and devastated state" [28].

placed on internal factors leading to malfunctions. He went on to explain that no thought was given to malfunctions occurring simultaneously at a number of plants due to external factors, such as tsunami, tornado, a plane crash or an act of terrorism."

Based on our reading of the record, most of the decision-making challenges during 3/11 appear to have been due to the knock-on effects of the earthquake and tsunami (notably the loss of all power and subsequent losses of equipment and indications), and not literally the earthquake (ground motion) and tsunami (inundation, dynamic forces, etc.) themselves. We can only speculate whether frustrations with the limited scope of pre-event planning affected the timing and nature of specific decisions.

5.1.4. Action Execution

As discussed earlier, onsite conditions induced by the seismic shock and induced hazards hampered the performance of needed actions. In addition to debris and flooding at Fukushima Daiichi[12] and road damage at both Kashiwazaki-Kariwa and Fukushima Daiichi, the following are worth noting.

- Access system failure (loss of power to a security gate) at Fukushima Daiichi
- Heavy smoke from a high energy arc fault (HEAF) at Onagawa on 3/11
- Multiple major aftershocks and tsunami warnings at Fukushima Daiichi

Regarding aftershocks and warnings, these are important because of associated concerns with worker safety: a) delayed the initiation of needed activities (e.g., plant damage surveys), and b) interrupted ongoing work activities.

Although not seismic-specific, it is interesting to note that understaffing played a role during the Kashiwazaki-Kariwa event (the earthquake occurred on a national holiday) as well as during the Fukushima Daiichi reactor accidents. In the latter case, self- and directed evacuation of some onsite personnel contributed to the lack of organizational knowledge (e.g., operation of equipment, location of items).

5.1.5. Teamwork

Coordination challenges arose during responses to the Kashiwazaki-Kariwa and 3/11 events. The following are noteworthy from the standpoint of seismic PRA.

[12] One fire truck was carried away by the tsunami; another was unable to reach other parts of the plant because of road damage.

- For Kashiwazaki-Kariwa, the arrival of the local (offsite) fire department was delayed. Given the scale of offsite destruction caused by the earthquake, it seems possible that offsite needs for emergency services played a role in this delay.

- For 3/11, this was a regional event with widespread impact on national infrastructure and emergency response systems (including a key offsite emergency response center as well as communications[13]).

- For 3/11, coordination difficulties also arose due to the involvement of multiple offsite organizations which demanded information and provided suggestions and directions. Such difficulties are not unique to seismic events but could have been amplified by the regional scale of the event (which is characteristic of a major earthquake).[14]

Note that the IDHEAS-G methodology has more detailed structure underlying the five macrocognitive functions used to structure our observations. Two key elements of this detailed structure are cognitive failure modes (CFMs) and performance influencing factors (PIFs). Table 2 maps our observations from the reviewed seismic events to IDHEAS-G's "mid-level" CFMs and PIFs. (Appendix D provides a complete list of the IDHEAS-G CFMs and PIFs.[15])

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13 The Off-site Center (OFC) at Okuma, some 5 km away from Fukushima Daiichi, was initially non-functional due to loss of normal power, loss of emergency power (the diesel generator fuel transfer pump was damaged by the earthquake), limited staffing (due to transportation network damage and heavy traffic congestion), and loss of primary telecommunications systems. A Vice Minister who was supposed to lead the OFC activities tried but was unable to leave the Tokyo area by car because of traffic congestion; he eventually had to take a military helicopter. [28]

14 From a positive standpoint, despite these coordination challenges, Fukushima Daiichi did receive assistance from offsite organizations, including less-affected NPPs

15 Appendix D provides draft descriptions of the CFMs and PIFs. Work to finalize these descriptions, including some rewording and re-categorization of PIF attributes is ongoing

Table 2. Mapping of Human Factors Observations to Mid-Level Cognitive Failure Modes (CFMs) and Performance Influencing Factors (PIFs)

Observation	Macrocognitive Function(s) and Applicable CFMs	Relevant PIFs
Unavailability of I&C (including seismic event detection)	**Detection** **Decisionmaking** D2 Fail to select, identify, or attend to sources of information DM3 Information is under-represented	pS2 human-system interface (HSI) pS3 equipment and tools pT1 information availability and reliability
Spurious alarms (e.g., fire alarms)	**Detection** **Action Execution** D1 Fail to establish the mental model for detection D3 Fail to perceive, recognize, or classify information E4 Fail to perform the planned action	pT2 multitasking, interruptions, and distractions
Degraded and dangerous site conditions (e.g., debris, road damage, unknown structural damage)	**Detection** **Action Execution** D2 Fail to select, identify, or attend to sources of information, E4 Fail to perform the planned action	pE1 accessibility/habitability of workplace including travel paths pE5 resistance to physical movement
Stress due to plant conditions and progressive loss of control	**Understanding** U3 Incorrect integration of data and mental model U4 Fail to iterate the understanding	pT5 time pressure and stress
Scenario dynamics (e.g., expectations of tsunamis after seismic shock)	**Decisionmaking** DM3 Information is under-represented DM5 Failure to simulate or evaluate the decision/strategy/plan	pT1 scenario familiarity

Observation	Macrocognitive Function(s) and Applicable CFMs	Relevant PIFs
Aftershocks (prompting precautionary measures as well as actual damage)	**Execution** E3 Fail to coordinate action implementation E4 Fail to perform the planned action	pE1 accessibility/habitability of workplace including travel paths pE3 noise in workplace and communication pathways pE5 resistance to physical movement pT6 physical demands
Offsite damage (local, including road damage)	**Teamwork** T1 Fail to establish or adapt the teamwork T6 Fail to implement decisions T7 Fail to control the implementation	pP1 staffing pP3 teamwork and organizational factors pE5 resistance to physical movement
Offsite damage (regional, including emergency response center damage)	**Teamwork** T2 Fail to manage information T3 Fail to maintain shared situational awareness	pP1 staffing pT1 information availability and reliability pP3 teamwork and organizational factors
Organizational interactions (e.g., demands for information, suggestions/directions for action; amplified for regional events)	**Teamwork** T4 Inappropriately manage resources T5 Fail to plan/make interteam decisions or generate commands	pT2 multitasking, interruptions, and distractions pT3 task complexity pT5 time pressure and stress

5.2 Seismic/Fire Interactions

In 1989, Sandia National Laboratories performed a Fire Risk Scoping Study (NUREG/CR-5088 [33]) that identified seven potential “seismic/fire interactions” based apparently on general principles and supported by non-nuclear seismic experience:

1. Cable pulling
2. Flammable liquid spills
3. Flammable gas release
4. Spread of fire from non-Category I SSCs
5. Failure of suppression systems
6. Spurious suppression actuation (leading to loss of suppressant inventory as well as SSC wetting)
7. Degradation of fire recognition and fire fighting in a post-earthquake environment (including spurious fire alarms, aftershocks, LOOP, loss of non-emergency lighting)

NPP operational experience in the 30 years since then provides examples for some of these interactions. It also introduces an interaction – seismically-induced HEAFs – not explicitly identified by the scoping study. The following discussion of observations is structured using a three-element fire PRA framework commonly used to describe fire PRA (e.g., [34, 35]). The elements are: fire initiation, fire-induced damage to SSCs (considering fire detection and suppression as well as fire growth), and plant response.

5.2.1. Fire Initiation

Seismically-induced fires occurred at Kashiwazaki-Kariwa and at Onagawa (on 3/11).

- Both events involved HEAFs.
    - The Kashiwazaki-Kariwa HEAF involved a large station (“house”) transformer at Unit 3. It was caused by differential ground subsidence leading to vertical displacement of the transformer relative to its secondary connection bus, leading to one or more ground and/or short circuit faults.
    - The Onagawa HEAF involved a non-emergency, 6.9 kV switchgear cabinet in the Unit 1 Turbine Building. It was caused by seismic shaking of Magne-Blast breakers, which have vertically oriented breaker stabs and are hung by buses in the cabinet (i.e., they are not fixed to the floor).

- No other seismically-induced fires have been reported for the Kashiwazaki-Kariwa and the 3/11 events.[16]

- Seismically-induced fires have not been reported in any of the other event descriptions reviewed.

We recognize the possibility that: (a) the project dataset might not include all significant seismic events involving NPPs, and (b) the reports reviewed (many of which are high-level summaries) might not mention induced or coincident fires if they are considered to be minor. Nevertheless, we think that for at least the PGA ranges observed, considering the large number of potential fire initiation sites at any NPP, a seismically-induced NPP fire at any specific initiation site is certainly possible but not highly likely.[17]

5.2.2. Fire Growth, Detection, and Suppression

Our observations regarding the extent of seismically-induced fires and associated fire-fighting efforts are as follows.

- At Kashiwazaki-Kariwa, the HEAF-induced fire involved leaking transformer oil from a failed bushing but did not spread further due to existing fire walls.

- At Onagawa, the HEAF-induced fire affected all ten sectors of the switchgear cabinet. It also involved some vertical cables rising from the cabinet but did not spread further.

- Dust re-suspended by seismic shaking led to spurious fire detection alarms at Kashiwazaki-Kariwa,[18] Onagawa, and Fukushima Daiichi.

- At Onagawa, dense smoke filled large portions of the Turbine Building and hindered identification of the fire location.

- Fire suppression efforts were affected by the previously discussed coordination issues and broken underground fire lines (at Kashiwazaki-Kariwa)[19] and damaged roads (at

[16] Reactor Building fires at Fukushima Daiichi Unit 4 apparently were initiated by a hydrogen explosion.
[17] A similar inference, with similar caveats, can be made considering non-nuclear industrial facilities with electric power components analogous to those at NPPs. See, for example, Ref. 12 which provides a photograph of damage caused by a seismically-induced fire at the Kobe Substation. From the information presented, it appears that the fire might have been due to fracturing of anchor bolts for a 275/77 kV 300 MVA transformer and subsequent transformer movement.
[18] This phenomenon is not mentioned in the Kashiwazaki-Kariwa documents in the project database but is mentioned in a report on 3/11 as something the Fukushima Daiichi shift supervisor knew about based on Kashiwazaki-Kariwa experience [28]. As with our discussion of seismically-induced fires, it should be cautioned that when an event report doesn't mention a particular phenomenon, this is not definitive proof that the phenomenon didn't occur.
[19] Interestingly, fire protection lines moved aboveground at Fukushima Daiichi as a result of the Kashiwazaki-Kariwa experience were exposed to and damaged by the tsunami on 3/11.

both Kashiwazaki-Kariwa and Onagawa). The Kashiwazaki-Kariwa fire lasted for 2 hours; the Onagawa fire lasted for 7 hours.

We note that within the U.S. and internationally, there are different strategies regarding reliance on onsite versus offsite fire brigades. These different strategies will likely lead to different firefighting challenges when responding to large scale events such as major earthquakes.

5.2.3. Plant Response

It does not appear that the seismically-induced HEAFs at Kashiwazaki-Kariwa and Onagawa, by themselves, led to major complications in plant response. Of course, in the case of the latter, the seismically-induced partial LOOP and the following (seismically-induced) tsunami provided significant challenges.

5.2.4. Comment – Seismically-Induced HEAFs

The HEAFs at Kashiwazaki-Kariwa and Onagawa did not have significant nuclear safety impacts. However, it is important to recognize that HEAFs can be safety-significant. A HEAF was a major contributor to a 2-hour station blackout at the Maanshan (Taiwan) NPP in 2001 [36],[20] and recent research activities have identified a HEAF-related damage mechanism (the creation of a cloud of conductive byproducts and particles) that, for certain plants, has the potential to affect SSCs outside of previously assumed zones of influence [37].

Current PRA standards (e.g., [38]) and guidance (e.g., [18, 39]) indicate there are significant challenges in quantitatively treating seismically-induced fires (including HEAFs) and rely heavily on walkdowns to qualitatively identify potential scenarios.

Given our observation of the potential significance of seismically-induced HEAFs, we have performed a quick review of 24 HEAF events (all non-seismically initiated) experienced by U.S. NPPs (see Appendix E). Our review identified several HEAF root causes (including loose or degraded connections, foreign material) that might be triggered or exacerbated by a seismic event. It is not clear if many of these root causes are readily identifiable by visual inspection conducted as part of a typical seismic PRA walkdown. However, HEAF-targeted preventative maintenance activities described in Ref. 39, including bolted connection torque checks, foreign material exclusion (FME) measures, stab connection thermography and corona tracking efforts would likely be effective.

5.3 Reactivity Effects

As indicated earlier in this report, two earthquakes in our dataset led to neutron-flux related reactor trips at Onagawa (1993) [19] and North Anna (2011) [41], rather than trips due to ground motion detection. (In the case of North Anna, the Seismic Monitoring Instrumentation Panel was

[20] Note that during the Maanshan event, heavy smoke from the HEAF was a key factor in preventing operator actions needed to terminate the SBO.

unavailable.) The fact that earthquakes have caused reactivity excursions: a) may not be widely recognized in the PRA community when considering the potential for ATWS, and b) might be an important observation in the development and analysis of new reactor designs.

Also relevant to ATWS, it is worth noting that post-event inspections at Kashiwazaki-Kariwa identified a stuck control rod at Unit 7 [42, 43]. (The rod was inserted but couldn't be withdrawn.)

6. INSIGHTS FROM EVENTS

6.1 Summary Insights

The large majority of the 50 events listed in Appendix A have had, at most, relatively minor impact on the operation of potentially affected NPPs. However, five earthquakes led to complicated (or at least non-routine) multi-unit and sometimes multi-site events and are of interest to seismic PRA modeling.

- 1999 Chi Chi (Taiwan) earthquake: affected Chinshan 2-3 and Kuosheng 1-3
- 2004 Sumatra-Andaman (Indian Ocean) earthquake and tsunami: affected Madras 1-2[21]
- 2007 Niigata Chuetsu-Oki (Japan) earthquake: affected Kashiwazaki-Kariwa 1-7
- 2011 Great East Japan earthquake and tsunami: affected Fukushima Daiichi 1-6; Fukushima Daini 1-4, Onagawa 1-3, Tokai Daini, and Higashidori 1-2
- 2011 Mineral (VA) earthquake: affected North Anna 1-2

Of specific interest, earthquakes (and subsequent induced hazards, particularly tsunamis and HEAFs) have caused:

- LOOP and (in the case of Fukushima Daiichi) SBO
- Degradation or loss of ultimate heat sink
- Damage (and concerns of potential damage), disruptions (e.g., due to aftershocks and tsunami warnings) and/or adverse environmental conditions (e.g., debris, smoke) affecting event recovery
- Seismically-induced reactivity excursions and associated reactor trips (i.e., reactor trips not caused by seismic ground motion detectors)

We observe that the above effects have occurred from events with onsite ground motions significantly less than the maximum values (on the order of 2-4g for Central-Eastern United States – CEUS – plants) considered by current seismic PRAs. (See Appendix F.)

We further observe that many non-seismically-induced HEAFs in U.S. plants have involved root causes that might be triggered or exacerbated by a seismic event.

Available project resources did not permit a formal comparison of these summary observations (and the detailed observations provided earlier in this chapter) against current seismic PRA standards and guidance. We expect that such a comparison would yield useful insights for the performance of seismic PRA.

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[21] Madras 1 was in cold shutdown and we have no information on the tsunami's effect. Based upon the general event description, it appears that various components and systems related to the plant's ultimate heat sink likely were affected.

6.2. Commentary: Seismic Community Viewpoint

Appendix F provides seismic CDF estimates from a number of historical and recent studies. The large uncertainties shown in the appendix illustrate the more general point that seismic risk estimates are subject to large uncertainties, with much of the uncertainty being attributed to seismic hazard estimates for severe earthquakes [18]. Despite these large uncertainties, there seems to be little concern within the seismic PRA community regarding the maturity of seismic PRA as a tool for practical decision support. Ref. 44 provides a recent affirmation in this regard.[22]

It's potentially instructive to contrast this situation with that facing the fire PRA community, where the maturity and realism of available methods, models, and tools have been hotly debated over the last several years [47, 48].[23] Since operational experience doesn't provide a useful benchmark for the ultimate results of a fire PRA (no fire-induced core damage accidents have yet occurred), critics have focused on intermediate results (e.g., the estimated frequency of fire-induced LOOP). These results appear to be larger than observed in operating plants. There are, of course, nuances and pitfalls associated with such comparisons – see Ref. 47 for detailed discussion. Nevertheless, we note that, some 50 years after Cornell's landmark paper on seismic risk analysis [49] and 40 years after the first-of-a-kind seismic PRA for Oyster Creek [50], a quantitative comparison of seismic PRA predictions with operational experience might usefully identify areas where improvements could support increased PRA realism. Such a comparison would supplement the qualitative exercise performed in this project.

[22] It should be recognized that there are also naysayers. See, for example, the 1981 discussion in Ref. 45 on differences in viewpoints that stem from different roles and interests; and the recent critique in Ref. 46. However, in our experience, currently such views seem to be in a minority, at least within the seismic PRA community.

