Improving Safety and Emergency Preparedness for Storage of Cs/Sr Capsules from Lessons Learned From Fukushima Events – 14022

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ABSTRACT

On March 11, 2011, the Fukushima Daiichi nuclear power station in Japan was damaged by a magnitude 9.0 earthquake and unprecedented tsunami that engulfed a 561 km^2 area and led to the death or disappearance of approximately 25,000 people. Both events individually exceeded the facility design basis, and combined, resulted in the loss of external and backup power and on-site cooling capacity that severely compromised the plant's safety systems and resulted in a core melt down. Emergency response was directly impacted by a total and sustained loss of electrical power, along with the resultant inability to apply cooling water to either reactor cores or spent fuel storage pools. This resulted in a partial meltdown of nuclear fuel and a buildup of hydrogen inside the reactor building, causing severe additional damage at the Japanese nuclear plants and contaminating the surrounding environment.

The Hanford Waste Encapsulation and Storage Facility (WESF) is one of a handful of facilities in the U.S. that is used for wet storage for long-term protection of highly radioactive materials. WESF was designed and constructed to process, encapsulate, and store the Strontium-90 (Sr) and Cesium-137 (Cs) radionuclides extracted from wastes generated during the chemical processing of defense fuel on the Hanford Site. The Hanford Site inventory of cesium and strontium capsules (approximately 100 million curies of total radioactivity) is currently stored in the WESF pool cells (Fig. 1).

Fig. 1. Radiation from the WESF capsules casts an eerie blue glow called the Cherenkov Effect as the radioactive material decays and loses radioactivity

The Fukushima Daiichi nuclear disaster drove significant re-evaluation of existing nuclear facilities world-wide. At WESF, by rearranging capsules, we decreased the temperature that the capsules would be expected to reach following a complete loss of pool cell water. Therefore, the time that it would take before capsules would begin to fail is significantly increased. This allows enhanced planning and coordination of emergency response actions following a Beyond Design Basis Accident (BDBA) event.

INTRODUCTION

Soon after the significance of the events at Fukushima became apparent, the Department of Energy (DOE) and its contractors conducted reviews of beyond design basis accidents (BDBA) at all DOE Hazard Category 1 and 2 nuclear facilities. WESF, a Category 2 facility operated by CH2M HILL Plateau Remediation Company (CHPRC), was one of the Hanford facilities identified as having the potential for a severe earthquake to hamper or delay emergency response actions similar to those experienced at Fukushima (i.e., a loss of cooling water that resulted in unacceptable consequences to workers and the public.)

CHPRC assessed WESF facility vulnerabilities to BDBA events and evaluated whether appropriate provisions were in place to mitigate BDBA event consequences. This evaluation postulated an earthquake that would fail the basin structure, causing a loss of cooling water that would result in a failure of the Cs/Sr capsules. It further considered other natural phenomenon hazards (NPHs), including flooding from dam breakage up river of the Hanford Site; the effects of ash loading from nearby, active volcanos; potential effects of high winds; and the possible impact from uncontrolled wild land fires – each a credible threat to the Hanford Site.

Fig. 2. Workers used long-handled tongs and video cameras to complete the relocation of Cs/Sr Capsules.

Finally, CHPRC engineers assessed the heat given off by the capsules and its impact on the structural integrity of the capsules. In light of events at Fukushima, additional assessments were undertaken to determine a capsule configuration that would allow the greatest response time possible before a loss of cooling water could drive failure of the capsules. During the assessment, engineers analyzed the wattage output of 1,936 capsules to determine the best way to rearrange them in order to balance the heat load.

Work to relocate more than 800 capsules began in February of 2012 and was completed in June, six months earlier than planned. CHPRC workers standing on walkways above the water used long-handled tongs and "pushers" to reach to the bottom of the water and move the capsules. The team used underwater lighting and a video camera to direct their efforts and verify that the capsules were correctly placed (See Fig. 2). Shortly after the project started, workers assigned to the project suggested ways to redesign the tools and collaborated with engineers to optimize the plan of execution for the project. Two shifts worked on the project every Thursday, with the same workers assigned each week. Some workers canceled vacations so they could be there with the rest of the crew to move the capsules. This was the first time a major relocation of the capsules was undertaken in about 20 years.

Long-term plans for WESF include continued preparations for transfer of the capsules to dry storage on the central plateau by 2018. This project is essential to placing the materials of concern into a condition that will significantly reduce or eliminate the potential for release to the environment in any emergency situation.

