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Computational Evaluation and Mitigation of Wind-Driven Missile Impact against Condensate Storage Tanks and Associated Piping Connections

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ABSTRACT

In responding to the United States (U.S.) Nuclear Regulatory Commission's Order EA-12-049 *Issuance of Order to Modify Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events*, many of the operating nuclear power plants have identified a need to evaluate the robustness of certain on-site, liquid-contained storage tanks. Because many of these storage tanks were not originally designed for their site's licensing-basis tornado event, the present evaluations must address the effects of wind-driven missile impact on storage tank structural integrity and inventory security.

This paper describes one such evaluation for two condensate storage tanks (CSTs) and associated piping connections at an East Coast U.S. nuclear power plant (Plant). The impact of a wind-driven missile against a thin-walled, liquid-contained structure gives rise to a complex and transient engineering problem involving highly localized stresses, nonlinear constitutive behaviour, material damage/failure, and fluid-structure interaction. The multi-physics finite element code LS-DYNA was used to carry out a rigorous computational assessment involving a spectrum of design-basis tornado missile threats. Based on results from the assessment, it was concluded that a barrier mitigation strategy would need to be employed on site. This paper describes the computational modelling approach utilized during the missile impact assessment and discusses results from the nonlinear dynamic finite element simulations. In addition, the concept and design of a novel perforated barrier system comprising ring-net panels is presented.

INTRODUCTION

On March 11, 2011, northern Japan was struck with a 9.0 magnitude earthquake, resulting in a large tsunami that hit their north eastern coast almost an hour later. As a result of this earthquake and tsunami, the Fukushima Dai-ichi Nuclear Power Station experienced an extended loss of AC power (ELAP) that severely compromised the key safety functions of core cooling and containment integrity, ultimately leading to core damage in three reactors. The loss of power also impaired the spent fuel pool cooling function, but sufficient water inventory was maintained in the pools to preclude fuel damage from loss of cooling. Following this disaster, the U.S. Nuclear Regulatory Commission (NRC) established a senior-level task force to review NRC regulations and processes to determine if the agency should make safety improvements in light of the events in Japan. Based on one of the task force's recommendations, the NRC issued Order EA-12-049 (NRC, 2012), which outlined a three-phase approach for coping with a beyond-design-basis external event (BDBEE).

Following the issue of Order EA-12-049, Nuclear Energy Institute (NEI) 12-06, *Diverse and Flexible Coping Strategies (FLEX) Implementation Guide* (NEI, 2012) was developed, outlining the acceptance criteria and process for meeting new industry standards for coping with a BDBEE. U.S. nuclear power plants then developed FLEX Overall Integrated Plans (OIPs), which outlined their strategies for coping with BDBEEs and demonstrated how they will meet the requirements that were set forth in EA-12-049 and NEI 12-06. One such requirement is to maintain or restore reactor core cooling after a BDBEE, in which case normal access to the ultimate heat sink (UHS) would no longer be available. This need to ensure access to a water supply immediately following a BDBEE is what ultimately led to the evaluation and mitigation of wind-driven missile impact against the Plant's CSTs and associated piping connections.

Project Overview

The Plant currently has two 500,000-gallon CSTs that normally supply the reactor vessel with makeup water to maintain inventory. Existing Plant documentation confirmed that the CSTs were not originally designed to withstand seismic events. As a result, the Plant required another reliable source of clean water to be available after a BDBEE. Consideration was given to finding a secondary path of moving the UHS water supply to the reactors in a way that would survive a BDBEE. This option was rejected based on Electric Power Research Institute (EPRI) Report 1025295, *Severe Accident Management Guidance Technical Basis Report* (EPRI, 2012), which states that clean water must be used to cool the reactor core. Such could not be ensured if the Plant were to utilize the UHS. The Plant then decided to install a new clean-water tank that could withstand BDBEEs and be credited for a FLEX event. This course of action would satisfy the above mentioned requirements, but was later determined to be a cost-prohibitive endeavour. As a result, project team seismic experts performed a deterministic and probabilistic study to determine whether the CSTs were seismically robust. This study, based on a combination of precise methods including nonlinear finite element analysis, soil-structure interaction (SSI) analysis, probabilistic analyses, and other industry accepted formulae, determined that the CSTs would be available for FLEX following a seismic BDBEE. However, to consider the CSTs available for FLEX, they must be available following all potential BDBEEs, including Seismic, Flood, High Wind, and extreme Heat and Cold external events.