[23] Interestingly, as discussed in Ref. 3, there have been a number of nuclear power plant fires that have posed severe safe shutdown challenges and can be viewed as significant accident precursors. In contrast, we believe there have been no significant accident precursors due directly to the strong ground motions that are currently the focus of most seismic PRAs. (The accidents at Fukushima Daiichi and the challenges to Fukushima Daini and Onagawa on 3/11, of course, were primarily due to the tsunami, although ground motion did cause LOOP at a number of plants.)

7. KNOWLEDGE MANAGEMENT

As discussed in Chapter 2, the second project objective was to provide an educational experience for the authors that would support NRC's risk-informed initiatives. In particular, the intent was for team members, each of whom has a particular area of interest (e.g., HRA, fire PRA, structural engineering), to learn more about other aspects of seismic risk and seismic PRA through the performance of PRA-oriented event reviews and discussion of these reviews.

The individual project team members learned a number of lessons, some confirmatory and some surprising. Notable lessons include the following:

- Project lead (PRA generalist):
  - The lack of major NPP safety impacts for the large majority of events reviewed
  - The lack of ground-motion/displacement induced damage for most NPP SSCs even for the most severe events reviewed
  - The occurrence of seismically-induced reactor trips due to the exceedance of neutron flux parameters (as opposed to ground motion measurements)
  - The potential risk importance of seismically-induced HEAFs
- HRA expert: the variety and nature of contextual factors (e.g., obstacles, visibility) potentially affecting post-earthquake operator actions
- Fire PRA expert:
  - The lack of minor, seismically-induced fire events in the LER database. This raises the question as to whether only larger plant impacts are captured in LERs and minor fire challenges are judged unimportant for documentation, or if there have indeed been no minor fires.
  - The limited number of fire events on 3/11 following the tsunami.
  - The importance of collecting information on fire related systems in future seismic event follow-ups. This includes information related to fire suppression system effectiveness and robustness, fire alarm activation (including spurious alarms), and fire initiations (major and minor).
- Structural engineer 1: the lack of ground-motion induced damage at Fukushima Daiichi, Fukushima Daini, Onagawa, and Tokai Daini plants from the 3/11 earthquake despite the severe recorded free-field and in-structure motions (which exceeded the current U.S. and Japan shutdown thresholds) [77] and the difficulty in obtaining information on the seismic responses for key equipment at these plants.
- Structural engineer 2:
  - Confirmation that seismic design approaches provide margin to prevent damage to safety-related components at the plants affected by the 2007 Kashiwazaki-Kariwa earthquake, the 2011 Great Eastern Japan earthquake and the North Anna earthquake despite the severe recorded free-field (for the first two earthquakes) and in-structure motions (which exceeded the current U.S. and Japan shutdown thresholds [77]).

- Occurrence of seismically-induced fires in the 2007 Kashiwazaki-Kariwa and 2011 Great Eastern Japan earthquake, which is related to ground motion effects on the affected components.
- Difficulty in obtaining information on the seismic response of key equipment to ground motion and value of reliable seismic instrumentation.
- Significance of human and organizational factors and how they can be affected by damage to non-safety-related components.

However, due to competing work priorities, most of the team members were unable to perform detailed reviews of key events, and the team as a whole had only limited discussions of the events and their implications. Thus, although all of the team members considered the project to be a useful exercise, the project was unable to completely achieve the intended objective.

8. INSIGHTS FOR ADVANCED KNOWLEDGE ENGINEERING TOOL DEVELOPMENT

As discussed in Refs. 51 and 52, rapid advances in natural language processing and text analytics are opening new possibilities for using operational event reports to develop PRA-relevant insights. Similar to an earlier data mining project addressing storms and floods [3, 80] and therefore, this project included a project objective to identify lessons regarding the mining of seismically-related operational experience that might be useful in the development of advanced knowledge engineering (KE) tools that help users identify, review, and assess key pieces of information in event reports.[24]

Based on our work developing the technical insights discussed in Chapter 5, we make the following observations and KE insights. We elaborate on these observations and insights in the following subsections, noting that most are not unique to seismic events.

- Most of the event reports reviewed lack direct statements on human-factors related information important to HRA. Thus, many insights on performance influencing factors and cognitive failure mechanisms must be inferred from indirect indications.
- Some of the project insights rely on knowledge as to when an issue arose during an event. Thus, the KE tool needs to develop and use an understanding of the event chronology.
- Some of the new project insights, notably the potential risk importance of seismically-induced HEAFs and seismically-induced reactivity excursions, required knowledge of information outside the normal realm of seismic engineering. This implies that even for a domain-specific investigation, a broad knowledge base (as encoded in a project corpus[25]) can be very useful.
- Most of the event descriptions are brief and lack details. A few events (most notably, 3/11) are covered by a multitude of reports, papers, and presentation slides. Both extremes of information volume present challenges to KE tool developers.

8.1 Inferencing from Indirect Indications

As indicated in Chapter 5, a good HRA requires consideration of situational context as well as actual decisions and actions. In principle, operational event reports can provide empirical information on these matters. Thus, for example, they could answer:

- Were operators severely stressed during the event?
- Were they stressed by the earthquake?
- Did earthquake-induced stress affect macrocognition?

[24] There appears to be no commonly accepted definition for the term “knowledge engineering.” In this report, consistent with Refs. 51 and 52, we it to refer to engineering activities associated with the development and maintenance of information systems

[25] In KE terms, a project corpus is a selected set of documents which provides the search space for the project.

Unfortunately, however, much information is either lacking or only indicated indirectly in actual event narratives.

Examples of information not provided include:

- The experience of the operating crews on shift when the earthquake struck.[26]
- The immediate effects of the earthquake and any seismically-induced hazards on operator situation assessment and decision making.[27]

Of course, a KE tool can't supply factual information if none was reported. However, using some sort of model structure (such as that provided by IDHEAS), a tool can indicate if there are gaps in the factual record. In such heavily documented situations as 3/11 (see Section 8.3 below), such a tool could be very useful in helping a user identify which documents to review and which ones are unlikely to be helpful.

Examples of situations where potentially useful HRA insights can be inferred include:

- An apparent understaffing problem during the Kashiwazaki-Kariwa event.
- The lack of a major impact on operations of spurious fire alarms triggered by the 3/11 earthquake.

Regarding the former, available reports and presentations don't directly state that staffing was an issue during the event. However, one presentation provides indirect information: in a section titled "Measures for a Disaster-resistant Power Station," on a slide titled "Enhancement of Self Fire Fighting System," under a bullet titled "Weakness in Radiation Measurement System," one sub-bullet reads "More radiation technicians on holiday and at night." [54]. (It's also helpful to know that a separate presentation thought it important to state that the event occurred during a national holiday.)

Regarding the latter, a report on the events at Fukushima Daiichi states [28]:

> *'The shock of the earthquake caused the earthquake and fire alarms to sound in the Units 1&2 main control room at that time. The shift supervisor knew that even dust blown up into the air inside rooms activated the fire alarms at TEPCO's Kashiwazaki-Kariwa Nuclear Power Station (hereinafter called "Kashiwazaki-*

[26] Of course, no crews prior to 3/11 had any experience with the conditions experienced at Fukushima Daiichi and other hard-hit plants. However, as indicated in Appendix A, some of the plants affected by 3/11 had been affected by previous seismic events. Further, overall experience could affect operator knowledge of SSC details that could be useful in event response. Note that operator experience was judged sufficiently important to warrant detailed characterization in past HRA-oriented simulator studies [53].

[27] As discussed in Section 5.1, we judge that the effects were largely minor for most of the events reviewed. However, and important to the current discussion, the event descriptions lack direct statements of minor (or even no) effects. This can be contrasted with typical post-event descriptions of structural effects, which routinely indicate if a structure has not been damaged as well as if it has.

Kariwa NPS") at the time of the Chuetsu-oki Earthquake in July 2007. Since the fire alarm was designed so that it could not be turned off if a fire actually broke out, he tried turning it off to find out whether or not a fire had started. The shift supervisor was able to stop the fire alarm and thereby he judged that there was no fire within or near the Units 1&2 main control room.'

It appears that although the situation required some attention, this was not a major distraction to the decision maker. (This impression is corroborated by informal discussions at another plant affected by 3/11, where a similar situation and response arose.)[28].

From a KE tool development standpoint, the inference of a staff shortage requires understanding of the context established by the presentation section, slide title, and major bullet. The inference of a small effect from fire alarms is heavily influenced by the lack of discussion of complications, i.e., by what was not said. Both of these inferencing challenges indicate a need for substantial subject matter expert (SME) involvement in KE tool development as technical expertise is needed to characterize the context and expectations for text passages.

We note that some of our insights are much easier to develop from event descriptions. In particular, simple word associations are often sufficient. For example, in the passage

> *"The lack of food, working toilets, and relief personnel during the early stages of the accident as well as the extended length of the accident response added greatly to personnel fatigue and distress."* [30]

the terms "fatigue" and "distress" can be used as indicators of operator stress. SME involvement is still needed to create the appropriate associations, but this is a relatively straightforward activity at least in principle. However, as with the more complicated examples mentioned earlier, care is still needed. Consider, for example, the passage

> *"…the female employees screamed during each aftershock."* [55]

This would appear to be a clear indication of high stress caused by the earthquake. However, a more complete version of the passage

> *"… because we had just conducted an emergency-preparedness drill the previous week, things were surprisingly orderly. TEPCO employees handed out water and crackers, and we took turns using a PHS that was able to connect to*

[28] Of course, care is generally needed in interpreting situations for which explicit statements are not provided. For example, as can be seen in Appendix C, official reports provide little information on the psychological state of plant staff immediately following the earthquake. Given the likely professional and personal experience of the staff with past earthquakes, and given the measured description of operator responses, it is reasonable to infer that the staff were reasonably calm. However, as also indicated in Appendix C, an eyewitness account by a plant worker provides a very different, emotionally-charged picture of the situation. More investigation would be needed to determine if there were indeed stronger reactions among the control room operators than assumed.

the outside world to confirm the safety of our families. Meanwhile, some foreigners sat on the floor and chatted, and the female employees screamed during each aftershock." [55]

could be read as indicating a less emotionally charged (or even a playful) situation. Regardless of the specifics of this particular episode, it can be seen that context still plays a role even when using simple word associations. The associated KE tool challenges are not only how to use such contextual text, but even how to decide how much contextual text is needed.

8.2 Temporal Reasoning

The reports on 3/11 provide numerous narratives indicating that the operators at Fukushima Daiichi were severely stressed. One question of interest to seismic HRA is whether the operators were stressed by the immediate effects of the earthquake/tsunami (e.g., ground motion, site flooding), as opposed to the effects of earthquake/tsunami-induced SSC failures.[29] To answer this question, the narratives need to be associated with different chronological phases of the event. It can be seen that this is just one example of a situation where a KE tool capable of temporal reasoning is needed to develop desired PRA insights.

8.3 Need for and Use of Broad Knowledge Bases

This project has identified two phenomena that might be worth further investigation to determine their risk significance for operating and new reactors:

- seismically-induced HEAFs
- seismically-induced reactivity excursions

Figure 2 shows the simple reasoning chain for the HEAF insight; Figure 3 shows the analogous chain for reactivity excursions. In both cases, the insight relies on technical information that might not be considered in a review limited to consideration of actual plant effects due to seismic events.

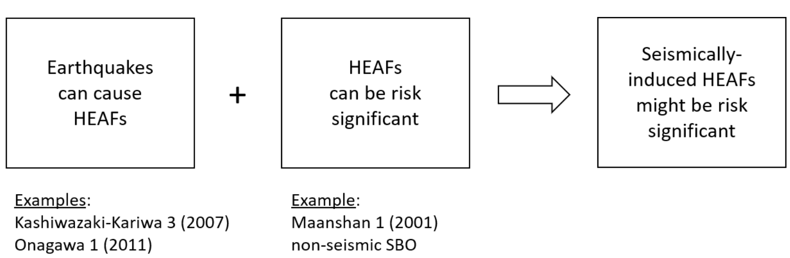

Figure 2. Reasoning Chain for Seismically-Induced HEAFs

[29] Arguably, the latter source of stress is not unique to seismically-induced scenarios.

As a different example, consider the following passage [19]:

> *"The magnitude 7.8 earthquake off the coast of Hokkaido in July 1993, had no effect on nuclear facilities. Tomari 1 and 2 reactors (550 MWe, PWRs), located 95 km from the epicentre, continued normal operation."*

Recognizing that offshore earthquakes might be the source of tsunamis, a search for earthquakes in that month and location results in identifying the Hokkaido-Nansei-Oki earthquake (July 12, 1993) and further searching identifies a paper discussing the subsequent tsunami [56]. This paper indicates that the earthquake indeed caused very large tsunamis in the region (e.g., 7-9 m runup some 45-60 km away) and a runup of around 4 m in the general vicinity of the plant. (See Figure 4.)

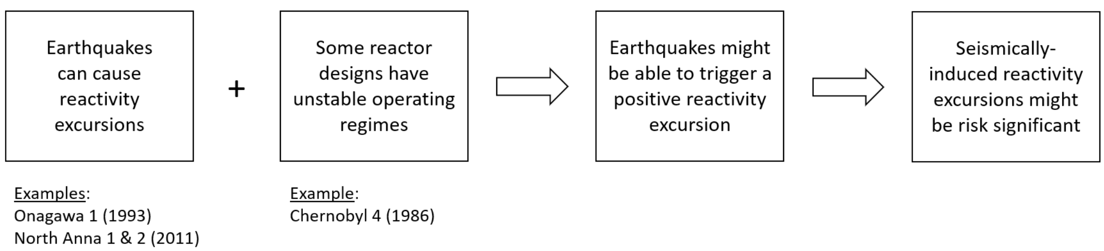

Figure 3. Reasoning Chain for Seismically-Induced Reactivity Excursions

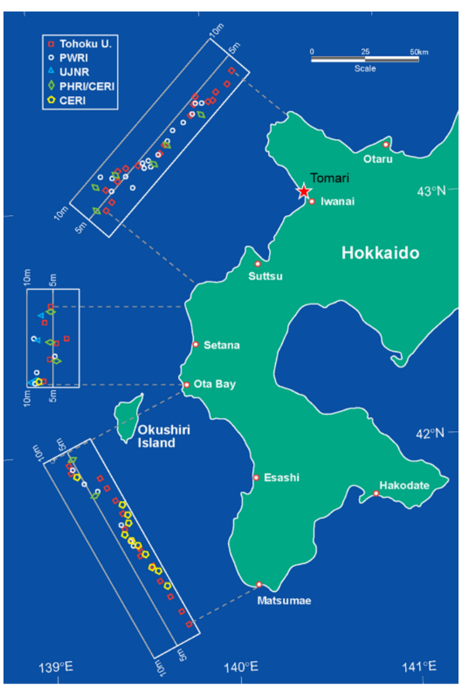

Figure 4. Tsunami runups from Hokkaido-Nansei-Oki earthquake (adapted from [56])

We do not know if the tsunami runup presented any challenge to the plant, nor if slightly different earthquake locations or intensities would have had any significant effects. However, the available information indicates that this event might be interesting to investigate further.

In general, the challenges for a KE tool raised in this section include:

- Determining the appropriate breadth of the project corpus
- Identifying facts in this corpus that are related to facts in the event description (i.e., "connecting the dots")
- Generating and exploring reasonable possibilities as well as actual observations
- Identifying when an expected fact is not reported[30]
- Determining which inferences from the above are potentially important (e.g., to require SME review for plausibility and significance)

8.4 Varying Information Quantity and Quality

The useful event descriptions reviewed in this project range from very short – perhaps a single sentence – to extremely long – multiple reports, papers, and presentations in the case of 3/11. Both extremes provide challenges to KE tool development.

As an example of an important but short description, consider the following passage on a 1993 event in Japan.

> *"In November 1993, a magnitude 5.8 earthquake in northeast Honshu produced a ground acceleration of 121 Gal at Tohuku's Onagawa 1 power reactor (497 MWe, BWR), located 30 km from the epicentre. The design conditions for the S1 and S2 events at the site were 250 and 375 Gal respectively and the reactor was set to trip at a measured peak ground acceleration (PGA) of 200 Gal. In fact it tripped at a lower level due to variations in the neutron flux outside the set parameters."* [19][31]

This is the sole record of the earthquake reviewed by the project. Aside from the challenges of a) recognizing that the last sentence refers to a reactivity excursion, and b) recognizing the potential significance of this event (as discussed in Section 8.2 above), this example illustrates a

[30] Ref. 57 suggests using measures of "surprise" based on the prior probability of the observation: the lower the probability, the greater the surprise. It would appear that this general principle could be applied to non-observations.