DESCRIPTION

WESF was designed and constructed to process, encapsulate, and store ^{90}Sr and ^{137}Cs separated from Hanford's single-shell waste tanks to reduce the temperature of the high-level radioactive waste inside those tanks. Construction of WESF began in 1971 and ended in 1973. WESF began operations in 1974, and processed cesium and strontium capsules until 1985. Some of the capsules were leased and shipped off-site for use as radiation sources. All of the capsules have been returned to WESF for safe storage until they are transferred for final storage in a repository.

The facility (shown in Fig. 3) is a two-story building constructed of steel-reinforced concrete and partitioned into seven hot cells, the hot cell service area, operating areas, building services

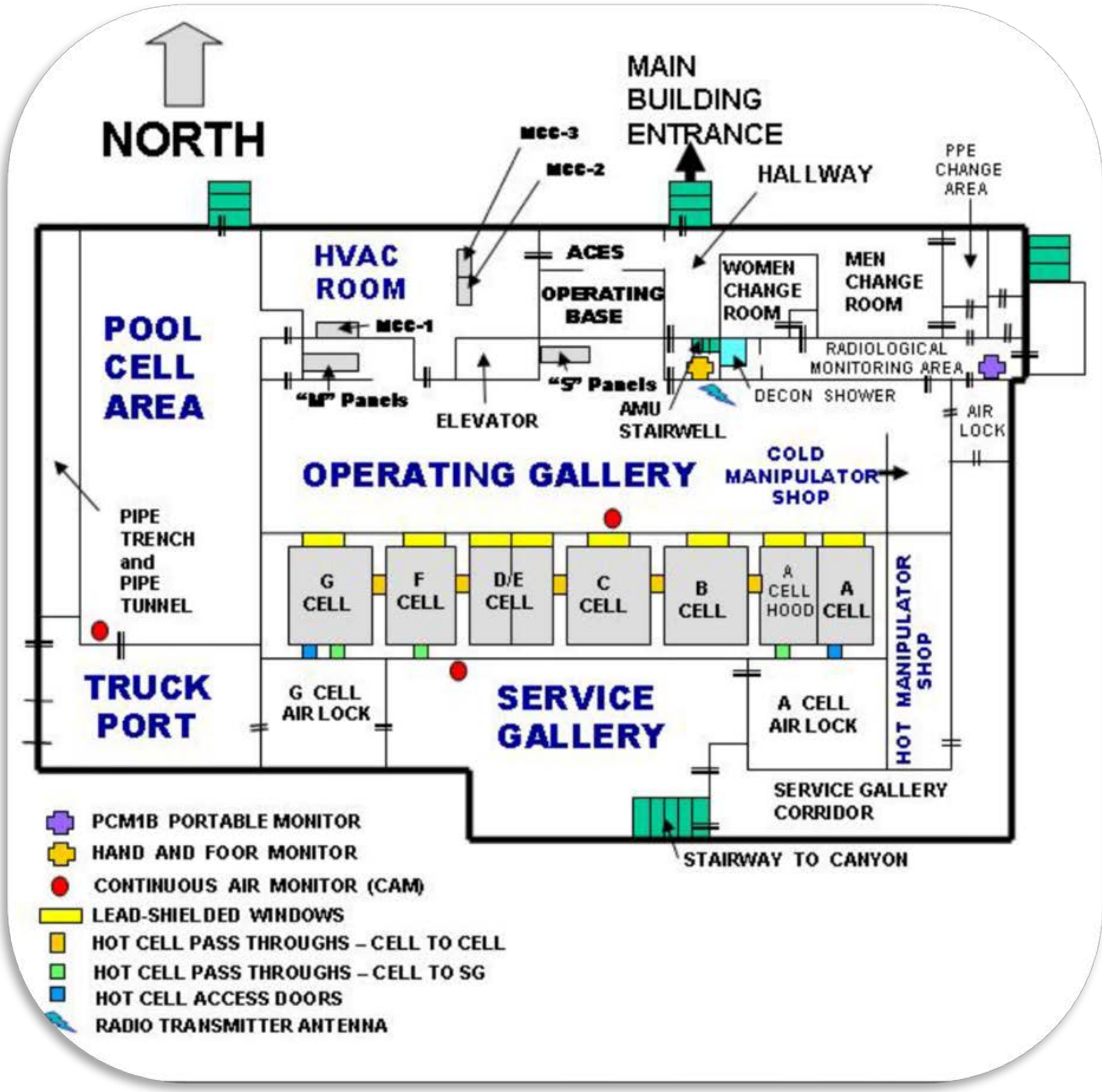

Fig. 3. Main Floor Layout of WESF

areas, and the pool cell area. The hot cells are labeled A through G and activities within the hot cells are performed remotely using manipulators. Waste and drum load out was performed in hot cell A. Hot cells B through E were used to convert strontium nitrate and cesium carbonate removed from the tanks into strontium fluoride and cesium chloride salts. Only hot cells F and G may be used for dry storage of defective Cs/Sr capsules. The pool cell area consists of 12 pools lined with stainless steel. Pool Cells 1, 3 through 7, and 12 are used for underwater storage of Cs/Sr capsules. Each pool has about 4 meters (13 feet) of water that provides radiation shielding and serves to cool the capsules. Each pool has monitoring systems to detect leakage from capsules.

Both the Cs and Sr removed from the tank wastes were purified to form cesium carbonate and strontium nitrate, respectively, and transferred to WESF for further processing. At WESF hydrochloric acid was added to the cesium carbonate to produce cesium chloride which was then evaporated to a molten salt and encapsulated. The strontium nitrate was transferred to WESF and converted to strontium fluoride, which was then filtered, dried, and encapsulated. The Cs/Sr salts were packaged in double-shelled stainless steel capsules and placed in long-term storage in the WESF pool cells.

Initially, hundreds of the capsules were loaned for research or industrial use. The cesium capsules were used off-site to sterilize medical devices, sterilize sewage sludge and strengthen wood, among other uses. But the capsules were meant to be stored underwater, and taking them in and out of water to be used for irradiation processes damaged the metal, even though the capsules have two layers of steel. In 1990, one of them developed a microscopic leak, forcing closure and cleanup of an irradiation plant in Georgia. The capsules were recalled and returned to Hanford in shipping casks in an effort that took years because of safety concerns. Several of the capsules were placed in overpacks to ensure their integrity.

