When Model Meets Reality – A Review of SPAR Level 2 Model Against Fukushima Accident

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WHEN MODEL MEETS REALITY

– A REVIEW OF SPAR LEVEL 2 MODEL AGAINST FUKUSHIMA ACCIDENT

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ABSTRACT

The Standardized Plant Analysis Risk (SPAR) models are a set of probabilistic risk assessment (PRA) models used by the Nuclear Regulatory Commission (NRC) to evaluate the risk of operations at U.S. nuclear power plants and provide inputs to risk informed regulatory processes. A small number of SPAR Level 2 models have been developed mostly for feasibility study purposes. They extend the Level 1 models to include containment systems, group plant damage states, and model containment phenomenology and accident progression in containment event trees.

A severe earthquake and tsunami hit the eastern coast of Japan in March 2011 and caused significant damages on the reactors in Fukushima Daiichi site. Station blackout (SBO), core damage, containment damage, hydrogen explosion, and intensive radioactivity release, which have been previously analyzed and assumed as postulated accident progression in PRA models, now occurred with various degrees in the multi-unit Fukushima Daiichi site.

This paper reviews and compares a typical BWR SPAR Level 2 model with the "real" accident progressions and sequences that occurred in Fukushima Daiichi Units 1, 2, and 3. It shows that the SPAR Level 2 model is a robust PRA model that could very reasonably describe the accident progression for a real and complicated nuclear accident in the world. On the other hand, the comparison shows that the SPAR model could be enhanced by incorporating some accident characteristics for better representation of severe accident progression.

Key Words: probabilistic risk assessment (PRA), SPAR model, severe accident, station blackout, Fukushima Accident

1 INTRODUCTION

The Standardized Plant Analysis Risk (SPAR) models are a set of PRA models used by the Nuclear Regulatory Commission (NRC) to evaluate the risk of operations at U.S. nuclear power plants and provide inputs to risk informed regulatory process. They were originated in 1995 to support NRC's risk analysis program. The models and the SAPHIRE code were developed at the Idaho National Laboratory (INL). The SPAR models have been used by the NRC to provide inputs to the following risk informed regulatory processes:

- Significance Determination Process (SDP)
- Management Directive 8.3

- Accident Sequence Precursor (ASP)
- Mitigating Systems Performance Index (MSPI)
- Notice of Enforcement Discretion (NOED)

There are 79 linked fault tree/event tree SPAR Level 1 models for 104 U.S. operating nuclear power plants. A small number of SPAR Level 2 models have also been developed mostly for feasibility study purpose. The Level 2 model extended the Level 1 model to include containment systems, group plant damage states, and model containment phenomenology and accident progression in containment event tree.

Early on March 11, 2011, a severe earthquake that was the largest Japan has ever experienced occurred off the coast of the Fukushima Daiichi Nuclear Power Station operated by Tokyo Electric Power Company (TEPCO). Fukushima Daiichi consists of six boiling water reactors (BWRs). Unit 1 is a BWR 3 reactor, Units 2 through 5 are BWR 4, and Unit 6 is a BWR 5. Units 1 through 5 have Mark I containments, and Unit 6 has a Mark II containment. Units 1, 2, and 3 were operating at full power and Units 4, 5, and 6 were out of service for refueling or maintenance when the earthquake occurred. The earthquake resulted in a scram and a regional loss of electrical power. The emergency diesel generators (EDGs) started and loaded to maintain cooling at the plants. Fifty-one minutes later, a series of tsunamis produced by the earthquake hit the Daiichi site. The tsunamis exceeded the design basis of the plants and submerged buildings resulting in the loss of EDGs and station blackout (SBO). DC power was also lost at Units 1 and 2. With no or limited core cooling to remove decay heat, Units 1, 2, and 3 suffered core damage of varying degrees. Challenges in venting containments contributed to containment pressures exceeding design pressure, which may have caused containment damage and leakage. Hydrogen generated from the damaged fuel in the reactors accumulated in the reactor buildings from containment venting operations or other leaks, and finally ignited, producing explosions in the Unit 1 and Unit 3 reactor buildings. The hydrogen generated in Unit 3 may have migrated into the Unit 4 reactor building, resulting in a subsequent explosion and damage. The loss of primary and secondary containment integrity resulted in ground-level releases of radioactive material.