[31] Notes:
1) A Gal is a measure of acceleration, where 1 Gal = 1 cm/s^2.
2) Per Ref. 31: "S1 and S2 are the two levels of severity of design basis ground motions that should be taken into account. IAEA Safety Series No. 50-SG-S2 defined the application of these two levels in design as follows: (1) ground motion level 1 (S1), which is the maximum that reasonably can be expected to be experienced at the site area once during the operating life of the nuclear power plant; (2) ground motion level 2 (S2), which is considered to be the maximum earthquake potential at the site area."

challenge to analytics-based algorithms: a project corpus might not have many references to potentially important facts.

As an example of a massively documented event, consider 3/11. Figure 5 shows how the number of pages describing the event increased over time. This figure covers only reports in our project corpus and is therefore a lower bound.

Clearly analysts seeking to develop insights from those reports would greatly benefit from KE tools that go beyond simple searches. Aside from the previously discussed challenges regarding inferencing, challenges in dealing with a large (and growing) corpus include:

- Identifying and assessing the potential significance of changes across a series of documents from the same source (e.g., the series of post-investigation progress reports issued by TEPCO [58-61]), and even recognizing when one member of the series (the 2nd TEPCO post-investigation report in our case) is missing.
- Identifying and assessing the potential significance of differences in reporting across documents from different sources.
- Recognizing when information in a report is a replication of information provided in another report (which affects text analytics).

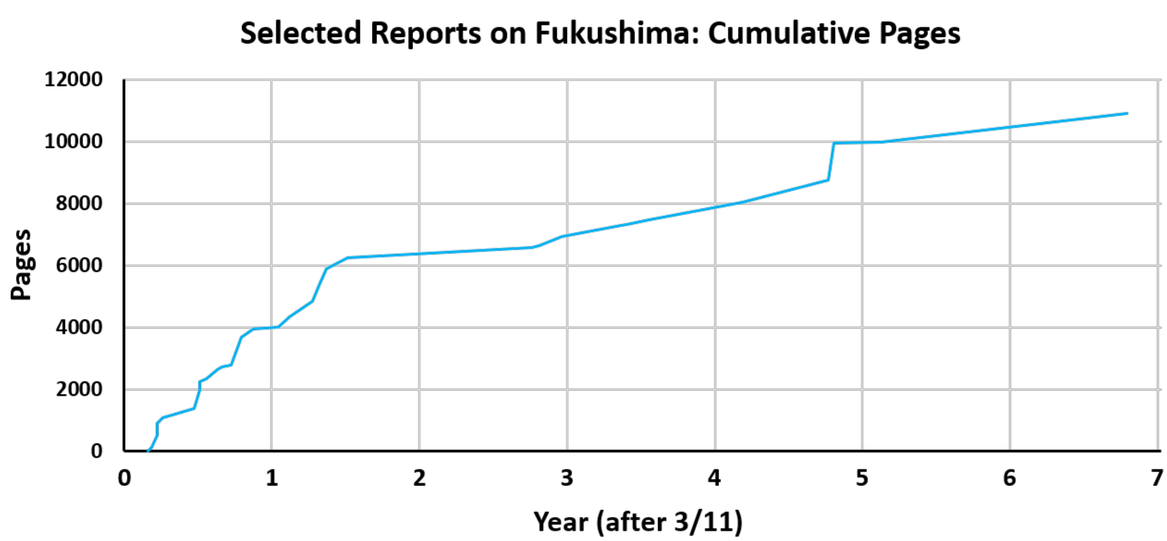

Figure 5. Page Count for Selected 3/11 Reports

8.5 Commentary – Near-Term KE Tool Improvements

The previous sections describe a number of inferencing problems that appear to present considerable challenges to KE tool developers. Even with the rapid rate of developments in KE, it is unclear whether "complete" solutions can be developed in the near term. However, based on recent experience, there are two problems where partial solutions might not be difficult to develop and could be immediately useful.

1) Identification of text passages supporting a particular assertion about an event
2) Identification of documents that are unlikely to have information on a specified topic

As an example of the first problem, consider the passage

> *"The Fukushima event provides multiple examples of performance delays and performance failures, resulting from miscommunications, lack of clear understanding of roles and responsibility, and complex chains of command and control."*

Considering the tens of thousands of pages covering the event, if challenged, it is not easy to quickly find a specific citation supporting this passage, let alone citations in other reports that might support or contradict it.[32]

The second problem is related to the first. If a KE tool is not able to find specific passages of interest, it still could provide valuable help by helping users screen out documents (or even document sections) if these are unlikely to have useful information.

In both cases, it appears that, at least in principle, relatively simple word association approaches could be helpful in a use-mode where the KE tool serves as an aide and not an oracle.

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[32] Such a challenge arose during a staff presentation to the Advisory Committee on Reactor Safeguards (ACRS) [62]. The challenge concerned not only the statement but also whether the statement was current, given numerous TEPCO reports issued since 3/11.

9. SUMMARY CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

In this project, we have reviewed descriptions of 50 seismic events that potentially affected NPP operations and have developed a number of qualitative observations relevant to seismic PRA methods and models. Given the variety of sources consulted, we are reasonably confident our search has captured most significant events relevant to U.S. NPPs. We recognize that there are likely many minor events (e.g., low intensity earthquakes felt but not affecting NPP SSCs) that we have not captured but expect that they will add few insights to those developed from more severe events.

9.1.1 Technical Insights Relevant to Seismic PRA

The large majority of the events reviewed have had, at most, relatively minor impact on the operation of potentially affected NPPs. However, five earthquakes led to complicated (or at least non-routine) multi-unit and sometimes multi-site events and are of interest to seismic PRA modeling.

For the more severe events, earthquakes (and subsequent induced hazards, particularly tsunamis and HEAFs) have caused:

- LOOP and (in the case of Fukushima Daiichi) SBO
- Degradation or loss of ultimate heat sink
- Damage (and concerns of potential damage), disruptions (e.g., due to aftershocks and tsunami warnings) and/or adverse environmental conditions (e.g., debris, smoke) affecting event recovery
- Seismically-induced reactivity excursions and associated reactor trips (i.e., reactor trips not caused by seismic ground motion detectors)

These effects have occurred from events with onsite ground motions significantly less than those considered by current seismic PRAs.

Finally, we note that this project has identified two phenomena that might be worth further investigation to determine their risk significance for operating and new reactors:

- seismically-induced HEAFs
- seismically-induced reactivity excursions

9.1.2 Knowledge Management Insights

The observations developed by this project concern factors, mechanisms, and scenarios of interest to the human and organization, fire protection, and reactor physics technical communities. This breadth points out the importance of an integrated, multidisciplinary approach to seismic PRA. It also emphasizes the need to ensure that seismic event reports address these other phenomena, going beyond descriptions of ground motion and direct effects on SSCs.[33]

We also note that the activity of reviewing past events for PRA-related lessons was generally successful as a knowledge management exercise; all team members gained technical insights they considered to be useful.

9.1.3 Knowledge Engineering Tool Insights

This project has identified a number of challenges to the development of advanced KE tools aimed at helping users extract PRA-relevant insights from operational event narratives. These challenges involve:

- the use of indirect indications of phenomena/events
- temporal reasoning
- the needed breadth of a project corpus
- “connecting the dots” across a broad range of (often disparate) documents
- generating and exploring reasonable possibilities
- identifying when expected information is not provided
- assessing the relative importance of inferences (e.g., to prioritize for SME review)
- non-text analytic approaches for identifying important insights
- identifying and assessing changes across a series of related documents (e.g., a series of progress reports)
- identifying and assessing differences in reporting across documents from different sources
- recognizing when information is replicated across multiple reports

Two KE tool advances that appear to be both useful and achievable in a relatively short time frame involve tools supporting

- the identification of text passages supporting a particular assertion about an event
- the identification of documents that are unlikely to have information on a specified topic

9.2 Near-Term Actions

- Informal communications to date indicate that many staffers (and likely broad technical communities) are unaware of the fact that the 2011 North Anna earthquake-induced trips were due to a seismically-induced reactivity excursions (rather than the actions of seismic ground motion detectors). None were aware of the 1993 Onagawa event. The project team will disseminate this information to appropriate staff, including those involved in the review of advanced reactor designs.

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[33] Note that from a PRA perspective, it is important to have information on successes (e.g., definitive statements that an earthquake did not cause a fire at a particular location) as well as failures.

- The list of earthquake events in Appendix A is a useful resource for staff. The project team will ensure that potentially interested staff are aware of this list and will consider developing a summary version for NRC's Nuclepedia initiative.

- This project has identified two potentially useful and near-term candidates for Artificial Intelligence/Big Data use cases. As discussed in Section 9.1.3, these involve the identification of text passages supporting a particular assertion about an event and the identification of documents that are unlikely to have information on a specified topic. The project team will provide these ideas to cognizant staff.

9.3 Recommendations

- Due to resource limitations, this project has not compared its technical observations against current seismic PRA standards and guidance (e.g., [18, 38, 63-68, 81-82]), and against the findings of recent analyses (e.g., [69-75]). Given the continuing importance of seismic PRA in current risk-informed decision making applications, we recommend that such comparisons be made.

- We have found the information on post-earthquake environments useful when considering conditions operators face when performing needed actions. We recommend that: a) this information be summarized in a form suitable for HRA training, and b) be incorporated into NRC training courses.

- More generally, similar to the earlier project on storms and floods [3, 80], this project has demonstrated that qualitative reviews of past events can provide useful information for PRA analysts and reviewers. We recommend that additional reviews be performed for KM as well as immediate technical purposes. Recognizing that the KM benefits are directly related to level of effort, we further recommend that the review activity be given sufficient priority to enable active involvement by all team members.

- The project team has become aware of an ongoing activity at ETH Zurich to create a public, authoritative database on nuclear accidents [17]. We recommend consideration of the development and transmittal of a public version of the list of events in Appendix A. We note that different intended uses of the information may dictate revisions in the table terminology, information highlighted, and commentary.

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APPENDIX A – NOTABLE SEISMIC EVENTS AND EFFECTS ON NPPS

This appendix lists the 50 seismic events reviewed during the project. For events where the only plant impact information we reviewed was non-public, we only indicate the country and some of the earthquake specifics. Reactor trips are highlighted with green boldface.

It is important to note that this appendix, which draws upon information from multiple documents, is a synthesis that we consider adequate for the needs of the project. However, the data have not been peer reviewed and should not considered to be authoritative.

A.1 Events

Note that the following table includes some earthquakes without a numerical identifier in the left-hand column. These are notable earthquakes for which we collected information but did not identify any records specifically indicating effect (or lack of effect) on a nuclear power plant.

Table A.1.1. Summaries of Reviewed Events

No.	Date	Plants	Notes
1	1975-06-07	Humboldt Bay 3	Ferndale CA Earthquake (M 5.5, Intensity V) [1]. Plant ~15 mi south of epicenter. **Exceeded/OBE/SSE response spectrum levels** [2].
2	1978-06-12	Japan	Miyagi-Oki Earthquake (M 7.7, Intensity VIII). [1] No tsunami identified by International Tsunami Information Center (ITIC) [3].
3	1978-09-07	V.C. Summer	Summerville SC Earthquake (M 2.7) [1]. Plant ~175 km from epicenter. **Exceeded OBE and SSE** above 10 Hz; plant awaiting operating license (OL) [2].
4	1979-12-07	V.C. Summer	Summerville SC Earthquake (M 2.7) [1]. Plant ~175 km from epicenter. **Exceeded OBE and SSE** above 10 Hz; plant awaiting OL [2].
5	1980-11-08	Humboldt Bay 3	Eureka Earthquake (M 7.2, VIII) [1]. Plant ~45 km from epicenter. **Exceeded OBE/SSE**; plant already shut down [2]
6	1980-11-23	Italy	Campano-Lucano Earthquake (M 6.9) [1].
7	1983-05-02	USA (CA)	Coalinga Earthquake (M 6.5) [1].
8	1983-05-26	Japan	Nihonkai-Chubu Earthquake (M 7.4, VII) at 12:00 (02:59:59 UTC) [1]. Estimated tsunami heights 14 m (Minehama, Honshu), 2-6 m (southern Hokkaido and northern Honshu), 4 m along coast of South Korea [3]..
9	1983-07-02	Japan	Earthquake (M 5.8) [1]. No tsunami per ITIC [3].
	1985-09-19		Michoacan, Mexico (M 8.0, VII) at 07:18 (13:17:47 UTC), one major aftershock at Guerrero, 100 km away (M 7.6, VII) at (9/21, 01:37:13 UTC). Major ground motion at Mexico City despite being ~300 km away from epicenter. Industrial damage [25]. Per Wikipedia ("Mexico City earthquake"), intensity IX, 5000-45000 dead, 30000 injured. Laguna Verde 1 started operation 7/29/1990; Unit 2 started 4/10/1995; on Gulf of Mexico (not Pacific).
10	1986-01-31	Perry	Leroy OH Earthquake (M 5.0, VII) [1]. Plant 11 mi north of epicenter. **Exceeded OBE and SSE** above 10 Hz. Plant not yet fueled. Staff observed no indication of damage to systems in operation, were even unsure an earthquake had occurred. [2]
11	1987-06-10	Clinton, Dresden, Quad Cities, D.C. Cook, Palisades, Prairie Island	Sumner IL Earthquake (M 5.2, VI) [1]. **Exceeded OBE/SSE response spectrum level at Clinton** (~180 km NW). Clinton and other plants declared UEs. No damage. [2]
	1987-10-01		Whittier Earthquake (M 5.9, VIII-IX) at 07:49 (14:49:05 UTC) [1]. Quake at 07:42. Non-nuclear industrial damage, also due to 10/4 M 5.5 (5.3 per [1]) aftershock at 03:59 [27].
12	1988-12-07	Armenia 1-2	Armenia Earthquake (M 6.8, IX) at (07:41:24 UTC) [1]. M 6.9. Plant is 75 km south, not damaged [5]. Plant was closed due to public pressure after the earthquake but was reopened to meet energy needs (multiple sources).

No.	Date	Plants	Notes
	1989-10-17		Loma Prieta ("World Series") Earthquake (M 6.9, IX) at (10/18, 00:04:15 UTC), multiple aftershocks (one above 5.0) [1]. Industrial impacts [24]. Diablo Canyon nearest NPP.
13	1993-07-12	Tomari 1-2	Hokkaido-Nansei-Oki Earthquake (M 7.7, IX) at 21:17 (13:17:11 UTC). Several major aftershocks including a M 6.3 1 hr 28 min after and a M 6.0 2 hr 44 min after [1]. Per NOAA Hokkaido Tsunami Survey Group, large tsunami (15-20 m runup) five minutes after EQ, maximum runup 31 m (Okushiri Island). Hokkaido runup 5-10 m in most heavily affected area; runups are 7-9 m some 45-60 km southwest of plant. Runup around plant appears to be around 4 m [6]. WNA article: M 7.8, Tomari plants are nearest (95 km away) but not affected [5].
14	1993-11-27	Onagawa 1	M 5.8 at 14:11 (06:11:22 UTC) [1]. No tsunamis listed by ITIC [3]. U1 (30 km away) PGA 121 gal. Design reactor trip at 200 gal, S1 design level 250 gal, S2 design level 375 gal. **Reactor tripped on neutron flux variation**. [5].
15	1994-01-17	San Onofre, Diablo Canyon	Northridge (Reseda) Earthquake (M 6.7, IX) at 04:31 (12:30:55 UTC) [1]. M 6.6, both plants continued to operate normally. San Onofre about 112 km from epicenter [5]. San Onofre 85 km from epicenter, PGA = 0.025g. Units 2 and 3 operating (Unit 1 no longer in operation), not affected [23].
16	1994-09-01	USA (CA)	
17	1994-12-28	Higashidori, Ohma, Onagawa, ?	Honshu Earthquake (7.8, VII) at 20:19 (12:19:23 UTC). Major aftershocks include a M 6.2 8 hr 30 minutes later [1]. No tsunamis listed by ITIC [3]. M 7.5 in northern Japan, no damage to 11 BWRs or nuclear fuel facilities in area [5].
18	1995-01-17	Takahama, Oki, Mihama	Great Hanshin-Awaji (Kobe) Earthquake (M 6.9, X) [1] at 05:46 (20:46:52 UTC), multiple aftershocks but none above M 5.0. No tsunamis listed by ITIC [3]. PGA: 817 gal (H), 332 gal (V). No reactors sustained damage; those running at the time continued to operate at capacity. Takahama and Oki (130 km); Mihama (180 km). Research reactors in Osaka and Kyoto also unaffected [5]. Return period ~1000-1500 years. PGAs up to 0.818g (Kobe City); several recordings 0.5-0.8 g. No damage to 500 kV transmission system, cluster of fossil plants to SE, NPPs more than 100 km to the north. Damage to 187 and 275 kV substations, a few fossil plants, a gas turbine plant. PGAs for gas turbine and NPPs 0.013-0.07g (H) and 0.006–0.06 g(V). Shin-Kobe Substation: 0.56g (H), 0.49g (V) (**beyond 1980 design criteria**). Fossil plants up to 0.34g (H), 0.20g (V) [22]. All substations restored by 08:00, 1/18 (1 day after earthquake).
	1997-01-11		Michoacan Earthquake (M 7.2, VIII) at 14:28 (20:28:26 UTC). Unlike 1985, no major shocks in Mexico City [1]. M 7.3, industrial damage [26].
	1999-08-17		Izmit Earthquake (M 7.6, IX) at (00:01:39 UTC) [1]. M 7.4, Industrial damage [28]. Akkyu NPP site appears to be distant from most major historical quakes. Closest (~100 km) was M 6.3 (VIII) at 13:55:52 (UTC), 1998-06-27.
19	1999-09-21	Chinshan, Kuosheng, Maanshan	Chi Chi Earthquake (M 7.7, IX) at 01:47 (17:47:18, 9/20 UTC). Multiple aftershocks including at least 8 over M 6.0 [1]. No tsunamis listed by ITIC [3]. M 7.2. **Three reactors at Chinshan (~185 km) and Kuosheng (similar) shutdown automatically**, restarted 2 days later. (Chinshan 1 was down for refueling [20].) Maanshan continued to operate but reduced power later due to damage to distribution facilities [5]. EQ led to major (~8 m) displacements at a reinforced concrete gravity dam [7]. PGA at Chinshan/Kuosheng 0.3g [19] – very different from EPRI report [20]. Plants located ~150 km from epicenter. **Power grid instability due to damage to 345 kV transmission towers caused plant trips**. Free-field accelerations: Chinshan PGA: 0.037g (N-S), 0.034g (E-W), 0.029g (V). Kuosheng < 0.05g. No recorded ground motion at Maanshan (too low). OBE (H): 0.15g (Chinshan), 0.2g Kuosheng. [20]
20	1999-10-16	USA (CA, AZ)	Hector Mine Earthquake (M 7.1, VIII) at 02:47 (09:46:44 UTC). [1]
21	2000-07-21	Japan	Ibaraki Prefecture Earthquake (M 6.0, VI) [1]. No tsunami listed by ITIC (magnitude cutoff = 6.5) [3].
22	2003-05-26	Onagawa 3	Honshu Earthquake (M 7.1, VIII) at 17:25 (09:24:33 UTC) [1]. No tsunami per ITIC [3]. M 7.1, PGA of 225 gal, **U3 tripped**. U1 and U2 were not operating [5].
23	2003-06-30	USA (OH)	Lake Erie EQ (M 3.6, V) at 19:21:17 UTC [1].