This project was led and principally executed by Nexus Engineering. Protection Engineering Consultants served as a specialty consultant to Nexus Engineering providing high-fidelity computational modelling and structural engineering support. The combination of highly specialized and detailed analyses required to substantiate the robustness of the CSTs against the aforementioned external events with the design and implementation of a missile barrier made this a challenging, innovative, and truly unique project within the commercial nuclear power industry.

Vulnerability Assessment Approach for Condensate Storage Tanks

Several approaches were used to assess the vulnerability of the CSTs to the applicable external events (seismic, flood, high wind, and extreme heat and cold). For the CSTs to be considered available following a BDBEE, there must not be a loss of water inventory, either through failure of the CST shell or associated piping connections. The various external event assessment strategies and outcomes are summarized in Table 1.

As shown in Table 1, seismic, flood, extreme heat, and extreme cold external events did not lead to a loss of CST inventory; however, wind-driven events did result in failure. Initial computational analysis performed on the CSTs determined that the CSTs would survive impacts from wind-driven missiles, but certain missiles would cause damage to the CST piping connections. Damage to the CST piping connections carries the potential for loss of CST inventory and thus was deemed unacceptable. In light of this potential failure scenario, it was concluded that a tornado missile barrier was needed to protect the CSTs' piping connections during a high wind event.

Table 1: BDBEE Vulnerability Assessment Summary

EXTERNAL EVENT	ASSESSMENT TYPE	LOSS OF CST INVENTORY?
Seismic	Probabilistic and deterministic approaches, computational analysis	No
Flood and Flood Driven Missiles	Computational analysis	No
Wind and Wind Driven Missiles	Computational analysis	**Yes**
Heat	NEI 12-06 criteria	No
Cold	NEI 12-06 criteria	No

Description of Design-Basis Tornado Missiles

The Plant's design-basis tornado event considers four wind-driven missiles, as shown in Table 2. These missiles were used as input to the computational analyses of direct missile impacts against the CSTs and associated piping connections. They were also used in direct missile impact analyses against the missile barrier that was ultimately deemed necessary in order to eliminate potential loss of CST inventory following a high wind external event.

Table 2: Design-Basis Wind-Driven Missile Spectrum

WIND-DRIVEN MISSILE	SPECIFICATIONS
Corrugated steel sheet	4-ft x 8-ft, weighing 100-lb, traveling at 225-mph
Bolted wood decking	12-ft x 4-ft, weighing 450-lb, traveling at 200-mph
Automobile	Frontal area of 25-ft^2, weighing 4,000-lb, traveling *on the ground* at 50-mph
Cedar fence post	6-in. x 6-in., weighing 33-lb, traveling end-on at 150-mph

COMPUTATIONAL MODELING APPROACH

The multi-physics finite element code LS-DYNA was used to perform nonlinear dynamic analyses involving various wind-driven missile impact scenarios. All computational models were constructed with pure Lagrangian mesh descriptions. Where shell elements were utilized, a fully integrated element formulation with five through-thickness integration points was implemented. Where three-dimensional solid elements were utilized, LS-DYNA's default brick element formulation having a single, centrally located integration point was utilized. Mechanical interaction between different computational parts was represented with penalty-based contact definitions. Also, material-level behaviour was represented with nonlinear, strain-rate-dependent constitutive models that were either calibrated to experimental test data or minimum ASTM-specified control points (i.e., yield strength, ultimate strength, and maximum uniaxial elongation). In considering heat-affected-zone (HAZ) effects in the vicinity of welds, appropriate reductions in effective plastic failure strain were implemented in the metal constitutive models (NRC, 2000).