The Fukushima accident was the most severe nuclear accident occurred in the world since the 1986 accident at Unit 4 of Chernobyl nuclear power plant. Unlike Chernobyl accident, the BWR designs of Fukushima Daiichi plants were widely used in United States. A comparison of a typical SPAR BWR model (Level 1 and Level 2) with the Fukushima accident will be a good practice to check the model with the reality.

2 COMPARING FUKUSHIMA ACCIDENT WITH SPAR MODEL

Only Daiichi Units 1, 2, and 3 accident progressions are compared with the SPAR at-power model. Daiichi Units 4, 5, and 6 were out of service for refueling or maintenance when the earthquake occurred. The SPAR model represents a typical BWR 4 plant with Mark I containment, same design with Daiichi Units 2 and 3. Although Daiichi Unit 1 is a BWR 3 reactor which has different design features from the BWR 4 used as the basis for the SPAR model, such as the using of isolation condensers for high pressure core injection, it is included in the comparison since it represents the unique short-term SBO scenario.

While there are different reports and sources on the Fukushima accident progressions, this paper is mostly based on the information from the Institute of Nuclear Power Operations (INPO) report [1] and the Sandia National Laboratories (SNL) analysis [2]. The postulated general sequence of events occurred at the Fukushima Daiichi site, according to the SNL analysis, is presented in Figure 1 for a high level of review.