No.	Date	Plants	Notes
	2003-10-31		Honshu Earthquake (M 7.0) at 9:06 (01:06:28 UTC) [1]. 50 cm tsunami [8].
	2004-09-05		Kii Peninsula Earthquake (M 6.9 at 10:07 UTC and 7.4 at 14:57 UTC) [1]. Tsunamis less than 1 m [3].
24	2004-10-23	Kashiwazaki-Kariwa	Honshu Earthquake (M 6.6, IX) at 16:56 (08:56:00 UTC). Onshore, 16 km depth. Several aftershocks, including a M 6.1 ~7 min later and a M 6.3 ~38 min later [1]. No effect on plant [5].
25	2004-11-04	Kashiwazaki-Kariwa 7	Honshu Earthquake (M 5.3, VII) at 8:57 (11/03, 23:57:28 UTC), around 13 km from site. Multiple aftershocks including: M 5.1 at 11/5, 02:53 (~25 km from site); M 4.3 at 11/8, 10:43 (~14 km from site); M 5.5 at 11/8, 11:16 (~22 km from site); M 5.1 at 11/10, 03:19 (~20 km from site) [1]. **M 5.2 "two weeks after" 10/23 event caused U7 trip**. [5]. Per Wikipedia: Earthquake was on 11/4/2004. Measured 4 on Japanese seismological intensity scale. (Intensity was 6 at other places). All reactors except Unit 4 were operating normally and continued to do so during the quake. Unit 4 was shut down due to routine maintenance.
26	2004-12-26	Madras 1 and 2	Sumatra-Andaman Earthquake (M 9.1-9.3, IX) at 06:28 (0058 UTC). Major aftershocks include M 7.2 (12/26, 04:29 UTC) and several at M 6.0+ [1]. Tsunami arrival times at Colombo station 03:52, 03:58; height ~2 m per [9]. According to NOAA natural hazards database, runup at Madras is 1.62 m; runup at Kalpakkam is 2-4 m. Runups at other places in Tamil Nadu state as high as 12 m [10]. Unit 1 already under long shutdown. Unit 2 operating. Tsunami flooded pump house, tripped condenser cooling pumps. **Manual turbine trip, reactor trip**. Other pumps lost due to submergence or clogging. Fire water used for cooldown. Offsite power available, EDGs started as precautionary measure. Emergency alert declared at 1025, lifted 2143 2004-12-27 [35]. "Battered but safe" [11] **plant shutdown automatically**. Restarted January 1, 2005 (6 days after tsunami.) [5, 11]
27	2005-03-20	Genkai, Sendai, Shimane, Ikata	M 6.6, VII-VIII) at 09:54 (01:53:41 UTC) [1]. No tsunami information listed by ITIC [3]. M 7.0, no plants affected [5].
28	2005-08-16	Onagawa 1-3	Miyagi Earthquake (M 7.2, VII) at 11:46 (02:46:28 UTC) [1]. ITIC links to wrong event (3/28/2005 Sumatra). Per Wikipedia, only two small waves "several centimeters" high. **All 3 units (~50 km) shut down automatically**. Set to trip at 200 gal, S1 design basis of 250 gal was reached. U2 restarted January 2006 (with S2 of 580 gal – equivalent to M 8.2 – upgraded from 350-400 gal). U3 restarted March 2006. U1 restarted May 2007. [5]
29	2005-10-08	Pakistan	Earthquake (M 7.6) at 0852 (03:50:40 UTC). Major aftershock M 6.4 (10/8, 10:46:28 UTC) [1].
30	2006-12-26	Taiwan	Earthquake (M 7.1, VII) at 06:26 (12:26:21 UTC). Another earthquake (M 6.9, VI-VII) at 08:34 (12:34:13 UTC) [1].
31	2007-03-25	Shika 1 and 2	Earthquake (M6.7, V to IX) at 09:41 (00:41:57 UTC). Multiple aftershocks (none above 5.2), two (4.1, 4.6) near plant [1]. Plant ~35 km SE. Minor tsunami (22 cm at Suzushi Nagahashi; 18 cm at Kanazawa, some ways down the coast from plant. **EQ said to be beyond seismic design standard.** Appears that both units were already shutdown: Unit 1 due to an order from METI after utility admitted it should have reported a criticality event in June 1999; Unit 2 due to turbine blade failure in July 2006 [12].

No.	Date	Plants	Notes
32	2007-07-16	Kashiwazaki-Kariwa 1-7	Niigataken Chuetsu-oki Earthquake (M 6.6, intensity VIII to IX) at 1013. Aftershock (5.7, IV-VI) 5 hr 24 min later. Earthquake (which was a shallow crustal event) was followed by an independent “deep focus” earthquake (M6.8) some 13 hours later and 330 km away [1]. No notable tsunami [3]. Plant 16 km SE. **Units 3, 4, and 7 operating, Unit 2 in startup. All shutdown**. Fire caused by bus duct subsidence (16-18 cm), collision with transformer terminal, insulator damage and oil leakage ignited by arc from short circuit [34]. Per Wikipedia, fault was previously unknown. Per WNA article, **PGA exceeded S1 design values (170-270 gal) in all units**; S2 (450 gal for bedrock) exceeded for U1, U2, U4. **Four reactors shut down automatically** at pre-set level of 120 gal with no apparent complications; other three were not operating at time. TEPCO proposed new standard of 2280 gal (2.33g) for U1-4, 1156 gal (1.18 g) for U5-7. While standard was under review by NISA and NSC, construction undertaken to withstand 1000 gal. NISA approved new estimates in November 2008. U7 restarted May 2009, U6 August, U1 May 2010, U5 November 2010. U2-4 remained shutdown [5]. Post-event inspections identify a stuck control rod (Unit 7). Cause unknown [21]. Some water/mud in-leakage to the “composite reactor building” (radwaste) through gaps in piping housing (penetration?); water from broken underground fire line. Some contaminated water from the U6 SFP sloshed out and reached the ocean through the storm drain system. Extensive roof collapse of administration building, one door jammed (blocking access to emergency phones).
33	2008-04-18	USA (IL, MI)	Mount Carmel, IL (M 5.2, VII) at 09:36:59 UTC; aftershock (M 4.6, V) at 15:14:17 UTC [1]
34	2008-06-14	Onagawa, Higashidori, Fuukushima Daiichi, Fukushima Daini	Iwate-Miyagi Nairiku Earthquake (6.9, VII-VIII), 08:44 (23:43:45, 6/13 UTC). Onshore, shallow (7.8 km), large number of aftershocks including some above 5.1 [1]. No tsunami per ITIC [3]. 75km from Onagawa (100 gals), 175 km from Fukushima (300 gals) [numbers look wrong]. Reactors “operated normally through the earthquake.” Minor SFP spilling at 2F2 and 2F4. No alerts at Rokkasho reprocessing facility, tremors but no effect at Rokkasho enrichment facility and LLW storage [13].
35	2009-08-11	Hamaoka 3-5	Honshu Earthquake (M 6.2, VI-VII) at 04:07 (20:07:09 8/10 UTC) [1]. Very small (0.60 cm) wave per ITIC [3]. M 6.5. PGA = 426 gal at Hamaoka 5 (apparently much higher than others). **U4 and U5 automatically shut down**. U3 and U4 restarted after checking. U5 restarted January 2011. U1 shutdown since 2001, U2 shutdown since 2004 (seismic upgrades). Decided too expensive to upgrade. Original S1 450 gal, S2 600 gal. Ss 800 gal (September 2007), now 1000 gal. [5].
36	2010-04-08	USA (AZ)	Baja CA (M 5.3, VII) at 16:44:25 UTC [1]
37	2010-06-13	Onagawa, Fukushima Daiichi, Fukushima Daini	Honshu Earthquake (M 5.9, V) [1]. No tsunami listed by ITIC (below 6.5 cutoff) [3]. M 6.2. Reactors unaffected. Fukushima Daiichi: 60 gal [5].
38	2010-06-23	USA (VT, IL)	Related to Ontario-Quebec (M 5.4, VI) at 17:41:42 UTC or aftershocks [1].
39	2011-03-11	Fukushima Daiichi,1-6, Fukushima Daini 1-4, Onagawa 1-3, Tokai Daini, Higashidori 1-2	Great Tohoku Earthquake and Tsunami (M 9.1, IX). First foreshock 3/9 (M 7.3); many other foreshocks including three 6+ on 3/9 (6.0, 6.0, 6.5); aftershocks include a M 7.9 event some 30 minutes after main shock and a M 7.7 event some 10 minutes after that. Total of 47 shocks with M 6.0 or greater from 3/9 through 3/12 [1]. **SBO at Fukushima Daiichi (U1-U3 at power, all tripped). LOOP at Higashidori (maintenance shutdown) and Tokai Daini (at power, tripped), EDGs operated. (Wikipedia says 2/3 EDGs at Tokai were out of order). Partial LOOP at Fukushima Daini (all units at power, tripped) and Onagawa (all units at power, tripped).**

No.	Date	Plants	Notes
40	2011-08-23	North Anna 1 and 2	Mineral Earthquake (M 5.8, intensity VII-VIII). No fore shock (>M 2.5) in days before. One minor aftershock (M 2.8) roughly an hour later (well after Alert declared); a larger aftershock (M 4.2) roughly 5 hours later (T+6 hr). [1]. Also see [14, 15]). Per [16]: EQ at 1351, **dual unit trip (High Flux Rate) and LOOP** (latter caused by sudden pressure relays for xfmrs). No seismic alarms on Seismic Monitoring Instrumentation Panel due to momentary loss of semi-vital power (LOOP, EDG start). Alert emergency classification declared at 1403 (T+12 minutes) due to seismic activity and LOOP condition. Shutdown per EOPs; operators also used additional operating and abnormal procedures to deal with plant conditions. U1 TDAFW pump was under surveillance; manually re-aligned 1424 (T+33). Other ESF equipment (MDAFW, charging, service water, EDGs) started as designed. U2 “H” EDG tripped 1440 (T+49) due to coolant system leak. Second Alert classification declared 1455 (T+64). Alternate AC DG aligned 1527 (T+86). Offsite power to buses by 2055 (T+7hr 4 min). EDGs and alternate AC DG shut down at 2138 (T+7 hr 43 min). Commenced cool down to Cold Shutdown 8/14 0851 (U1); U2 followed. Alert downgraded to NOUE 8/14 1116. NOUE terminated 8/24 1315. Later determined that **EQ spectral accelerations had exceeded the OBE and DBE**. EQ caused reactivity excursion (“synergistic effects” of core barrel movement, detector movement, core movement, thickening of thermal boundary layer along fuel rods; momentary under-moderated conditions leading to oscillatory but overall decreasing flux profiles). U1 power increase turned around before control rod motion; U2 increase arrested by control rod motion. Did not exceed 100%. No significant physical or functional damage to safety-related plant SSCs; limited damage to non-safety-related, non-seismically designed SSCs. Per [17]: Spalled concrete on condensate polishing tank support pedestal (no functional impact), Generator Step Up (GSU) transformer bushing leakage (needed repair), limited cracking of ceramic/porcelain components on switchyard equipment, limited cracking of non-safety related walls, movement of ISFSI casks. Per WNA M 5.8, 20 km away. PGA = 255 gal, design basis = 176 gal [5]. NRC IN 2012-25: “several licensees” (including Surry) felt seismic vibration, declared UEs. IN points out that seismic instrumentation, in addition to post-EQ walkdown, is used to determine EQ severity and whether plant should be shut down. At NAPS, seismic instrumentation was not powered by a UPS; power was lost for 8 sec (and EQ strong ground motions lasted for 3.1 sec). Operators could not determine if OBE or SSE were exceeded, could not use seismic entry criteria to enter EAL matrix. (Shift Manager did this based on judgment.) At Surry, sensors were misaligned and could not trigger the 0.01g setpoint. [18]
41	2012-01-30	USA (VA)	Luisa, VA (M 3.1, V) at 23:39:47 UTC [1]
42	2012-03-25	USA (VA)	Luisa, VA (M 3.0, IV) at 03:21:50 UTC [1]
43	2012-10-16	USA (NH)	Maine (M 4.7, VI) at 23:12:25 UTC [1]
44	2012-10-21	USA (CA)	Central CA (M 5.3, VII) at 06:55:09 UTC [1]
45	2014-02-14	USA (SC)	
46	2014-06-28	USA (AZ)	Lordsburg, NM (M 5.3, VII) at 04:59:35 UTC [1]
47	2015-05-02	USA (MI)	Galesburg, MI (M 4.2, V) at 16:23:07 UTC [1]

No.	Date	Plants	Notes
48	2015-11-01	Krško	EQ (M 4.2) at 08:22 “close to” plant. No automatic shutdown, plant continued to operate [29]. Ref. 30 also mentions earthquake.
49	2016-09-12	Wolsong 1-4, Shin Kori 3, Hanul, Gori	EQ (M 5.4, VI-VII) at 20:32 (11:32:55 UTC) [1]. Foreshock (M 4.9, VI) at 19:44 (10:44:33 UTC). M 5.8, largest ever in Korea. Foreshock was M 5.1. Wolsong, Hanul, and Gori close to epicenter, affected by earthquake but still producing electricity. Shin Kori 3, not yet commercial, taken offline. Was already offline for maintenance. Other Shin Kori units may have been offline already. A combined cycle plant at Ulsan had one thermal unit shutdown automatically. Wolsong 1-4 suspended operations as precautionary measure [31]. EQ felt in Seoul, over 300 km away [32].
50	2017-11-30	USA (NJ)	Dover, DE (M 4.1, V) at 21:47:31 UTC [1]

Table A.1.2. Seismically-Induced Effects (See Table A.1.1 for more details)

Trip			Complicated Transient[a]			Multi-Site Effect[b]		
No.	**Date**	**Unit**	**No.**	**Date**	**Unit**	**No.**	**Date**	**Sites (Effect)**
1	1983-07-02	Japan	1		Chinshan 2	1	1980-11-23	Latina and Garigliano (seismic system actuation while shutdown)
2	1993-11-27	Onagawa 1	2		Chinshan 3			
3		Chinshan 2	3	1999-09-21	Kuosheng 1	2	1987-06-10	Multiple U.S. (UE)
4		Chinshan 3	4		Kuosheng 2	3	1999-09-21	Chinshan and Kuosheng (LOOP)
5	1999-09-21	Kuosheng 1	5		Kuosheng 3	4	1999-10-16	USA (CA, AZ)
6		Kuosheng 2	6	2004-12-26	Madras 2	5	2008-04-18	USA (IL, MI)
7		Kuosheng 3	7	2007-07-16	Kashiwazaki-Kariwa 4	6	2010-06-23	USA (VT, IL)
8	2003-05-26	Onagawa 3	8		Fukushima Daiichi 1			
9	2004-11-04	Kashiwazaki-Kariwa 7	9		Fukushima Daiichi 2	7	2011-03-11	Fukushima Daiichi (accidents); Fukushima Daini, Onagawa, Tokai Daini, and Higashidori (various losses)
10	2004-12-26	Madras 1	10		Fukushima Daiichi 3			
11		Onagawa 1	11		Fukushima Daini 1	8	2011-08-23	North Anna (LOOP); Harris and Susquehanna (UE)
12	2005-10-08	Onagawa 2	12		Fukushima Daini 2			
13		Onagawa 3	13	2011-03-11	Fukushima Daini 3	9	2016-09-12	Wolsong (suspended operations), Shin Kori (taken offline)
14	2006-12-26	Taiwan	14		Fukushima Daini 4			
15		Kashiwazaki-Kariwa 2	15		Onagawa 1	10	2017-11-30	USA (NJ)
16	2007-07-16	Kashiwazaki-Kariwa 3	16		Onagawa 2			
17		Kashiwazaki-Kariwa 4	17		Onagawa 3			
18		Kashiwazaki-Kariwa 7	18		Tokai Daini 1			
19	2009-08-11	Hamaoka 4	19	2011-08-23	North Anna 1			
20		Hamaoka 5	20		North Anna 2			
21		Fukushima Daiichi 1						
22		Fukushima Daiichi 2						
23		Fukushima Daiichi 3						
24		Fukushima Daini 1						
25		Fukushima Daini 2						
26	2011-03-11	Fukushima Daini 3						
27		Fukushima Daini 4						
28		Onagawa 1						
29		Onagawa 2						
30		Onagawa 3						
31		Tokai Daini 1						
32	2011-08-23	North Anna 1						
33		North Anna 2						

[a] A subset of seismically-induced reactor trips. For the purposes of this report, a “complicated transient” involves a reactor trip and potentially significant additional failures (e.g., LOOP, challenges to ultimate heat sink, failures requiring significant offsite resources in response).