In computationally representing contained water, either within the CST itself or within an interfacing pipe, it was decided to utilize a Lagrangian mesh description. The main objective of the water meshes was to provide a realistic representation of in-situ hydrostatic pressure as well as inertial resistance afforded by the water during an impact event. This objective was adequately achieved with a Lagrangian mesh description and penalty-based contact algorithms between the water and any containing metal surfaces. If this computational analysis was focused on assessing seismic performance, an Eulerian mesh description of the contained water would have been a more appropriate choice. An Eulerian mesh description, which is commonplace for typical fluid flow problems, is better suited to capture sloshing behaviour of a liquid (i.e., impulsive and convective modes of fluid-structure interaction) during base excitation of a liquid-contained structure than a Lagrangian mesh description.

VULNERABILITY ASSESSMENT OF CST STRUCTURE AND PIPING CONNECTIONS

The computational vulnerability assessment was carried out in two phases. The first phase of the assessment focused on scenarios involving a direct missile impact against the CST shell. During this phase, the bolted wood decking and corrugated steel sheet missiles were considered. The cedar fence post missile was not considered because it was shown via empirically based penetration equations that such a missile would not perforate the CST shell. In addition, the automobile missile was not considered because it was determined during the course of the project that a mitigation strategy consisting (in part) of a concrete barrier near grade elevation would likely need to be employed to defeat the design-basis automobile missile. Several impact scenarios involving the bolted wood decking and corrugated steel sheet missiles were carried out for both liquid-filled and empty CST conditions. Results from all Phase 1 impact simulations demonstrated that the CST shell was not vulnerable to perforation.

The second phase of the assessment focused on scenarios involving missile impact against various piping connections that interfaced with the CSTs. Example finite element representations of two such interfacing pipes are shown in Figure 1. Results from Phase 1 of the assessment revealed that the bolted wood decking missile was the most severe of the design-basis tornado missiles. As such, various impact scenarios involving the bolted wood decking missile impacting CST piping connections were carried out. Results from these computational simulations showed that the CST piping connections were vulnerable to connection failure when subjected to certain bolted wood decking impact scenarios. A computational image of one such failure is shown in Figure 2, where the impact event resulted in complete failure of a nozzle-to-CST welded connection. In light of these unfavourable results, additional impact simulations were conducted to identify critical impact velocities below which CST piping connection failure would not occur. These critical impact velocities were then used as performance criteria for the design of a more elaborate tornado missile barrier system that would not only protect the CSTs against the ground-based automobile missile but also protect critical CST piping connections against potential tornado missile impacts.