DISCUSSION

WESF Documented Safety Analysis (DSA)

The Safety Basis and Documented Safety Analysis Rule contained in 10 CFR 830, Nuclear Safety Management [1], requires that Department of Energy (DOE) contractors and operators establish and maintain a safety basis for DOE-STD-1027-92 [2] Hazard Category 1, 2, and 3 nuclear facilities. In establishing the safety basis for a nuclear facility, Subpart B of the rule describes how the responsible contractor must prepare a Documented Safety Analysis (DSA) that in part: 1) describes the facility, activities, and operations, 2) systematically identifies hazards, 3) evaluates normal, abnormal, and accident conditions, and 4) derives hazard controls to provide an adequate level of safety to the public, workers and the environment.

The WESF DSA considers numerous facility vulnerabilities and beyond design basis events (BDBE), including floods, ash and snow loading, external fires, high winds, external man-made events, station blackouts, and seismic events. It further identifies the impact of these events on safety significant systems and methods to mitigate catastrophic system failures. The general categories of failures considered for each BDBE listed above include:

- Collapse of building structure and interior walls
- Breach of water storage pools, or collapse of storage racks
- Loss of electrical power and emergency power equipment (transformers, switchgear, motor control centers, etc.)

- Loss of electrical distribution systems (conduit and cable trays)
- Operational failure of active mechanical equipment (pumps, compressors, fans, etc.)
- Loss of pressure boundary of static equipment (tanks, vessels, glove boxes, etc.)
- Failure of distribution systems (piping, tubing, ducts, etc.)
- Adverse spatial seismic interaction (failure of adjacent buildings, failure of adjacent stacks, etc.)
- Adverse flood-inducing interaction (failure of adjacent water tank, etc.)
- Failure of alarms, emergency response center

Analyzed WESF vulnerabilities and BDBEs and their effects on the facility are summarized in Table I. As shown in the table, the primary concern in the DSA BDBE analyses is failure that would result in:

- Loss of capsule cooling provided by pool water
- Failure of ventilation systems that reduce flammable gas concentrations
- Loss of capsule integrity
- Loss of radiation shielding via pool water