[b] Includes events where units were already shutdown, as well as events with minor effects (e.g., the declaration of an Unusual Event – UE)

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APPENDIX B – LICENSEE EVENT REPORTS

This appendix lists the results of a search using a search tool developed for an earlier knowledge engineering project [1].

<u>Search Parameters</u>:

LER dates: 1980-2014
Search string: “earthquake” AND “reactor trip”

The search resulted in 26 matching events. It can be seen that the North Anna event of August 23, 2011 is the only event that led to a reactor trip; the rest of the LERs refer to seismically-relevant issues with plant conditions.

B.1 Events

Year	Plant	LER	Title	Notes
1980	San Onofre 1	2061980027R00	Report of Information Presented at May 13, 1980 NRC Meeting Regarding Preliminary Results of Main Steam Line Break Analyses and Auxiliary Feedwater System Automation Modifications	Analysis considers OBE and DBE loads
1981	D.C. Cook 1	3151981033R00	None. [Inadequacy in installation of safety equipment]	Anchorage of 4KV and 600V switchgear cabinets and reactor trip and bypass breaker cabinets inadequate to prevent overturning during a DBE. (Design deficiency.)
1986	Oconee 1-3	2691986002R00	Some EFW and LPSW Piping and Valves Do Not Meet Seismic Criteria	In response to GL 81-14, determined some valves and pipes were not seismically qualified (lacking certification to meet 0.3g) and some manual valves were not normally closed.
1987	Vogtle 1	4241987075R0	Missing Screws in the Nuclear Instrumentation Drawers Leads to Tech Spec 3.0.3 Entry	Despite missing screws, Nuclear Instrumentation System (NIS) functioned properly; would have taken an earthquake to fail.
1987	Robinson	2611987024R00	Discovery of Reactor Protection and Control Analog Instrumentation Rack Inadequate Anchorage Due to Installation Discrepancy	Preliminary calcs indicated RPS analog instrumentation racks (Hagan Racks) anchorage needed additional seismic supports to assure operation during DBE
1987	San Onofre 3	3621987011R02	Reactor Trip on Low Steam Generator Water Level	Intermittent circuit due to loose volt in 120VAC non-1E Instrument Bus, inability to control MFW, reactor trip. During subsequent ECCS testing, some HPSI pump snubbers found frozen. System would have performed during DBE.
1988	ANO 1	3131988002R00	Plant Instrumentation Found Not Seismically Qualified Due to Improperly Sized Anchor Bolts for Mounting Rack	During plant mod, bolts found to be loose and pulling out of wall. Rack was for safety-related pressure transmitters which provide input to RPS. Rack might have failed during a seismic event.
1989	Catawba 1 and 2	4131989025R01	Technical Specification 3.0.3 Entered on Both Units For Inoperable Power Range Nuclear Instrumentation Due To Power Reduction During Hurricane Hugo	High winds and rainfall from Hurricane Hugo, leak on switchgear, loss of power to Condenser Circulating Water Cooling Tower Fans. Response per operating procedure RP/0/A/5000/07 “Natural Disaster and Earthquake.”
1991	Catawba 1	4131991006R00	Technical Specification Violation When Nuclear Service Water Valves Were Left Without an Emergency Power Supply Due To Inappropriate Action	DBE assumed to fail Wylie dam, leading to loss of lake level as well as LOOP. SNSWP would be required some 10 hours later.
1991	San Onofre 2	3611991018R01	Safety Related Instrumentation Not Installed in a Seismically Qualified Configuration	Process Instrumentation cabinets missing guide rails and/or bumpers. Later testing showed instruments without bumpers would have functioned properly during and after DBE.
1993	South Texas 1	4981993007	Technical Specification Required Shutdown due to the Inoperability of an Auxiliary Feedwater Pump	Shutdown b/c TDAFW pump not restored in time. Analysis indicated Units 1 and 2 could achieve cold shutdown following a SSE with single failure and LOOP. Note: same problem (water intrusion) led to TDAFW pump overspeed at both units.

Year	Plant	LER	Title	Notes
1995	Salem 1 and 2	2721995001R00	Technical Specification (TS) 3.0.3 Entry; Both Trains of the Solid State Protection System (SSPS) Being Inoperable	Discovered AC power distribution within SSPS vulnerable to CCF (design fault). SSPS signals were susceptible to short circuits due to DBE. Event discovery followed issued identification by Diablo Canyon.
1996	Shearon Harris	4001996013R02	Condition outside of design basis where the RWST had been aligned with a non-seismically qualified system	Non-seismic portions of SFP purification system had been aligned to the RWST for cleanup; non-seismic portions of hydrostatic test pump have been aligned to the RWST to fill SI accumulators. Earthquake could have failed non-seismic portions of systems, drained RWST.
1996	Comanche Peak 1 and 2	4451996009R01	The 480V Switchgear Breakers Racked Out in the Cubicle in Remove Position Resulting in Seismically Unqualified Conditions Outside the Design Basis	9 spare breakers racked out in the “REMOVE” position; not seismically qualified for this position.
1998	D.C. Cook 1	3151998002R01	Degraded Solid State Protection System Master Relays Result in Condition Outside the Design Basis	Degraded SSPS master relay (MR) covers are susceptible to being loosened during 12g [!] earthquake. Notes that SSE is 0.2g, and that no SSEs have occurred over 1988-1998.
1998	Davis-Besse	3461998009R00	Reactor Coolant System Pressurizer Spray Valve Not Functional with Two of Eight Body to Bonnet Nuts Missing	Nuts replaced due to improper materials (carbon steel, not SS), boric acid corrosion One nut not properly attached, another nut degraded. In combination with maximum design pressure, SSE could have caused failure, RCS leak.
1999	Diablo Canyon 1 and 2	2751999007R00	Plant Outside Design Basis Due to degraded Indicating Lamp Sockets	Increasing trend in control room lamp socket failures, some affecting control circuits for redundant safety related components in both units. Lamp failures could affect response to a DBE. (Licensee analysis indicates critical functions not impacted, or had redundancy, or had sufficient time for operator action.)
1999	Diablo Canyon 1 and 2	2751999007R01	Plant Outside Design Basis Due to Degraded Indicating Lamp Sockets	Increasing trend in control room lamp socket failures, some affecting control circuits for redundant safety related components in both units. Lamp failures could affect response to a DBE. (Licensee analysis indicates critical functions not impacted, or had redundancy, or had sufficient time for operator action.)
2000	Prairie Island	2822000005R00	Failure to Test Cooling (Service) Water Strainer Backwash Valves Due to Inadequate Surveillance Procedure	Recognized that DBE could result in river water supplies could contain “a significant amount of disturbed and unsettled solids”
2001	Diablo Canyon 1	2752001003R00	Technical Specification 3.7.6 Not Met When the Fire Water Storage Tank Was Isolated from the Auxiliary Feed Water Pumps Suction Due to Personnel Error	AOT exceeded due to manual valve isolation between FWST and CST. CST and FWST are designed to withstand earthquakes.
2011	North Anna 1 and 2	3382011003R00	Dual Unit Reactor Trip and ESF Actuations During Seismic Event with a Loss of Offsite Power	

Year	Plant	LER	Title	Notes
2012	Summer	3952012001R00	Core Exit Thermocouples Inoperable due to an Inadequate Maintenance Procedure	Core Exit Thermocouples (CETCs) would have been inoperable if a LOCA had occurred, due to lack of Control Rod Drive Mechanism (CRDM) Cable Bridge hold-down bolts. Design calculation for Cable Bridge includes OBE and SSE as well as LOCA loads.
2013	TMI 1	2892013001R00	Technical Specification Prohibited Condition Due to an Inoperable 33 Station Battery Caused by a Cell Crack	Battery declared unable to perform design function in the event of a seismic event
2013	TMI 1	2892013001R01	Technical Specification Prohibited Condition Due to an Inoperable 33 Station Battery Caused by a Cell Crack	Battery declared unable to perform design function in the event of a seismic event

B.2 References

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APPENDIX C – SEISMICALLY-INDUCED STRESS AND SITUATION ASSESSMENT AT FUKUSHIMA DAIICHI

C.1 Discussion

As discussed in numerous post-mortems of the Fukushima Daiichi reactor accident (e.g., [1-4]), particularly post-accident interviews of Site Superintendent Masao Yoshida [5] and an anonymous TEPCO contractor [6], it is clear that the operating staff (including onsite contractors as well as TEPCO employees) were under considerable stress. Much of that was due to the unforeseen and deteriorating plant situation, but some was also due to concerns with offsite damage with consequent effect on families, homes, etc.[34]

It's also well-known that stress can affect operator situation assessment (as modeled by the IDHEAS macro-cognitive function "Understanding"). As discussed in NUREG-2114 [9], stress can cause

- Attentional narrowing and even tunneling
- Disorganization in scanning patterns
- Decreases in amount of information a person can attend to
- Decision making without considering all available information

This is particularly important in severe accident response since, as stated in the National Research Council's investigation of the Fukushima Daiichi reactor accident [3], "reliance on cognitive skills can become critically important when ad hoc responses are required for coping with unanticipated situations that are not well handled by the available procedural guidance and decision-support."

However, of interest to our project, it is less clear if stress due specifically to the earthquake and tsunami had a significant effect on the operators' situation assessment beyond that due to:

- the loss of information and control caused by the loss of power (this is addressed by the IDHEAS macro-cognitive function "Detection") and
- the stress due to the increasingly desperate plant conditions as the accident progressed (as such conditions can arise during non-seismically initiated accidents).

This appendix provides the evidence from numerous reports on the stress on plant personnel from the earthquake (including aftershocks and tsunamis), and of potential effects on situation assessment. We observe the following:

[34] In an analogous situation during Hurricane Andrew, the Turkey Point staff's expectation of severe offsite damage, in combination with loss of offsite communication, increased stress due to concerns regarding families and homes [7, 8]

- Not surprisingly, the eyewitness narratives provide a much more dramatic picture of the frames of mind of various actors.
- Although it is reasonable to hypothesize that the earthquake- and tsunami-induced stress affected such cognitive activities as situation assessment, we have not found any direct indication of such effects.[35]

[35] Note that Koike et al. [13] characterize the operators' decision to isolate the Unit 1 isolation condenser due to dryout concerns as a misinterpretation of the situation, i.e., a failure in situation assessment. However, this failure: a) was attributed to a lack of training and education, not stress; and b) occurred well into the accident (i.e., it was not an immediate effect of the earthquake or tsunami),

C.2 Data

Table C.1. Evidence of earthquake-induced stress and effects – before tsunami arrival

Reference	Quote	Notes
Investigation Committee Interim Report [1], p. 97	[Summary of state prior to tsunami arrival]: "The shift teams, the NPS ERC and the Tokyo Headquarters thought that they could put the reactors into a state of cold shutdown before the loss of all AC power sources due to the tsunami so long as they implement the prescribed procedures."	Indicates a reasonable state of confidence
Investigation Committee Interim Report [1], p. 98	[Immediately after initial shock]: "The shock of the earthquake caused the earthquake and fire alarms to sound in the Units 1&2 main control room at that time. The shift supervisor knew that even dust blown up into the air inside rooms activated the fire alarms at TEPCO's Kashiwazaki-Kariwa Nuclear Power Station … at the time of the Chuetsu-oki Earthquake in July 2007."	No evidence of surprise, likely not a major stressor.
Investigation Committee Interim Report [1], pp. 101-102	[Immediately after initial shock]: "Dust blown up in the air by the shock of the earthquake filled the main control room for Units 3 and 4 … In the white smoke screen, the shift team waited for the quake to cease and then started the normal scram response operation …"	Implies a calm response.
Investigation Committee Interim Report [1], pp. 101-102	[Before tsunami arrival]: "The [Units 3 & 4] shift team thought that they should activate the containment cooling system. At that time, however, a major tsunami warning had already been issued. If the tsunami arrived after the pumps were activated, the pumps would run dry and fail because they would be unable to pump water up as the water level fell due to the backrush of the tsunami. Unlike the shift team of the Units 1&2 main control room, the shift team on duty at the Units 3 & 4 main control room decided not to activate the pumps for the time being in preparation for the arrival of the tsunami and to wait and see what would happen."	Implies a calm consideration of situation, recognition of potential tsunami effects.
Investigation Committee Interim Report [1], pp. 109-110	[After tsunami warning, before tsunami arrival]: "Site Superintendent Yoshida first learned from the news on television that a three-meter high tsunami would hit the Fukushima Daiichi NPS then he learned that the estimated height had been changed to six meters. Site Superintendent Yoshida feet an apprehension that the Residual Heat Removal System (RHR) might lose its cooling function when (if) the emergency seawater pump facilities would be damaged by the backrush of the tsunami. At that moment, however, Site Superintendent Yoshida did not yet expect that more than one unit were to lose all AC power sources at once and station blackout would continue for a long time. He thought that even if the emergency seawater pump facility were damaged, the IC of Unit 1 and the RCICs of Units 2 and 3 could be used to cool down the reactors or they could recover cooling capability by restoring the pump facility while constructing power interchange facility between the units."	Implies calm consideration of situation, expectation of success.

Reference	Quote	Notes
Bulletin of the Atomic Scientists [6]	[During shock] “I first felt the earthquake as I walked from the vicinity of Units 5 and 6 – which are located near the ocean – to the site’s entrance gate. Suddenly, the asphalt began to ripple, and I couldn’t stay on my feet. In a panic, I looked around and saw a 120-meter exhaust duct shaking violently and looking like it would rupture at any second. Cracks began to appear on the outside of Unit 5’s turbine building and on the inside of the entryway to the unit’s service building. The air was filled with clouds of dirt.”	Direct reference to panic.
Bulletin of the Atomic Scientists [6]	[Workers trying to evacuate after initial shock] ‘”Let us out of here,” we yelled. “A tsunami may be coming!” Screams and shouts filled the air.’	Direct indication of panic.