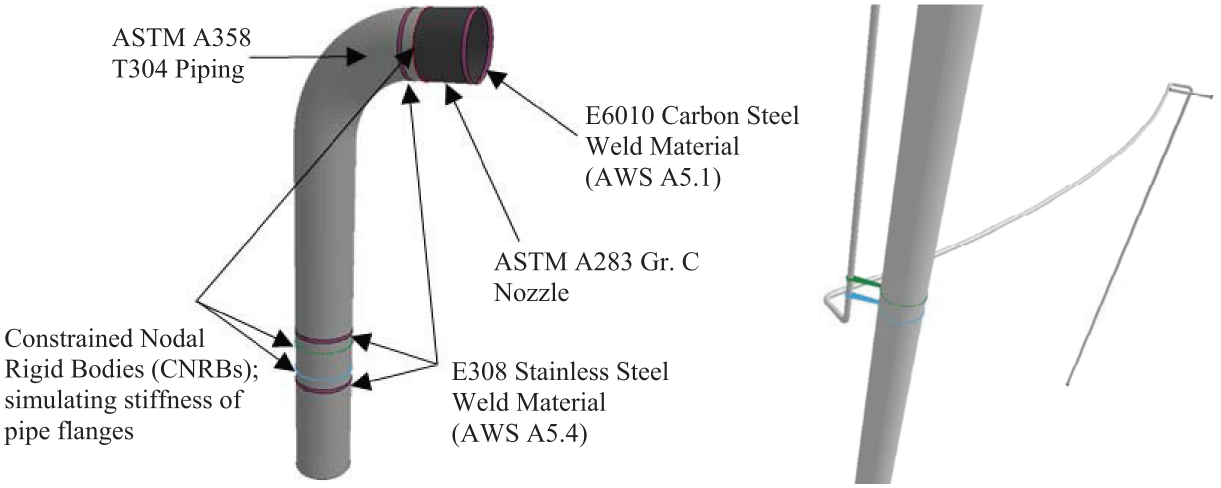


Figure 1. Example Finite Element Representations of Interfacing CST Pipes

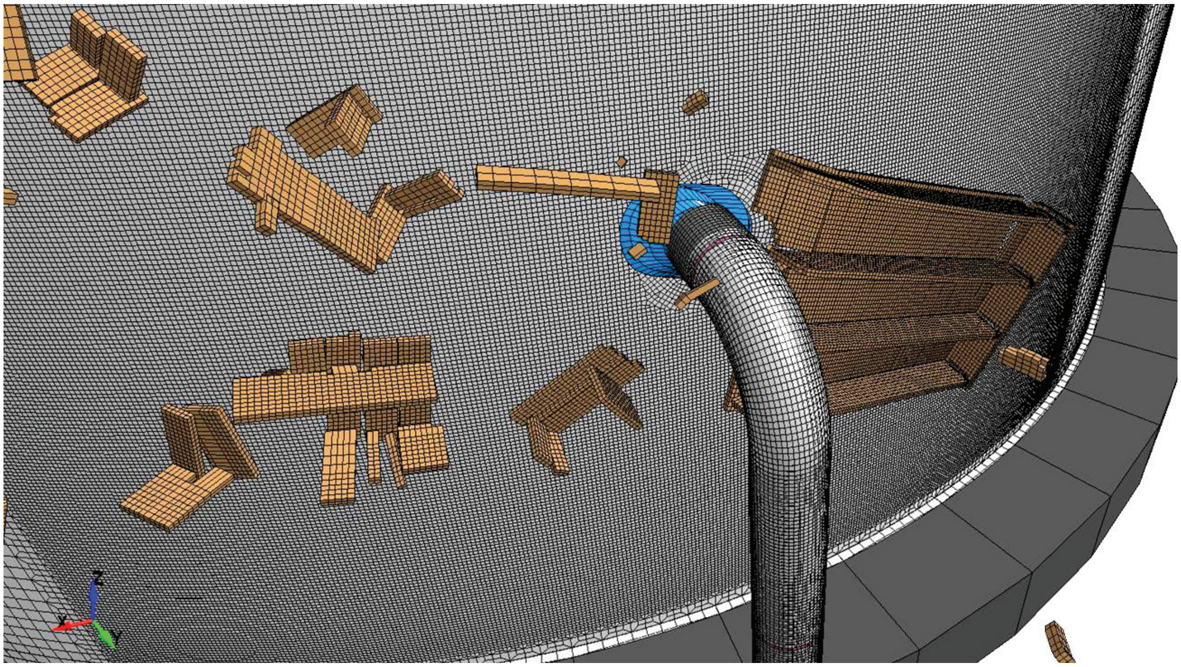


Figure 2. Image from Computational Analysis showing Failure of CST Piping Connection

DEVELOPMENT AND IMPLEMENTATION OF PERFORATED BARRIER MITIGATION STRATEGY

Following the determination that extensive missile protection was required, several conceptual solutions were developed and evaluated against the wind-driven missile spectrum and the Plant's design and construction criteria. It was determined that the tornado missile barrier would have to protect the entire circumference of the CST and all connections up to a height of fourteen feet from the CST base. The Plant mandated that the solution not require any excavation and not impair line-of-sight or line-of-fire from security officers above a three-foot height from the CST base. Additionally, the Plant requested that the CSTs not be taken out of service, no existing structures, systems, or components (SSCs) be relocated, the solution not hinder pedestrian or vehicular access, and that the barrier be capable of being moved if necessary.