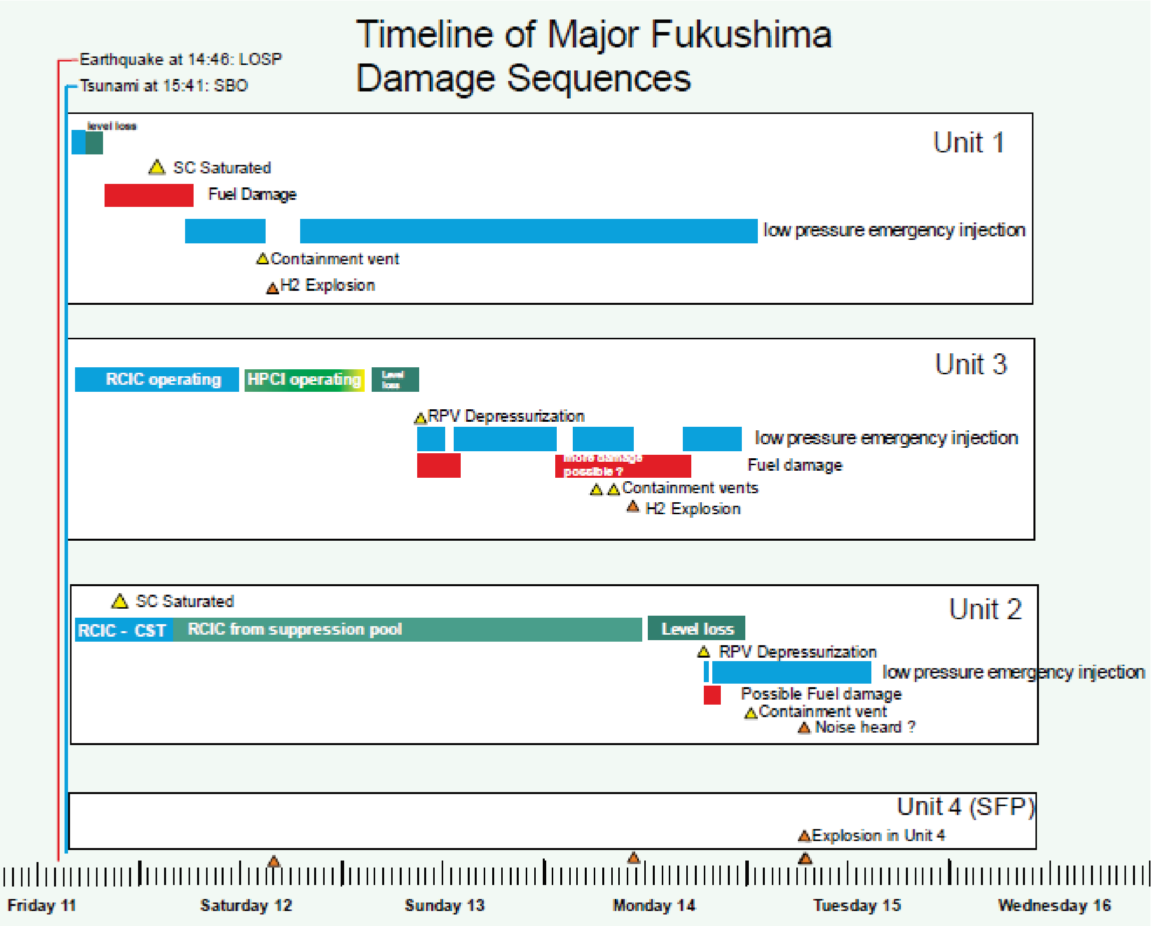

Figure 1. Postulated General Sequence of Events at the Fukushima Daiichi Reactor Site [2]

2.1 Initiating Event - Earthquake

The initiating event of the Fukushima Daiichi nuclear accident is a magnitude 9.0 earthquake that occurred off the eastern coast of Japan. The earthquake damaged breakers and distribution towers, causing a loss of all off-site power (LOOP) to the site. This is modeled in Sequence 2 of the SPAR EQK-BIN-3 event tree (Figure 2): IE-EQK-BIN-3 * LOOP-EQ3. Note that the peak ground acceleration (PGA) measured at Fukushima Daiichi was 0.469g, 0.561g, and 0.517g in the horizontal direction at Units 1, 2, and 3, respectively [1]. The SPAR EQK-BIN-3 event tree models the seismic event category with PGA > 0.5g in a three-seismic-bin approach [3], and is used here to represent the severe earthquake occurred in Japan.

The sequence is transferred to the SPAR EQK-LOOP event tree.

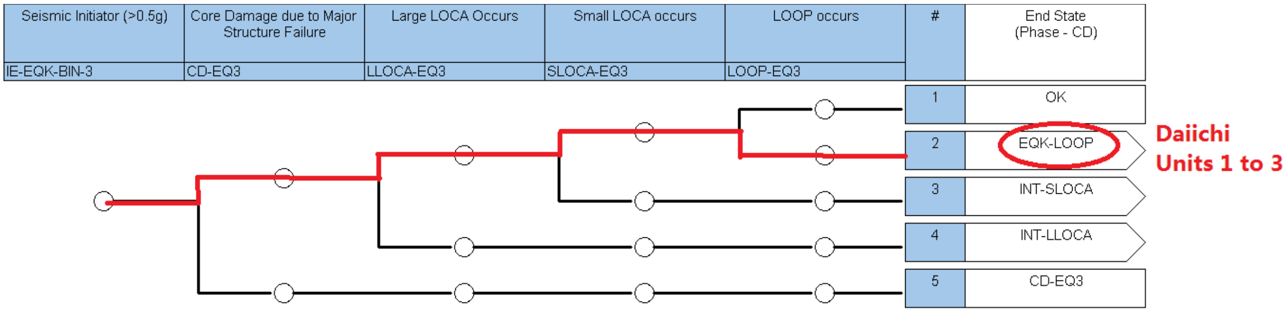

Figure 2. Fukushima Daiichi SPAR Accident Sequence – EQK-BIN-3-S2

2.2 LOOP and SBO

2.2.1 LOOP

After the earthquake, Daiichi Units 1, 2, and 3 automatically shut down. The emergency diesel generators (EDGs) automatically started and provided AC power to emergency systems. Yet the following tsunamis flooded the buildings fifty minutes after the earthquake, resulting the loss of EDGs and thus all AC power (SBO). DC power was also lost at Units 1 and 2. This is modeled in Sequence 45 of the SPAR EQK-LOOP event tree*.