Table C.2. Evidence of earthquake-/tsunami-induced stress and effects – after tsunami arrival

Reference	Quote	Notes
Investigation Committee Interim Report [1], pp. 110-111	“The NPS ERC received reports from the three main control rooms that the nuclear reactors were successively losing their power supplies and Units 1, 2 and 4 in particular had lost all of their power sources. Everyone at the NPS ERC was lost for words at the ongoing unpredicted and devastated state.”	Operators are stunned
Investigation Committee Interim Report [1], p. 111	“Site Superintendent Yoshida understood that a situation that far exceeded any expected major accident had actually taken place.”	Indicates surprise; presumably source of stress
Investigation Committee Interim Report [1], p. 112	“Site Superintendent Yoshida thought it would be impossible to take any action necessary to control the nuclear plants without the plant parameters, especially those for the reactor water level and pressure. He therefore directed the recovery team of the NPS ERC to give priority to restoring the equipment necessary for measuring the main parameters.”	Implies rational consideration of situation and alternatives.
Investigation Committee Interim Report [1], p. 113	“…the "Emergency Operating Procedure" for AM contained only internal events as causal events for AM and did not consider external events such as an earthquake or tsunami as causal events. There was no reference taking into account the events where all AC and DC power sources would be lost. In addition, the descriptions of the standards were written on the assumption that the state of the plants can be monitored by the control panel indicators and measuring instruments in the main control room and that the control panel could be manipulated. As a result, the shift team was forced to predict the reactor state according to a limited amount of information and take such procedures operators think best on the spot instead of following the instructions described in the standard manuals.”	Presumably a stress-inducing situation

Reference	Quote	Notes
Diet Report [2], Chapter 2, p. 17	"…the main control room had no information about events outside, including the status of the other reactors and power plants, and the safety of their families[31] Fear, stemming from a lack of information, caused mental stress among the workers[32] and made the emergency response even more difficult."	Direct statement of stress. References are to hearings with workers
TEPCO Report [10], p. 167	" the first floor of the S/B was flooded, meaning equipment and dosimeters needed to enter the controlled area were rendered unusable by seawater. Not only that, but entire racks were knocked down. Power from power source equipment within the building was entirely lost (both AC and DC). This shut down motorized valves and pumps, as well as monitoring instruments. By this point, events had already veered far from the conditions foreseen in procedures determined in advance. The return of an operator, sopping wet, shouting "There's seawater rushing in!" made MCR operators certain that a tsunami had struck. At this point, debris from the tsunami was scattered about the seaside area of the station, manhole covers had been washed away, and outdoor roads were sunken. It was in these dangerous conditions that building lighting was lost, leaving operators to grope through the darkness. Communication troubles meant no contact could be taken within the building (outside the MCR) or outside of it. Meanwhile, aftershocks kept striking and large tsunami alerts continued to stay in effect. Tsunamis of differing heights came relentlessly, meaning the risk of being swept away in a tsunami was far too great to leave the MCR on the second floor of the S/B and travel through the S/B 1F to go outside."	Unexpected condition: widespread damage and dangerous working environment; presumably a stress-inducing situation.
National Research Council Report [3], p. 111	"The lack of food, working toilets, and relief personnel during the early stages of the accident as well as the extended length of the accident response added greatly to personnel fatigue and distress. Plant personnel who responded to the accident exhibited a strong degree of self-sacrifice. Many suffered personal losses (homes destroyed or damaged, family members displaced or lost) but continued to work, in some cases for weeks following the tsunami."	Direct statement of fatigue and distress (based on Japanese reports)
Yoshida Testimony [5]	'Piecing together those bits of information led to the likely realization that the entire nuclear plant had been inundated by the tsunami. It finally dawned on Yoshida that he was confronting an unimaginable situation because events showed it was possible for all power sources at the plant to be lost. … Yoshida said, "To be honest, I was just devastated."'	Direct statement of frame of mind

Reference	Quote	Notes
Bulletin of the Atomic Scientists [6]	'…a section chief came rushing up to Fukushima's plant manager, Masao Yoshida, and reported: "A tank [has] been washed away and had sunk into the ocean." We all went pale with shock: The tank that had been lost was a surge tank of suppression pool water at the Fukushima Daiichi Nuclear Power Station. People continued coming in and out of the Crisis Center, delivering one report after another to Yoshida. Each time, the plant manager's shouts reverberated through a microphone: "That's not the question I asked!" and "Give me the answer to . . . this and that!" The workers surrounding Yoshida kept trying to get in touch with people at the reactor buildings at Units 1 through 4, but they were unsuccessful, because the dedicated on-site PHS [Personal Handy-phone System] base station had lost electrical power due to the tsunami.'	Direct indication of staff panic, decision maker stress.
Bulletin of the Atomic Scientists [6]	[Shortly after 4 pm, 3/11] "By this point, around 700 people had taken refuge in the earthquake-resistant building; and, because we had just conducted an emergency-preparedness drill the previous week, things were surprisingly orderly..TEPCOemployees handed out water and crackers, and we took turns using a PHS that was able to connect to the outside world to confirm the safety of our families. Meanwhile, some foreigners sat on the floor and chatted, and the female employees screamed during each aftershock."	Direct indication of panic.
New York Times article [11], 3/30/2011	'"My town is gone," wrote a worker named Emiko Ueno, in an email obtained by The Times. "My parents are still missing. I still cannot get in the area because of the evacuation order. I still have to work in such a mental state. This is my limit."'	Direct statement of stress due to offsite effects.
Inagaki presentation [12], p. 34	[Lesson] "In a total dark control room, operators feel strong fear."	Presumably reflects actual condition (i.e., not just a reasonable hypothesis)
Inagaki presentation [12], p. 45	[Operator testimony] '"In an attempt to check the status of Unit 4 D/G, I was trapped inside the security gate compartment. Soon the tsunami came and I was a few minutes before drowning, when my colleague smash opened the window and saved my life."'	Life threatening situation, presumably stressful
Koike et al. [13]	'Operators in high risk site were exposed to extreme conditions such as acute stress. The most important factors of extreme stressful conditions such as acute stress[7] are "Event that no one in the shift team had experienced", "Performance anxiety of equipments", "High radiation", and these factors had some impact on the operator's decision-making and actions which were required by the emergency procedures. Cognitive activity such as decision-making and task-planning has previously been found to be negatively affected by stress[8].'	Assessment based on reading of reports, press releases, on-site investigation. References [7] and [8] are general. Unclear if the link between human factors (e.g., stress) and problems with cognitive activities is assumed or the result of an investigation.

C.3 References

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APPENDIX D – IDHEAS-G CFMS AND PIFS

This appendix provides draft descriptions of the cognitive failure modes (CFMs) and performance influencing factors (PIFs). Work to finalize these descriptions, including some rewording and re-categorization of PIF attributes is ongoing.

Table D.1. IDHEAS-G CFMs

High-Level CFM	Mid-Level CFM	Detailed CFM
D – Failure of Detection	D1 - Fail to establish the mental model for detection	D1-1 Detection is not initiated (e.g., skip steps of procedure for detection, forget to check information, fail to realize the need to check information, fail to check the right information) D1-2 Wrong mental model for detection (e.g., incorrect planning on when, how, or what to detect) D1-3 Failure to prioritize information to be detected
	D2 - Fail to select, identify, or attend to sources of information	D2-1 Fail to access the source of information (e.g., fail to access, view, or measure partial or all sources) D2-2 Attend to wrong source of information
	D3 - Fail to perceive, recognize, or classify information	D3-1 Unable to perceive information D3-2 Key alarm not perceived D3-3 Key alarm incorrectly perceived D3-4 Fail to recognize that primary cue is not available or misleading D3-5 Cues not perceived D3-6 Cues misperceived (e.g., information incorrectly perceived; failure to perceive weak signals; reading errors; incorrectly interpret, organize, or classify information) D3-7 Fail to monitor status (e.g., information or parameters not monitored at proper frequency or for adequate period of time, failure to monitor all of the key parameters, and incorrectly perceiving the trend of a parameter)
	D4 - Fail to verify the perceived information	D4-1 Fail to self-verify the perceived information against the detection criteria D4-2 Fail to peer-check the perceived information
	D5 - Fail to communicate the acquired information	D5-1 The detected information not retained or incorrectly retained (e.g., wrong items marked, wrong recording, and wrong data entry) D5-2 The detected information not communicated or miscommunicated

High-Level CFM	Mid-Level CFM	Detailed CFM
U – Failure of Understanding	U1 - Fail to assess or select data	U1-1 Incomplete data selected (e.g., critical data dismissed, critical data omitted) U1-2 Incorrect or inappropriate data selected (e.g., failure to recognize the applicable data range or recognize that information is outdated)
	U2 - Incorrect mental model	U2-1 No mental model exists for understanding the situation U2-2 Incorrect mental model selected U2-3 Fail to adapt the mental model (e.g., fail to recognize and adapt mismatched procedures)
U – Failure of Understanding	U3 - Incorrect integration of data and mental model	U3-1 Incorrectly assess situation (e.g., situational awareness not maintained, and incorrect prediction of the system evolution or upcoming events) U3-2 Incorrectly diagnose problems (e.g., conflicts in data not resolved, under- diagnosis, fail to use guidance outside main procedure steps for diagnosis)
	U4 - Fail to iterate the understanding	U4-1 Premature termination of data collection (e.g., not seeking additional data to reconcile gaps, discrepancies, or conflicts, or fail to revise the outcomes based on new data, mental models, or viewpoints U4-2 Fail to generate coherent team understanding (e.g., assessment or diagnosis not verified or confirmed by the team, and lack of confirmation and verification of the results).
	U5 - Fail to communicate the outcome	U5-1 Outcomes of understanding miscommunicated or inadequately communicated
DM – Failure of Decisionmaking	DM1 - Incorrect goals or priorities	DM1-1 Incorrect goal selected DM1-2 Unable to prioritize multiple conflicting goals
	DM2 - Inappropriate decision model	DM2-1 Incorrect decision model or decisionmaking process (e.g., incorrect about who, how, or when to make decision, decision goal is not supported by the decision model or process) DM2-2 Incorrect decision criteria
	DM3 - Information is under-represented	DM3-1 Critical information not selected or only partially selected (e.g., bias, undersampling of information) DM3-2 Selected information not appropriate or not applicable to the situation DM3-3 Misinterpretation or misuse of selected information

High-Level CFM	Mid-Level CFM	Detailed CFM
	DM4 - Incorrect judgment or planning	DM4-1 Misinterpret procedure DM4-2 Choose inappropriate strategy or options DM4-3 Incorrect or inadequate planning or developing solutions (e.g., plan wrong or infeasible responses, plan the right response actions at wrong times, fail to plan configuration changes when needed, plan wrong or infeasible configuration changes) DM4-4 Decide to interfere or override automatic or passive safety-critical systems that would lead to undesirable consequences
	DM5 - Failure to simulate or evaluate the decision/ strategy/plan	DM5-1 Unable to simulate or evaluate the decision's effects (e.g., fail to assess negative impacts or unable to evaluate the pros and cons) DM5-2 Incorrectly simulate or evaluate the decision (e.g., fail to evaluate the side effects or components, or fail to consider all key factors) DM5-3 Incorrect dynamic decisionmaking
DM – Failure of Decisionmaking	DM6 - Fail to communicate or authorize the decision	DM6-1 Decision incorrectly communicated DM6-2 Decision not authorized DM6-3 Decision delayed in authorization
	E1 - Fail to assess action plan and criteria	E1-1 Action is not initiated E1-2 Incorrect interpretation of the action plan (e.g., wrong equipment/tool preparation, or coordination) E1-3 Wrong action criteria E1-4 Delayed implementation of planned action E1-5 Incorrect addition of actions or action steps to manipulate safety systems outside action plans (e.g., error of commission)
	E2 - Fail to develop/ modify action scripts	E2-1 Fail to modify, adapt, or develop action scripts for a high-level action plan E2-2 Incorrectly modify or develop action scripts for the action plan
E – Failure of Action Execution	E3 - Fail to coordinate action implementation	E3-1 Fail to coordinate the action implementation (e.g., fail to coordinate team members, errors in personnel allocation) E3-2 Fail to initiate action E3-3 Fail to perform status checking required for initiating actions
	E4 - Fail to perform the planned action	E4-1 Fail to follow procedures (e.g., skip steps in procedures) E4-2 Fail to execute simple action E4-3 Fail to execute complex action (e.g., execute a complex action with incorrect timing or sequence, execute actions that do not meet the entry conditions) E4-3A Fail to execute control actions E4-3B Fail to execute long-lasting actions E4-4 Fail to execute physically demanding actions E4-5 Fail to execute fine-motor actions

High-Level CFM	Mid-Level CFM	Detailed CFM
	E5 - Fail to verify or adjust action	E5-1 Fail to adjust action by monitoring, measuring, and assessing outcomes E5-2 Fail to complete entire action scripts or procedures (e.g., omit steps after the action criteria are met) E5-3 Fail to record, report or communicate action status or outcomes
T – Failure of Teamwork	T1 - Fail to establish or adapt the teamwork infrastructure	
	T2 - Fail to manage information	
	T3 - Fail to maintain shared situational awareness	
T – Failure of Teamwork	T4 - Inappropriately manage resources	
	T5 - Fail to plan/make interteam decisions or generate commands	
	T6 - Fail to implement decisions/commands	
	T7 - Fail to control the implementation	

Table D.2. IDHEAS-G PIFs

PIF Category	PIF
environment- and situation-related	pE1 – accessibility/habitability of workplace including travel paths
	pE2 – workplace visibility
	pE3 – noise in workplace and communication pathways
	pE4 – cold/heat/humidity
	pE5 – resistance to physical movement
system-related	pS1 – system and I&C transparency to personnel
	pS2 – human-system interface (HSI)
	pS3 – equipment and tools
personnel-related	pP1 – staffing
	pP1 – procedures, guidance, and instructions
	pP2 – training
	pP3 – teamwork and organizational factors
	pP4 – work processes
task-related	pT1 – information availability and reliability
	pT1 – scenario familiarity
	pT2 – multitasking, interruptions, and distractions
	pT3 – task complexity
	pT4 – mental fatigue
	pT5 – time pressure and stress
	pT6 – physical demands

APPENDIX E – HEAF EVENTS

This appendix provides a listing of U.S. HEAF events, including author judgments as to whether the event cause is potentially relevant to seismic PRA, and whether the cause would have been detectable by a typical seismic PRA walkdown.

E.1 Events

Date	Plant	LER/Event Notification	HEAF Bin[a]	Root Cause / Discussion	Seismic Implica-tions?	Detectable During Visual Walkdown?	Room
04/15/1980	Browns Ferry 1	2591980031	16.1	The root cause of this event was fault condition at busway joint. The apparent cause of the failure was a loose busway bolt. Bolted connections which have relaxed or loosened can be exacerbated by ground shake events.	Yes	No	Switchgear room
08/02/1984	Yankee-Rowe	0291984013	16.a	The root cause of the occurrence has been attributed to above normal electrical resistance in the main disconnecting contacts of the breaker. The resistance caused the fault when the contacts were called upon to carry the starting current of the LPSI pump motor. As seen in past seismic events, ground shake can damage or effect the alignment between the stabs in the cubicle and the breaker. This misalignment can affect the connection and misalignment can make the connection worse which could aggravate the underlying deficiency which could lead to an arcing event.	Yes	No, unless thermography included	Switchgear room
03/19/1987	La Salle 1	3731987014	16.1	The apparent cause of the event has been determined to be moisture intrusion into one of the bus ducts during recent temperature inversions coupled with the cycling of the UAT (during unit startups and shutdowns) over the same period. The moisture intrusion could have had the compounding effect of leaving contaminants on the bus bars and insulators which over a period of time could have contributed to the cause of the fault. The destructive nature of the fault hampered the investigation process, and it is not known on which bus duct (4.1 or 6.9 KV) the fault occurred. There is little information to indicate this event could have occurred due to a seismic event unless potential sources of seismic related flooding are investigated. The level of contamination overtime was unknown.	Unknown	No	Switchyard

Date	Plant	LER/Event Notification	HEAF Bin[a]	Root Cause / Discussion	Seismic Implica-tions?	Detectable During Visual Walkdown?	Room
07/10/1987	Kewaunee	3051987009	16.1	The root cause of the event was an insulation failure on the Bus Bar compounded by accumulation of particulate debris. The Bus Bar runs perpendicular to Turbine Building Ventilation Fans mounted in the Building exterior wall. The fan's suction pulled dust filled air through the section of the Bus Bar. Dust and metallic powder debris collected on the outside of the Bus Bar insulation. The insulation failure combined with the accumulated dirt provided a tracking path from phase to ground. The phase to ground fault progressed to a phase to phase fault which accounted for the extensive bus damage. FME and the buildup or aggravation of FME during a ground shake event could have led to an arcing event.	Yes	No (unless bus way was opened)	Switchgear room
03/02/1988	Kewaunee	3051988001	16.1	The root cause of the event was an insulation failure on the Bus Bar at the Bus Bar support combined with the accumulation of debris and water. The Bus Bar runs horizontally into the Auxiliary Building underneath various areas where debris can fall into the bus work. Above the faulted section of bus bar, a plastic hose which was designed to empty into a floor drain, was emptying on the floor and it is suspected that water may have dripped onto the bus work. The insulation failure combined with the accumulated dirt and water provided a tracking path for the fault. FME and the buildup or aggravation of FME during a ground shake event could have led to an arcing event.	Yes	No (unless bus way was opened)	Switchgear room
07/06/1988	Palo Verde 1	5281988010	16.b	The initial fault current path was from the "B" phase bus across the support bar to ground, which initiated a three-phase fault to ground. Although this is indicated by information obtained from the Digital Fault recorder, there was too much damage from the second fault to positively identify this. There was evidence of a buildup of dirt on the floor of the "B" cubicle and potential arc tracking conditions. FME and the buildup or aggravation of this dirt during a ground shake event could have led to an arcing event.	Yes	No, unless cubicle was opened	Switchgear room