TABLE I. Analyzed Effects of WESF BDBE Events

Event	DSA Assumptions	Effect
Flood	50% breech of Grand Coulee Dam	Loss of offsite power and restricted access to and from the site resulting in loss of active ventilation to the facility.
Ash/Snow Loading	Ability to withstand 20 lb/ft^2 loading	Structural failure and station blackout in the event of snow and ash accumulation at bottom of pools, potentially accelerating temperature rise of capsules.
External Fires	Wind-driven range fire affecting the facility	Loss of offsite AC power resulting in loss of active ventilation
High Winds	Wind speeds up to 91 mph	No effect, however BDBE considers much higher wind speeds that result in full structure failure and partial disruption of pool integrity.
External Events	Aircraft/Helicopter crash	Facility destruction causing catastrophic radioactive release at co-located facilities.
Blackouts	Loss of power on the order of days	Potential for heat buildup in pools.
Seismic	Designed to withstand 0.25g earthquake	Building structure and below-grade pool cell structure failure. Loss of power, loss of water in pool cells; loss of capsule integrity, catastrophic contamination release hampering response efforts.

A significant seismic event could result in all of these failures noted in Table 1. Therefore, a beyond design basis earthquake was selected for analysis because it is a common cause initiator and is assumed to impact the greatest amount of material available for release. This accident is essentially a loss of pool cell water accident with additional consequences due to structural failure of the hot cells and confinement ventilation system. The BDBE assumes facility systems, structures, and components (SSCs) fail in whatever configuration causes the greatest consequence.

Beyond Design Basis Earthquake

The BDBE analysis assumes the building structure fails and a release of contamination from the hot cells and K3 ventilation system occurs. In the pool cell area, the BDBE could cause the complete failure of the roof panels and structural supports resulting in substantial impacts and mechanical failure of several capsules. However, as shown in the loss of pool cell water accident analysis, the effects of failure of the structure may be cooling of exposed capsules by allowing natural convective heat removal from the capsules. As a general principle, it will not be assumed that failure of an SSC or administrative control will mitigate potential accident consequences, so it is assumed that the pool cell area structure survives the BDBE. The pool cell liners and underlying concrete foundations fail so that all pool cell water is lost in a short period of time.

If the aboveground pool cell structure did fail, the consequences would be similar to the analyzed hydrogen explosion in the pool cell area (with or without loss of pool cell water). If the pool cell concrete foundation also failed resulting in loss of water, the consequences for a loss of all pool cell water without the aboveground structure is bounding (failure of the aboveground structure would result in cooling of the capsules). If there was no failure of the pool cell foundation, the result could be failure of capsules that eventually result in boiling of contaminated water. The 2-hr dose consequences are less than for a complete loss of pool cell water without failure of the aboveground structure so the loss of pool cell water dose consequences are used in the BDBE.

However, it is noted that the failed capsule consequences and boiling of contaminated water could occur sooner than the loss of pool cell water consequences (boiling of the water could occur in approximately 9 days) [3]. Capsule failures due to corrosion from a loss of pool cell water with no failure of the structure would not start until approximately 50 days after a loss of all pool cell water assuming a packed rack configuration, and approximately 300 days after a loss of all pool cell water for a spaced rack configuration.

The DSA also discusses post loss of water concerns, regardless of the initiating event. The question of whether or not to add water to a pool after capsules have been uncovered for a period of time is addressed in the 2008 thermal analysis report. The particular concerns addressed were: (1) the potential for thermal stresses causing new capsule failures, (2) molten salt-water interactions potentially damaging capsules or the pool, or increasing the source term by mechanical aerosol generation, (3) water reacting with cesium chloride to create new trace species that exacerbate the source term, (4) contaminated water leakage through failed confinement boundaries, and (5) boiling of contaminated water. Proper accident management schemes can avoid the situations depicted in items 2, 3, 4, and 5. However, Item 1 is relevant anytime a pool cell is drained. It is assumed that in the event of complete loss of pool cell water, the capsules would heat up and begin to fail in as soon as two days, which would result in an increase in airborne radioactivity and the associated dose consequence through the inhalation pathway.

Additional Analyses Following Fukushima

Multiple analyses have been conducted over the life of the WESF facility, focused primarily on thermal generation in the pool cells, container and cell integrity, and the effects of events that could bring about catastrophic failure at the facility. Soon after the significance of the events at

Fukushima became apparent, the DOE and its contractors conducted additional reviews of BDBAs at all DOE Hazard Category 1 and 2 nuclear facilities.