EQK-LOOP-S45: EQK-LOOP * /RPS * EPS

EQK-LOOP:	earthquake caused LOOP event
/RPS:	reactor shutdown
EPS:	emergency power from EDGs failed

The sequence is transferred to the SPAR EQK-SBO event tree.

2.2.2 SBO

After entering SBO, accident progressions varied for Units 1, 2, and 3 due to different mitigation system availabilities.

Unit 1: Both the high pressure coolant injection (HPCI) system and the isolation condensers (ICs) were not in service when DC power was lost. TEPCO estimated that there was no injection into the Unit 1 reactor for 14 hours [1]. Conservative calculations [2] indicated that the core may have uncovered as early as three hours after the earthquake, and fuel damage might have commenced approximately 1.5 hours later. Core cooling was eventually established when reactor pressure lowered sufficiently and a fire engine was used to inject seawater / fresh water. By this time, the core is predicted to have already melted through the lower head of RPV and begun to thermally attack the concrete floor of the reactor cavity [2].

Unit 2: Although DC power was lost with the tsunamis, reactor core isolation cooling (RCIC) system was able to provide core cooling for nearly 70 hours. The injection was

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* Some SPAR event trees referred in the paper are not presented or not presented in full logic due to their large sizes. If interested, they can be obtained upon request.

eventually lost when RCIC degraded and failed. TEPCO estimated that there was no injection into the Unit 2 reactor for about 6.5 hours [1]. The core began to uncover and fuel damage occurred. Conservative calculations [2] indicated that some of the fuel may have relocated to the bottom head of the reactor vessel. Core cooling was eventually established when a fire engine was used to inject seawater.

Unit 3: With the loss of all AC power, both RCIC and HPCI remained available for injection. RCIC provided core cooling for about 21 hours before it failed. An hour after RCIC tripped, HPCI automatically started on a low-low reactor water level signal and began to restore reactor water level. As station batteries depleted, reactor water level indication was lost at 30 hours. HPCI system tripped at 36 hours. With no core cooling (TEPCO estimates that there was no injection into the reactor for 6 hours and 43 minutes [1]), the core began to uncover and core damage commenced. Some of the core may have relocated to the bottom head of the reactor vessel. Core cooling was eventually established when a fire engine was used to inject seawater.

Unit 1 accident is modeled in Sequence 57 of the SPAR EQK-SBO event tree (EQK-SBO-S57), while Units 2 and 3 are modeled in Sequence 9 of the SPAR EQK-SBO event tree (EQK-SBO-S9):

Unit 1 / EQK-SBO-S57: EQK-SBO * RCI * HCI * OPR * DGR

Units 2&3 / EQK-SBO-S9: EQK-SBO * /RCI * /EXT * OPR * DGR *CVS * LI

EQK-SBO: earthquake (and tsunamis) caused SBO
RCI: RCIC system failed
/RCI: successful injection provided by RCIC system
/EXT: successful extended RCIC operation
HCI: HPCI system failed
OPR: offsite power not recovered prior to core damage
DGR: diesel generator not recovered prior to core damage
CVS: containment venting failed
LI: late injection failed

All sequences are transferred to the SPAR INT-SBO-CD event tree.

With all AC power lost, TEPCO tried to use portable electric generators for quick power recovery which was hampered by the damaged roads and congested traffic. The portable generators were limited in their effectiveness since they could not be connected to the station electrical distribution system due to extensive damage caused by the tsunami and flooding. The explosion that occurred in Unit 1 further complicated the power recovery process. This is modeled in Sequence 3 of the SPAR INT-SBO-CD event tree (Figure 3): with no offsite power recovery prior to reactor vessel failure (OPR-RV) and containment failure (OPR-CF), core damage occurred.

The sequence is transferred to the SPAR L2-CSTET event tree, a bridge event tree between Level 1 and Level 2 models.