Date	Plant	LER/Event Notification	HEAF Bin[a]	Root Cause / Discussion	Seismic Implica-tions?	Detectable During Visual Walkdown?	Room
01/03/1989	Oconee 1	2691989002 (not electronically available on ADAMS)	16.b	The root cause was theorized to have been switchgear failure due to arcing at "plug-in" connections which resulted in cross phase arcing, or a fire in the DC control circuitry cabling which caused cross phase arcing. However it was not possible to determine the cause with any certainty due to the level of damage. If the "plug-in" connections were the cause of the arc then ground shake could have damaged or effected the alignment between the connections in cubicle and the breaker. The misalignment could have affected the connection and misalignment can make the connection worse which could aggravate the underlying deficiency which could lead to an arcing event. If a fire in the DC control circuitry was the cause it is uncertain if seismic activity would have led to this event.	Unknown	Unknown	Switchgear room
10/09/1989	Harris	4001989017 (not electronically available on ADAMS)	16.2	These ground faults were apparently caused by aluminum debris carried down the bus duct by the forced air cooling system. The aluminum debris entered the bus duct as a result of previous damper failures in the bus duct cooling system. These failures occurred on February 27, 1988, and in the summer of 1989. Arcing between the conductor and the enclosure occurred over a fifty (50) foot length of the "A" phase bus immediately upstream of the "B" main power transformer. Ionization from this arcing reduced the dielectric strength of the cooling air which was carried into the bushing box of the "B" main power transformer. This caused an "A" phase to ground flashover in the bushing box, which immediately propagated to the "B" phase bushing. The fault cracked both low voltage bushings, causing oil to leak from the bushings, and ignited the leaking oil. FME and the buildup or aggravation of FME during a ground shake event could have led to an arcing event.	Yes	No (unless bus way was opened)	Turbine building

Date	Plant	LER/Event Notification	HEAF Bin[a]	Root Cause / Discussion	Seismic Implica-tions?	Detectable During Visual Walkdown?	Room
06/10/1995	Waterford 3	3821995002	16.b	The root cause of this event was the failure of a lightning arrester with a combination of a failure of a breaker. This led to a non-vital switchgear failure and fire in the breaker cubicle for the startup transformer. The lightning strike was the underlying cause of the event.	No	No	Switchgear room
05/15/2000	Diablo Canyon 1	2752000004	16.1	The root cause is believed to be associated with long-term degradation, and/or inadequate preventive maintenance (PM) exacerbated by a marginal design. Long term degradation issues could potentially be exacerbated during seismic events.	Yes	Unknown	Switchgear room
02/03/2001	San Onofre 2/3	3622001001	16.b	The root cause of the event could not be determined due to the extensive damage.	Unknown	Unknown	Switchgear room

Date	Plant	LER/Event Notification	HEAF Bin[a]	Root Cause / Discussion	Seismic Implica-tions?	Detectable During Visual Walkdown?	Room
08/03/2001	Prairie Island 1	2822001005 2822001006	16.b	The root cause of this event was poor electrical connection between the Breaker phase primary disconnect assembly (PDA) and the bus stab, which led to overheating of the PDA, which in turn led to a failure of the PDA one or two seconds after the breaker was closed. The failure of the PDA led to a C-phase to ground arcing event, which quickly involved all phases. The arcing led to actuation of the protective relaying, which resulted in a turbine/reactor trip. The poor electrical connection was caused by poor conductive surfaces. A thinned silver coating on the connections exposed copper oxides in the conductors. Because copper oxide has resistance that is orders of magnitude higher than copper, silver, or silver oxide, this led to a high resistance connection, and overheating. The silver layer was most likely thinned by environmental and operating conditions and/or maintenance practices. As seen in past seismic events, ground shake can damage or effect the alignment between the stabs in the cubicle and the breaker. This misalignment can affect the connection and misalignment can make the connection worse which could aggravate the underlying deficiency which could lead to an arcing event.	Yes	No, unless thermography included	Switchgear room
07/27/2008	Browns Ferry 2	EN-44367	16.1	Unknown	Unknown	Unknown	Cooling Towers
08/05/2009	Columbia 2	3972009004	16.1	The most probable cause of the bus failure is a relaxation of bolted connections on the center phase flexible link(s) caused by repeated thermal cycles over time. The root cause identified for this event was the nonperformance of preventative maintenance (PM) tasks for torque checks of the non-segregated bus links. Bolted connections which have relaxed or loosened can be exacerbated by ground shake events.	Yes	No	Turbine building

Date	Plant	LER/Event Notification	HEAF Bin[a]	Root Cause / Discussion	Seismic Implica-tions?	Detectable During Visual Walkdown?	Room
03/07/2010	Palo Verde 1	[5282010001]()	16.1	The root cause of this event was a combination of water intrusion and the likely degradation of Noryl insulation resulting in a ground fault on phase A, which then ionized the air inside the bus duct, resulting in a phase A to B fault that was then interrupted by bus protective relays. There is little indication to indicate this event could have occurred due to a seismic event unless potential sources of seismic related flooding are investigated.	No	No	Switchyard
03/28/2010	Robinson 2	[2612010002]()	16.b	The cause of the fault was overheating of the center bus bar at the flex connection. This overheating may have resulted from repeated deferrals of portions of the preventive maintenance tasks that deal with the inspection of the flexible link bolt torque over an eight-year period. Long term degradation issues could potentially be exacerbated during seismic events.	Yes	No, unless thermography included	Turbine building
02/12/2011	River Bend	No public reference	16.a	Due to the extensive damage to the transformer bus duct, it was not possible to determine the definite cause of the bus fault. The most probable cause of the bus duct fault was loosening of the bus joint connector bolt due to relaxation of the torque at the connection joint caused by heating cycles. As the bolt torque reduced, the looseness in the connection of the joint created a hot spot. The excess heat damaged the insulating components between the bus duct phases in the joint. The damage to the insulation increased until a fault occurred between the phases. The bus duct in question is non-segregated and the bus phases are on top of each other only separated by the insulating components. Once the insulation between phases was damaged to the point that it could not separate 480 volts of potential, the degradation would have progressed rapidly. Failure of a bus duct due to connection joint loosening and localized heating is a failure mode that can be seen in past external operating experience. Between the times that the connector bolt torque is checked, a yearly thermography PM is in place so connection joint localized heating can be caught before it becomes excessive. Long term degradation issues could potentially be exacerbated during seismic events.	Yes	No, unless thermography included	Cooling Tower

Date	Plant	LER/Event Notification	HEAF Bin[a]	Root Cause / Discussion	Seismic Implica-tions?	Detectable During Visual Walkdown?	Room
06/07/2011	Fort Calhoun	2852011010	16.a	The most probable cause of the fault was a high resistance connection on the line side of the 1B4A cubicle. As seen in past seismic events, ground shake can damage or effect the alignment between the stabs in the cubicle and the breaker. This misalignment can affect the connection and misalignment can make the connection worse which could aggravate the underlying deficiency which could lead to an arcing event.	Yes	No, unless thermography included	Switchgear room
07/03/2013	Palo Verde 1	EN-49169	16.b	The root cause of this event was FME in the form of a shield wire which made contact with the A phase bus bar. FME effects or aggravation of FME during a ground shake event could have led to an arcing event.	Yes	No, unless enclosure was opened	Turbine Building
07/26/2013	Callaway	4832013008	16.2	The root cause of this event was FME. FME effects or aggravation of FME during a ground shake event could have led to an arcing event.	Yes	No, unless busway was opened	Turbine Building
12/09/2013	Arkansas 2	3682013004	16.1	The most Probable Root Cause to the bus faults is improper installation of the 6900V flexible links inside the Turbine Building which allowed degradation of the flex link connections. Contrary to Tech Manual instructions, the bolting around the 'A' and 'B' phase flex links contained little if any putty or Duxseal around the bolt heads. Also, there was a layer of what appeared to be light grey Scotch 70 Self Fusing Silicone Rubber Electrical Tape over the bolted joints and bolt heads. Long term degradation issues could potentially be exacerbated during seismic events.	Yes	Yes, portions of the root cause could be inspected through visual walkdown however it is noted that portions of the necessary inspections would be intrusive and not possible or recommended during inspection	Switchgear room
02/07/2016	Brunswick 1	3252016001	16.b	Unknown	Unknown	Unknown	Switchgear room

Date	Plant	LER/Event Notification	HEAF Bin[a]	Root Cause / Discussion	Seismic Implica-tions?	Detectable During Visual Walkdown?	Room
01/17/2017	Cooper	Inspection Report 05000298/2017011	16.1	The root cause of this event was corona tracking and potential long term degradation within the bus duct. Long term degradation issues could potentially be exacerbated during seismic events.	Yes	No	Switchyard
03/18/2017	Turkey Point 3	2502017001	16.b	The root cause of this event was FME. FME effects or aggravation of FME during a ground shake event could have led to an arcing event.	Yes	No, unless enclosure was opened	Switchgear room

[a]HEAF bins:

16.a Plant-Wide Components HEAF for low-voltage electrical cabinet (480-1000 V)
16.b Plant-Wide Components HEAF for medium-voltage electrical cabinet (>1000 V)
16.1 Plant-Wide Components HEAF for segmented bus duct
16.2 Plant-Wide Components HEAF for iso-phase bus duct

E.2 References

[1] NRC Information Notice 89-64, "Electrical Bus Bar Failures," September 7, 1989.

[2] IEEE Standard 142-1982, "Recommended Practice for Grounding of Industrial and Commercial Power Systems," 1982.

[3] IEEE, "The Reality of High Resistance Grounding," *IEEE Transactions of Industry Applications*, **1A-13**, No. 5, pages 469-475, September/October 1977.

APPENDIX F – U.S. SEISMIC PRA PERSPECTIVES

F.1 Results of Seismic PRAs

Seismic events have long been recognized as potentially important contributors to nuclear power plant risk. Figure F.1 shows the CDF results reported by the 1982 utility-sponsored Indian Point Probabilistic Safety Study [1]; Figure F.2 shows the CDF results reported by the NRC's NUREG-1150 study in 1990 [2].[36] These figures also illustrate the large uncertainties associated with the CDF estimates.

The understanding that seismic events can be important to risk has continued to today. Figures F.3-F.4 provide various views on seismic CDF produced by industry analyses as part of: a) the Individual Plant Examination of External Events (IPEEE) program of the late 1990s [3]; and b) more recent environmental impact statements supporting license renewal applications. The latter require cost-benefit analyses of Severe Accident Mitigation Alternatives (SAMAs), and these generally employ the results of PRAs. The NRC staff's evaluation of the submittals are documented in plant-specific supplements to NUREG-1437 [4].

The most recent publicly available, industry-developed seismic PRA results are provided in industry responses to NRC's March 12, 2012 request for information associated with recommendation 2.1 of the Fukushima Near-Term Task Force (NTTF) [5]. These analyses show that for the plants performing detailed analysis, seismic events can be significant or even dominant contributors to total CDF. They can also be important contributors to large early release frequency (LERF).[37]

Figures F.6 and F.7 how the seismic CDFs and conditional core damage probabilities (CCDP) vary with PGA at a number of plants.[38,39] Figures F.8 and F.9 present similar information for LERF. It can be seen that the recent analyses consider much higher PGAs than addressed in NUREG-1150. It can also be seen that there is considerable variation across plants. Even for the same plant (Peach Bottom), there are considerable differences between the NUREG-1150 and current analyses. Without more detailed investigation, we do not know to what degree the differences are due to fundamental changes in current state of knowledge (e.g., about Central-Eastern United States – CEUS – seismic hazard) versus different modeling choices. More investigation would also be needed to understand the underlying reasons for the different shapes shown for Diablo Canyon (a Western United States – WUS – plant) and for the CEUS plants.

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[36] The NUREG-1150 results shown are based on the EPRI hazard curves. Results based on hazard curves developed by Lawrence Livermore National Laboratory (LLNL) would indicate higher CDFs.

[37] Note that the Oconee plant has committed to performing modifications to reduce the seismic contribution to LERF at all three units [6].

[38] The data are from licensee submittals [7-13]. Results from NUREG-1150 are provided for comparison.

[39] The CCDPs are the conditional probabilities of core damage, given a seismic event with the specified PGA.

F.2 Seismic PRA Maturity – Views Within Seismic PRA Community

The large uncertainties shown in Figures F.1 and F.2 illustrate the more general point that seismic risk estimates are subject to large uncertainties, with much of the uncertainty being attributed to seismic hazard estimates for severe earthquakes [14]. Despite these large uncertainties, there seems to be little concern within the seismic PRA community regarding the maturity of seismic PRA as a tool for practical decision support. Ref. 15 provides a recent affirmation in this regard.[40]

F.3 References

[1] B.J. Garrick, "Accelerating implementation of contemporary nuclear safety assessment," Keynote Presentation, U.S.-Japan Probabilistic Risk Assessment Roundtable, Tokyo, Japan, February 20–21, 2014.

[2] U.S. Nuclear Regulatory Commission, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," *NUREG-1150*, December 1990.

[3] U.S. Nuclear Regulatory Commission, "Perspectives Gained from the Individual Plant Examination of External Events (IPEEE) Program," *NUREG-1742*, April 2002.

[4] U.S. Nuclear Regulatory Commission, "Generic Environmental Impact Statement for License Renewal of Nuclear Plants," *NUREG-1437, Rev. 1*, June 2013.

[5] U.S. Nuclear Regulatory Commission, "Request for Information Pursuant to 10 CFR 50.54(f) Regarding Recommendations 2.1, 2.3, and 9.3 of the NTTF Review of Insights from the Fukushima Daiichi Accident," March 12, 2012. (ML12053A340)

[6] U.S. Nuclear Regulatory Commission, Oconee Nuclear Station, Units 1, 2, and 3 – Staff Review of Seismic Probabilistic Risk Assessment Associated with Reevaluated Seismic Hazard Implementation of the Near-Term Task Force Recommendation 2.1: Seismic (EPID NO. L-2018-JLD-0173), November 29, 2019. (ML19267A022)

[7] Southern Nuclear, "Vogtle Electric Generating Plant Units 1 and 2, Fukushima Near-Term Task Force Recommendation 2.1: Seismic, Seismic Probabilistic Risk Assessment," March 27, 2017. (ML17088A130)

[8] Tennessee Valley Authority, "Seismic Probabilistic Risk Assessment for Watts Bar Nuclear Plant, Units 1 and 2 - Response to NRC Request for Information Pursuant to Title 10 of the Code of Federal Regulations 50.54(f) Regarding Recommendation 2.1 of the Near-Term Task Force Review of Insights from the Fukushima Daiichi Accident," June 30, 2017. (ML17181A485)

[9] Virginia Electric and Power Company, "Virginia Electric and Power Company North Anna Power Station Units 1 and 2 Response to March 12, 2012 Information Request, Seismic Probabilistic Risk Assessment for Recommendation 2.1," March 28, 2018. (ML18093A445)

[10] Tennessee Valley Authority, "Tennessee Valley Authority (TVA) - Watts Bar Nuclear Plant Seismic Probabilistic Risk Assessment Supplemental Information," April 10, 2018. (ML18100A966)

[40] It should be recognized that there are also naysayers. See, for example, Ref. 16. However, such views seem to be in a small minority, at least within the seismic PRA community.

[11] Pacific Gas and Electric Company, “Seismic Probabilistic Risk Assessment for the Diablo Canyon Power Plant, Units 1 and 2 - Response to NRC Request for Information Pursuant to 10 CFR 50.54(f) Regarding Recommendation 2.1: Seismic of the Near-Term Task Force Review of Insights from the Fukushima Dai-Ichi Accident,” April 24, 2018. (ML18120A201)

[12] Exelon Corporation, “Seismic Probabilistic Risk Assessment Report, Response to NRC Request for Information Pursuant to 1 O CFR 50.54(f) Regarding Recommendation 2.1 of the Near-Term Task Force Review of Insights from the Fukushima Daiichi Accident,” August 28, 2018. (ML18240A065)

[13] South Carolina Electric and Gas Co., “Virgil C. Summer Nuclear Station (VCSNS), Unit 1, Docket No. 50-395, Operating License No. Npf-12, Fukushima Near-Term Task Force Recommendation 2.1: Seismic, Seismic Probabilistic Risk Assessment,” September 28, 2018. (ML18271A109)

[13] American Society for Mechanical Engineers and American Nuclear Society, “Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications,” *ASME/ANS RA-Sb-2013, Addendum B to RA-S-2008*, ASME, New York, NY, American Nuclear Society, La Grange Park, Illinois, 2013.

[14] “Seismic Probabilistic Risk Assessment Implementation Guide,” Electric Power Research Institute, Palo Alto, CA, 2013: *3002000709*.

[15] M.K. Ravindra, “All’s Well in SPRA Land!,” Pre-PSAM 14 workshop on “Which way SPRA?” Los Angeles, CA, 2018.