A thermal analysis completed in 2008, included updated capsule decay values as well as an updated analytical model for heat distribution. Using this information, and in light of events at Fukushima, additional assessments were undertaken to determine a capsule configuration that would allow the greatest response time possible before a loss of cooling water could drive failure of either the pool structure or capsules. During the assessment, engineers analyzed the wattage output of 1,936 capsules to determine the best way to rearrange them in order to balance the heat load. In February of 2012, CHPRC initiated a process to re-locate more than 800 capsules in the WESF pool to minimize anticipated capsule failure in the event of a loss of pool cell water and provide additional time to respond if there was a serious incident at WESF. Work was completed in June, six months earlier than planned. This was the first time a major relocation of the capsules was undertaken in about 20 years.

Additional reviews were completed that included reviews of the DSA in response to questions about the loss of water accident, estimated time to capsule failure, number of anticipated capsule failures, release of capsule material, and dose consequences on and off the site.

Finally, based on a new sense of urgency after Fukushima events, reviews are underway to determine the likelihood of more destructive seismic events than were previously considered. A recent report from the U.S. Geological Survey finds that earthquakes may be more common, and potentially more powerful, in eastern Washington than previously thought [4]. Scientists are now studying swarms of miniature earthquakes that have been occurring recently on the Hanford site. The results of these new studies will be incorporated into DSAs and BDBAs across the Hanford site.

Revisions to Planning Documents

The reviews discussed above drove changes to numerous planning documents, including:

- The WESF DSA
- The Emergency Planning Hazards Assessment
- WESF Hanford Fire Department Pre-Incident Plan
- WESF Drill Program
- WESF BDBA Facility Response Procedures

The WESF DSA has been revised to incorporate changes regarding radiation degradation of pool cell concrete structures, to update helicopter crash analyses, identify inspections for credited design features, and to revise the pool cell water accident analysis.

The Emergency Planning Hazards Assessment (EPHA) has been revised to reflect the changes in the WESF DSA. The major changes are to ensure the events are realistically conservative, modeling of the events is consistent with the requirements, and add an Appendix to show the dose consequences of a long-term release from a loss of pool cell water event. Based on the Fukushima accident, the BDBE was evaluated to ensure the accident is representative of what would happen during an actual event.

The WESF Hanford Fire Department (HFD) Pre-Incident Plan was revised to include alternate water sources available to respond to a BDBE involving a WESF Loss of Pool Water event.

The assumption is that the BDBE would cause severe damage to hydrant water supply and facility make-up water system capabilities. HFD may need to shuttle water from alternate water sources. Also, there are special considerations for adding water. The revised plan references facility procedures to assist in decision making.

CONCLUSION

Multiple analyses have been conducted to understand and put into place adequate safety measures to mitigate the potential effects that could result from BDBEs at WESF. The WESF Drill Program has been revised as a result of the Fukushima event. The WESF team has conducted a series of drills to exercise facility and site responses to newly analyzed BDBA initiated events. Table II shows the drill scenarios, the dates the drills were performed, and lists the associated drill report numbers.

TABLE II – 2012 and 2013 WESF BDBA Drills

Drill Date	Drill Report #	Drill Scenario
01/10/2012	WESF-EPDT-011012	Slow Pool Cell Water Leak
01/17/2012	WESF-EPDT-011712	Slow Pool Cell Water Leak
03/27/2012	WESF-EPDF-032712	Slow Pool Cell Water Leak
04/18/2012	WESF-EPDF-032712	Slow Pool Cell Water Leak
09/25/2012	WESF-EPDT-011712	Rapid Water Loss
02/27/2013	WESF-ODL-021413	Loss of Ventilation
04/25/2013	WESF-EPDF-041613	Fire in Hot Cell
06/06/2013	WESF-EPDE-052113	Fire in G Cell
06/28/2013	WESF-ODL-061313	Loss of Power Event
07/09/2013	WESF-EPDE-062013	Seismic Event, Rapid Water Loss
07/17/2013	WESF-EPDE-071113	Explosion, Loss of Ventilation
07/26/2013	WESF-EPDE-071713	Plane Crash, Loss of Pool Cell Water
08/08/2013	WESF-EPDE-073113	Seismic Event, Loss of Pool Cell Water
08/23/2013	WESF-EPDE-080613	K3 Filter Pit Explosion Event

The practical aspects of the increased drill protocols and scenario development is the ability to better predict what areas may be weak in a worst case event. Numerous corrective actions generated during the drills have been, or are currently being implemented to improve responses to BDBE events. The corrective actions are generally centered on the development of emergency response procedures and plans to better monitor pool conditions and levels and manage failed capsules under scenarios that include loss of pool water and ventilation systems, and limited access within the facility as a result of a catastrophic BDBE. While drill protocols have been in place since the facility was constructed, the lessons of Fukushima have led to improved challenging of the postulated events to include truly identifying what the challenges would be to get to the facility, including better understanding of when that would be important, or not important.