Considering all limiting factors and criteria, it was concluded that the most efficient solution would be a perforated barrier system comprised primarily of ring-net panels. Ring-net products, consisting of interlocking high-strength steel-wire rings and a high-strength steel-mesh overlay, are produced by numerous manufacturers and have been used for decades to protect assets from landslides and falling rocks. Extensive experimental testing and operating experience provided confidence that a ring-net system could be engineered to arrest the design-basis tornado missiles and thus protect the vulnerable CST piping connections against potential impact scenarios. Additionally, the ring-net barrier system would provide the flexibility to meet the Plant's criteria and requests.

A perforated barrier offered many benefits compared to a solid barrier. A solid barrier with no subgrade foundation would be subject to considerable sliding and overturning demand due to tornado velocity pressures; whereas, a perforated barrier would be subject to comparatively much less sliding and overturning demand having only twenty percent of a solid barrier's projected surface area. The reduced wind loading would also decrease the size of all supporting structural components. A perforated barrier was favoured by security personnel, as it would not hinder line-of-sight or line-of-fire. From a seismic perspective, a perforated barrier would be less massive, more flexible, and likely possess greater inherent damping potential (e.g., ring slip and ring-to-ring interaction) than a solid barrier. Finally, a perforated barrier would be more cost-effective than a solid barrier because it could be competitively bid among several suppliers and would be lighter and thus easier to ship, handle, and construct than a solid barrier.

In typical applications, a ring-net system is supported by hinged cantilever columns stabilized by guy wires anchored into the ground. When a column sustains a direct impact in typical applications, it rotates about its hinged base but is “caught” by the guy wires and adjacent columns. Deflection of the impacted column and stretching of the guy wires and ring-net panel(s) provide the energy dissipating capacity necessary to arrest the impactor (falling boulders in typical applications). Because of the Plant’s excavation restrictions and desire to avoid the use of guy wires, a different support system was engineered. The hinge and guy wires were removed and replaced with a full-moment connection at the base of a support column. As a result, the columns themselves had to be designed to provide the strength (and ultimately the energy dissipating capacity) necessary to arrest the design-basis tornado missiles in the event of a direct impact. This support column concept also required the design of an above-ground foundation that could accommodate anchorage points for each support column that were capable of developing the full plastic moment capacity of the column section.

Initially, the performance objective of a support column was to remain in the elastic regime of response during direct impact of a design-basis tornado missile. Designing the support columns to remain elastic would ensure no undesirable column-to-CST interaction and reduce the potential for post-event support column repair and/or replacement needs. Owing to the fixed support condition of the barrier system columns, the size of the foundation was found to be directly proportional to the moment capacity of the column section. During preliminary sizing evaluations using traditional, linear-elastic analysis methods, it was determined that both the support column section and foundation size would need to be prohibitively large in order to meet the desired performance objective. The engineering team concluded that requiring the support columns to remain elastic during a direct impact event was not feasible given the project constraints. Accordingly, the engineering approach was modified to allow for a smaller foundation size and more reasonable support column section.