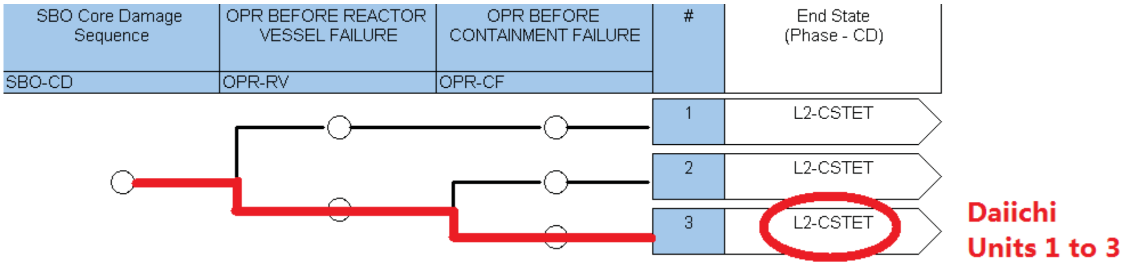

Figure 3 Fukushima Daiichi SPAR Accident Sequence – INT-SBO-CD-S3

2.3 Plant Damage State (PDS)

The SPAR Level 2 model consists of three transfer event trees. Containment Systems Transfer Event Tree (L2-CSTET) is a Level 1 extended event tree which models the containment system and accounting for the dependencies between the Level 1 core damage sequence systems and the Level 2 containment systems. When a Level 1 accident sequence results in core damage (CD), the sequence is transferred to the L2-CSTET to account for the containment system. The L2-CSTET sequences are then transferred to the Plant Damage State (PDS) Event Tree which receives the extended core damage accident sequences from the L2-CSTET, groups the accident sequences with similar characteristics into the same PDS bin, and then transfers the resulting PDS bins to the Containment Event Tree (CET) for accident progression analysis. The CET performs the severe accident progression analysis by modeling the challenges from the accident progression onto the reactor pressure vessel (RPV) and the containment building. The output of the L2-CET is a set of end states that delineate the various containment responses to the severe accident sequences, and subsequent releases of fission products into the environment.

Sequence 21 of the SPAR L2-CSTET event tree can be used to represent the containment system status of the Fukushima accident: failed suppression pool cooling (SPC), high RCS pressure with failed manual reactor depressurization (DEP), and failed containment venting (CVS). All kinds of core cooling measures are either not available or fully functional in order to prevent core damage. For manual reactor depressurization, note that although Unit 1 automatically depressurized due to main steam line rupture or stuck open SRV (at 6.5 hours) and manual reactor depressurization efforts were mostly successful for Unit 2 (shortly after 75 hours) and Unit 3 (at 42 hours) [1], the depressurizations are considered to occur after core damage commenced. So they are categorized as High RCS Pressure here and credited the manual or automatic depressurization in the Containment Event Tree.

The sequence is transferred to PDS event tree, with Sequence 35 of the PDS event tree for Unit 1 and Sequence 29 for Units 2 and 3 (Figure 4).

Daiichi Unit 1 sequence is defined as a Fast SBO with no high pressure injection (Isolation Condenser in lieu of RCIC, or HPCI) available. Units 2 and 3 are Slow SBOs with RCIC and/or HPCI available. Power recovery and core cooling efforts are considered not successful to prevent containment failure and fission products release to environment. Under such situation, SPAR model assumes that containment would fail before or at core damage.

Note that although offsite AC power was restored to Units 1 and 2 nine days after the event, restored to Unit 3 eleven days after the event, consistent efforts had been made to temporarily recover electric power with portable generator and temporary batteries. While their effectiveness might be limited, they played a key role in the mitigation by recovering control room lighting and critical instrument indications. For example, multiple indications including reactor water level indication was restored to Unit 2 at 7 hours [1], which supported the continuous operation of RCIC for nearly 70 hours.