Additional operational drills are planned during FY2014 to confirm the effectiveness of changes to response plans and procedures and to direct further improvements to emergency response capabilities at WESF. The drill program plan includes two full-up exercises at WESF for a response to a BDBE event.

Additional Areas for Improvement

A number of potential improvements have been identified which, if implemented, could impact how WESF would respond to a loss of water event. These improvements fall into two general categories; engineering analysis that will improve understanding of the conditions that might be experienced if pool cell water is lost, and facility modifications that can mitigate the consequences of the accident. In general, any action in either category is dependent on funding (outside the scope of current operations or beyond the expertise of existing staff).
Engineering analyses would include:

- More extensive modeling to determine what external radiation readings would be for a given water level. This could allow an actual water level to be established if radiation levels are high enough to prevent access to the pool cell area. The existing modeling was done to support safety basis development, is simplistic, and provides very conservative dose estimates. A more detailed model would provide more realistic information about the actual dose rates that would be expected during a loss of water event. Current conservative calculations may overstate the hazard and cause development of more complicated planning cases. The additional modeling would be expected to take several months. The HFD would like a better understanding of the actual water level to help them manage their resources. Upcoming procedure changes will direct use of a simplistic calculation to determine rate of water loss but will not address actual level.

- Perform an updated capsule failure analysis. The existing capsule failure analysis was completed as a part of the 1996 thermal analysis. It was performed to support safety basis development and is very conservative. The documentation available of the methodology used to perform the capsule failure analysis is not adequate to allow the capsule failure prediction to be updated using new information. An updated capsule failure analysis could provide a more realistic understanding of the extent and timing of any expected capsule failures.

- Investigate capsule thermal response to being covered with dirt or grout. If a loss of water accident were to occur, the capsules would lose both shielding and cooling. One potential mitigating action is to cover the capsules with something that would restore shielding. A number of different materials have been proposed as potential covers. A significant downside to this approach is that covering the capsules would make them hotter, increasing the risk of capsule failure. Investigating the response of the capsules to a variety of covers would help to determine if this is a feasible option (is the decrease in dose exposure worth the increased risk of capsule failure). If performed, this analysis should also look at the effect of adding a thickening agent to the water to minimize/stop any leakage and consider effects on long-term response actions (how will the capsules be permanently managed following this event).

Facility modifications being considered include clearing abandoned piping away from the north pool cell door as current accident response strategies rely on access to outside the pool cell area at the location of the north door. Piping associated with the deactivated steam and process condensate collection systems are located in close proximity to the door. The concern is that damage to the piping caused by a seismic event may prevent or impede access to the door. Removing this piping will require funding for work planning, work execution, and configuration change documentation. A work package has been initiated so that this work can be tracked and prioritized.

Information gathered during the post Fukushima evaluations was used to develop a comprehensive plan to improve post-BDBA response capabilities at WESF until such time as the capsules are transferred to dry storage. A critical step was the relocation/reconfiguration of the capsules in the WESF pool cells which allows the greatest response time possible before a loss of cooling water could drive failure of the capsules. Additional actions identified by that plan have been initiated or completed. They consider additional data regarding seismic activity at Hanford and include the conduct of a series of drills to exercise facility and site responses to BDBA initiated events similar to the Fukushima event.

REFERENCES

1. 10 CFR 830, *Nuclear Safety Management*
2. DOE-STD-1027-92, *Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports*
3. WHC-SD-WM-TI-770, *FAI/96-1 Thermal Analyses of Hypothetical WESF Pool Drain Accidents*
4. *Earthquake Risk Factors at the Columbia Generating Station (formerly known as WPPSS WNP-2),* Report to Oregon and Washington Physicians for Social Responsibility, Portland, OR/Seattle, WA, October 31, 2013