[16] F. Mulargia, P.B. Stark, R.J., Geller, “Why is Probabilistic Seismic Hazard Analysis (PSHA) Still Used?” *Physics of the Earth and Planetary Interiors*, 2016.0 doi: http://dx.doi.org/10.1016/j.pepi.2016.12.002

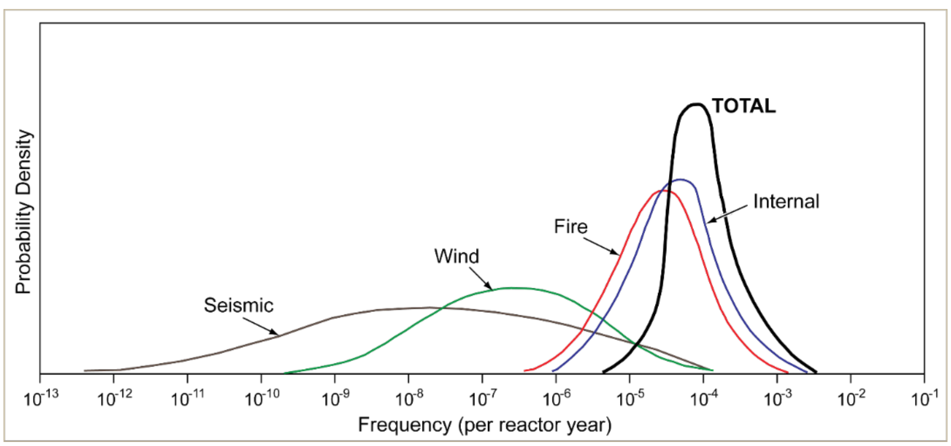

Figure F.1. CDF Contributors – Indian Point Probabilistic Safety Study [1][41]

[41] Some graphical elements have been enhanced for improved visibility.

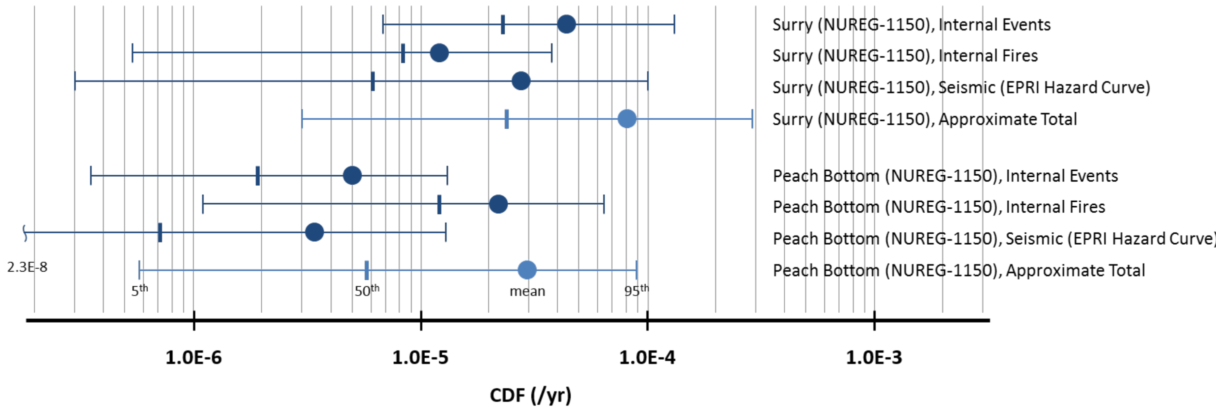

Figure F.2. CDF Contributors – NUREG-1150 (based on [2])

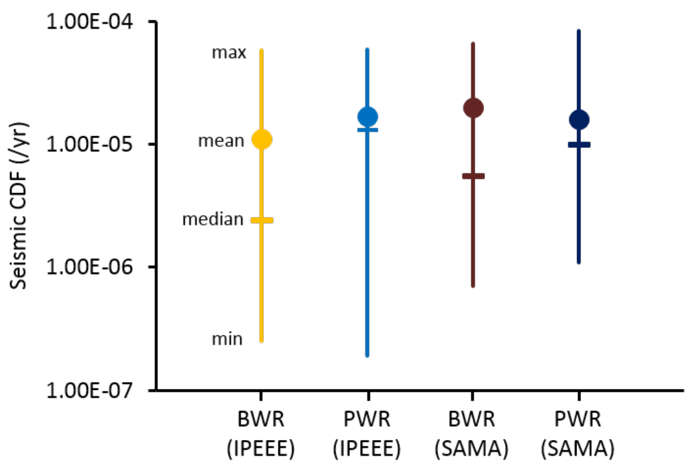

Figure F.3. Seismic CDFs – IPEEE and SAMA Analyses

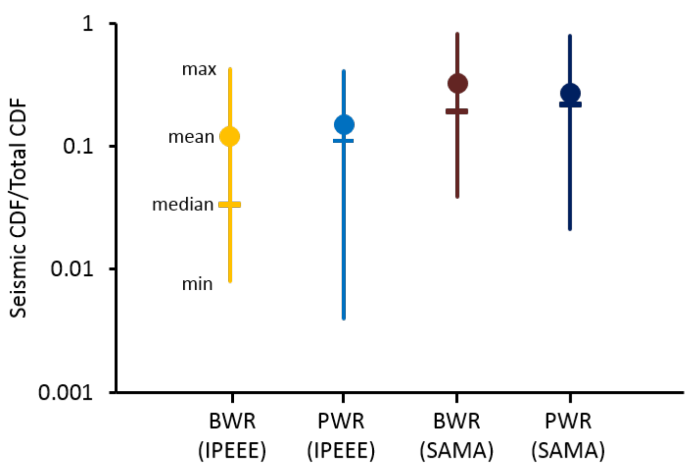

Figure F.4. Seismic CDF Contribution – IPEEE and SAMA Analyses

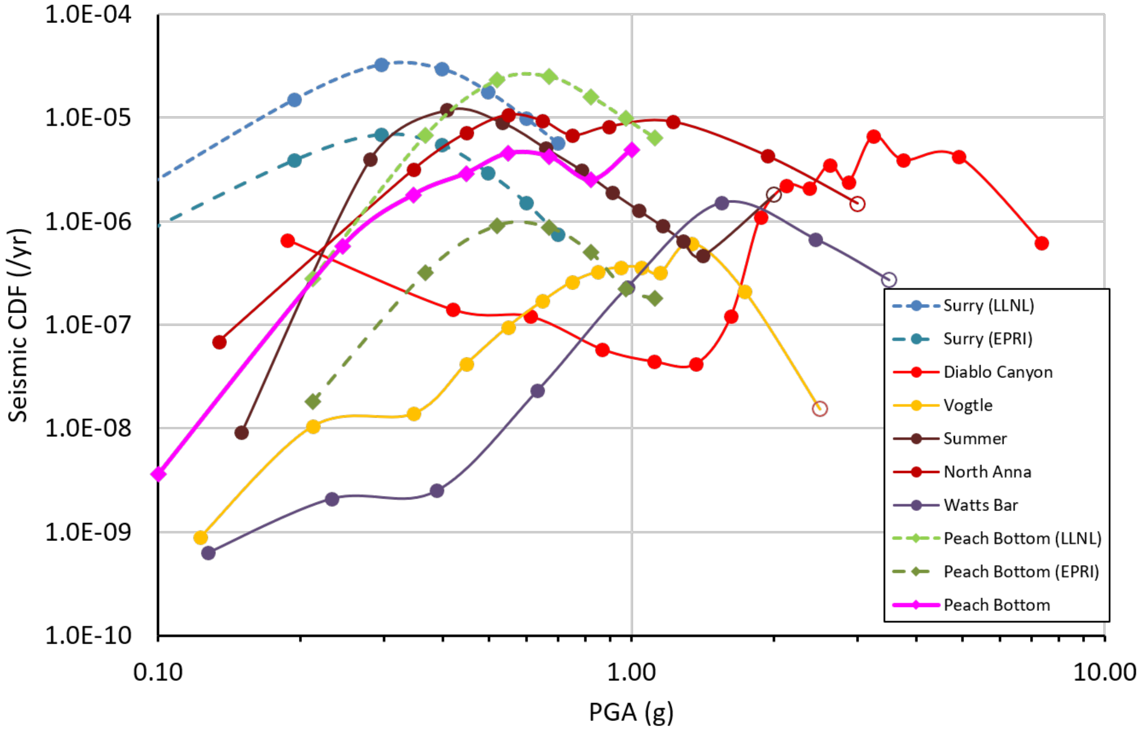

Figure F.6. Seismic CDF by PGA – NUREG-1150 to NTTF 2.1

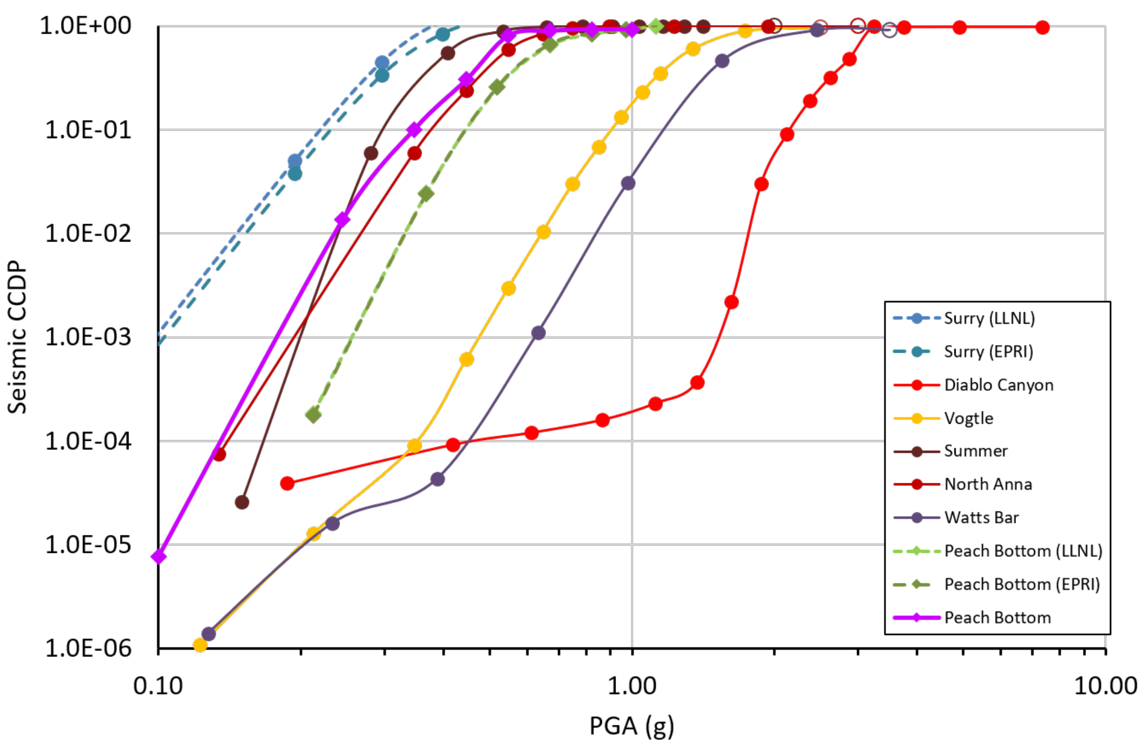

Figure F.7. Seismic CCDP by PGA – NUREG-1150 to NTTF 2.1

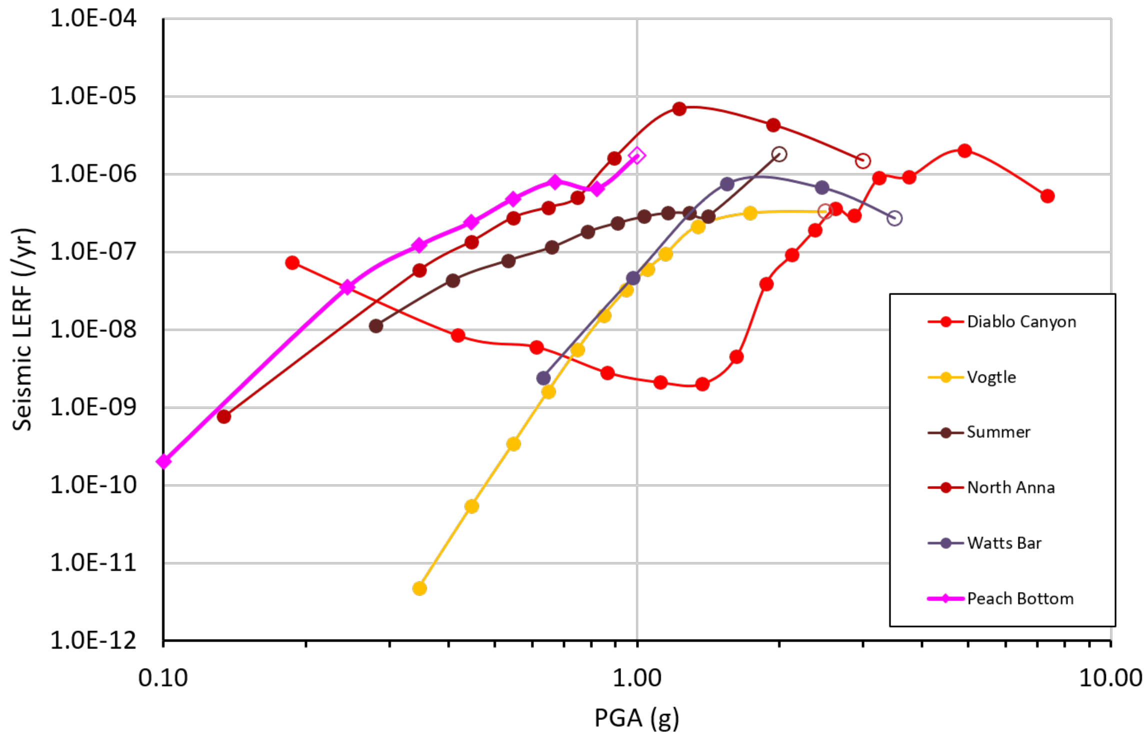

Figure F.8. Seismic LERF by PGA – NTTF 2.1

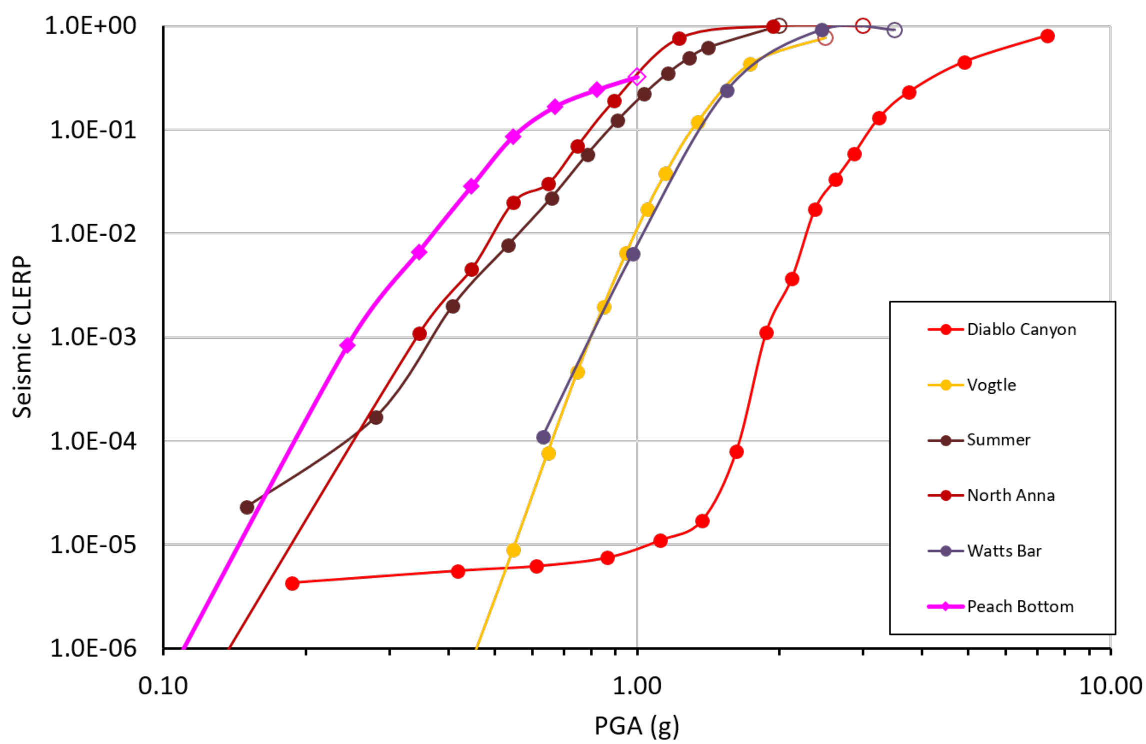

Figure F.9. Seismic CLERP by PGA – NTTF 2.1