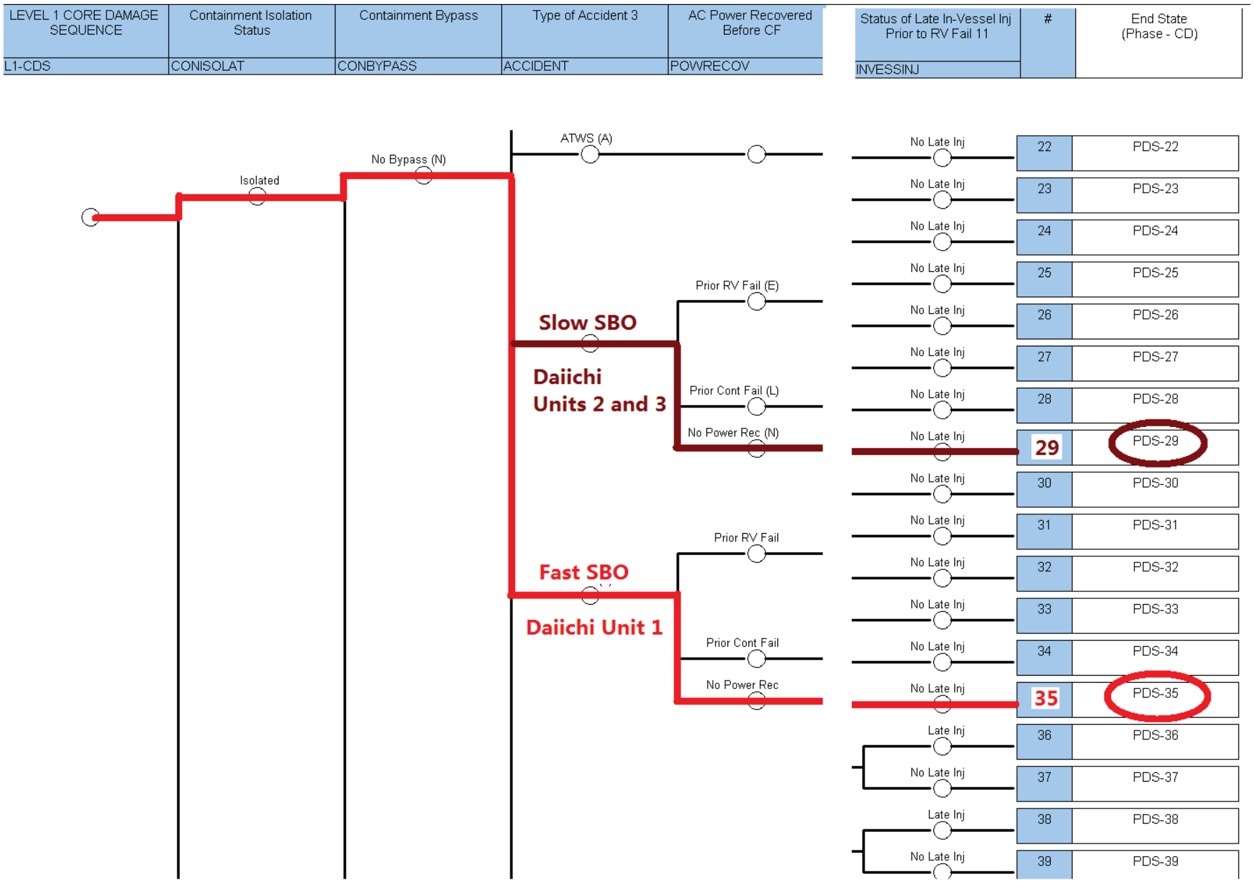

Figure 4 Fukushima Daiichi SPAR Accident Sequence – PDS-ET-S35(U1) or S29(U2&3)

On the core cooling side, fire engines were found and used to inject seawater or fresh water into the reactor through the core spray system to all three units. Although this might not be able to prevent the RPV and containment failure at Unit 1 (Sandia analysis [2] shows that by the time the water injection was commenced in Unit 1, the core was already melted through the lower head and begun to attack the concrete floor of the reactor cavity), it might have played more important role to mitigate the RPV and containment failure from inadequate core cooling at Units 2 and 3. In the analysis [2], the core material of Unit 3 is predicted to be retained in-vessel throughout its 96 hours simulation period, and the core of Unit 2 is largely intact. With such prediction, the accident progressions in Units 2 and 3 might take Sequence 24 of PDS event tree instead of Sequence 29. Yet the Sandia analysis admits that the actual core damage in Units 2 and 3 may be more significant and extensive than predicted in its analysis due to over-estimated injection water flow.

The sequences are transferred to the SPAR CET event tree.

2.4 Containment Event Tree (CET)

With the explanations in Sections 2.2 and 2.3, the SPAR Level 2 model predicts that the containment integrity of Daiichi Units 1, 2, and 3 would be compromised by overpressure failure prior to or at core damage, which would be further impaired by drywell shell melt-through after vessel failure. The containment failure mode is characterized by drywell shell melt-through for fission product release purpose (Sequence 35 of the CET in Figure 5). In the Sandia analysis [2], drywell head flange leak is postulated at Unit 1, while an unspecified leak equivalent to a two inch diameter hole is assumed in the containment boundary for Unit 2.

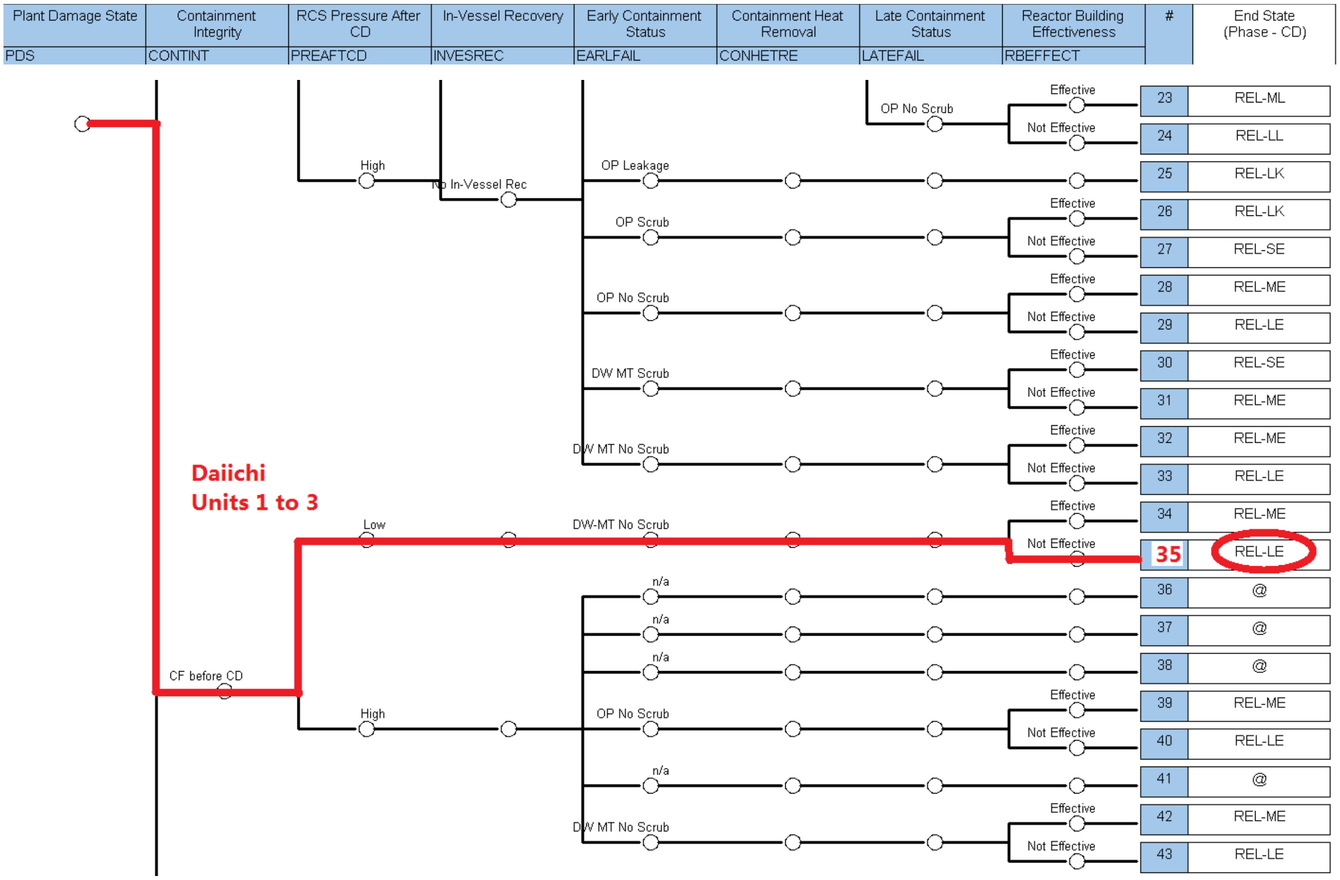

Figure 5 Fukushima Daiichi SPAR Accident Sequence – L2-CET-S35

Note that while containment venting efforts reduce the high containment pressure, they may also release significant amounts of radionuclides into the environment, depending on the mode and timing of venting, and the details of the accident progression. The effect of containment venting on radionuclide release is currently not modeled in SPAR Level 2 model.

The Reactor Building Effectiveness top event in the CET is deemed "Not Effective" for Daiichi Units 1 to 3. The hydrogen explosions in Units 1 and 3 breached the reactor buildings. The explosion in Unit 1 also caused a blowout panel in the Unit 2 reactor building to open, which resulted in a loss of secondary containment integrity.

The fission product release categories of Daiichi Units 1 to 3 are all classified as large early release (REL-LE) in SPAR model. In actual accidents, although Unit 1 is a large early release, Units 2 and 3 might be classified as late releases. The first off-site evacuations were reported as complete about 18 hours after the event, while the radionuclide release to environment occurred at 46 hours for Unit 3 when the drywell pressure began to decrease rapidly concurrent with the increasing of and site boundary dose rate, and more later for Unit 2 whose RCIC operated for nearly 70 hours. One of the reasons for the release category deviation is that Daiichi is a multi-unit site and the evacuation decision was first made for the emergency situation in Unit 1. The successful operations of RCIC and HPCI in Units 2 and 3 also delayed the occurrence of core damage as well as environmental releases. These factors are not reflected in the SPAR model for more accurate release categorization.

It should be pointed out that the above accident sequence analysis with the SPAR model is mostly based on the review and understanding of the accident narratives in the INPO report [1] and simulation analysis in the Sandia report [2]. There are still missing pieces for people to fully understand and depict what really happened inside the core, the reactor vessel, and the containment, which may never be known for sure since alternative but different theories and model could claim the same credit supported by limited and maybe erroneous data available. Also the actual accidents occurred in Daiichi Units 1, 2, and 3 are far more complicated than the static, simplified accident sequences as described in the above. Nevertheless, the above accident sequence analysis shows that the SPAR model is a robust PRA model that could very reasonably describe the accident progression for a real and complicated nuclear accident in the world. On the other hand, the comparison between the accident and the model shows that some of the accident characteristics could be modeled and incorporated into the SPAR Level 2 model for better representation of severe accident progression. For example, the potential for hydrogen explosions and their effects on containment, reactor building, and environment, and the modeling of containment venting process in containment event tree for its effect on environment release.

3 CONCLUSIONS

The SPAR models are a set of PRA models used by the regulator to evaluate the risk of operations at U.S. nuclear power plants and provide inputs to risk informed regulatory process. A small number of SPAR Level 2 models have been developed mostly for feasibility study purpose. A typical BWR SPAR Level 2 model was compared with the nuclear accident occurred in Fukushima Daiichi Units 1, 2, and 3 due to the earthquake and tsunamis.

The comparison shows that the SPAR Level 2 model is a robust and simplified PRA model that could very reasonably describe the accident progression for a real and complicated nuclear accident in the world. On the other hand, the SPAR model could be enhanced by incorporating some of the accident characteristics in the Fukushima accident for better representation of severe accident progression. For example, the potential for hydrogen explosions and their effects on containment, reactor building, and environment, and the modeling of containment venting process in containment event tree for its effect on environment release.

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