Per the Plant-specified design criteria, the tornado missile barrier was permitted to incur damage during a design-basis tornado event, provided its damage or failure did not result in loss of CST water inventory. As such, the modified engineering approach focused on capacity design of the support columns. By designing the support columns and their fixed-base connections to achieve the column section’s full plastic moment capacity, appreciable rotational ductility and thus energy dissipating capacity could be realized during a direct impact scenario. Based on this capacity design approach and the maximum foundation size desired by the Plant, preliminary design of an HSS support column section was carried out. A nonlinear dynamic analysis of an isolated support column was then conducted, during which direct impact of the design-basis bolted wood decking missile was analysed. Initial and post-impact states of the isolated support column are shown in Figure 3, where Von Mises stress contours throughout the HSS column are illustrated in the post-impact image. Results from this computational analysis confirmed the support column’s ability to form a plastic hinge at its base, adequately dissipate energy through plastic base rotation, and thus reduce the velocity of an impinging tornado missile during a direct impact scenario. In the right image of Figure 3, the Von Mises stress contours clearly depict the spread of plasticity in the plastic hinge zone near the base of the support column.

The design of an above-ground foundation for the perforated barrier system proved challenging as well. It was decided to implement a series of discrete foundation blocks, each of which supporting a modular section of the barrier system. At the request of Plant security, the foundation block height was limited to 3 feet. For structural stability purposes and to achieve the desired function, the foundation blocks were designed to withstand the demand from two scenarios involving direct impact of a support column; specifically, an impact to the top of a column creating an 11-ft moment arm and an impact at the foundation-to-column connection creating the maximum dynamic shear demand. The foundation blocks were sized such that they would neither appreciably displace nor overturn during either of the aforementioned support column impact scenarios. In order to ensure structural stability and meet desired functional objectives, each foundation block was designed to be 30 feet long with 3 support columns

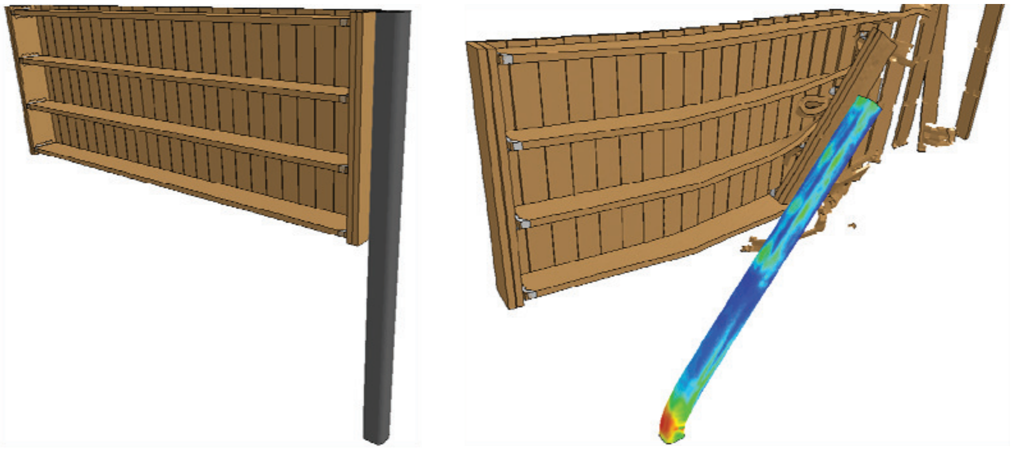


Figure 3. Initial and Post-Impact States of Isolated Support Column

spaced evenly along the foundation block's length. A single modular block unit weighed less than 70,000 lbs and could be lifted and moved by crane after installation should site conditions necessitate such action. The foundation design included supplemental steel reinforcement to restrain the embedded anchor rods used in the full-moment connections between the foundation and each support column. The foundation size restrictions prevented the embedded anchor rods from meeting code-specified minimum edge distance requirements. Thus, the supplemental steel reinforcement was designed to provide sufficient concrete breakout resistance. Additional supplemental steel reinforcement was also placed at the ends of each foundation block to mitigate any undesirable torsional response about a foundation block's longitudinal axis due to direct impact against an end support column.

Once a preliminary design of the perforated barrier system was complete, a computational model of the system was developed and used to support detailed design activities and assess global stability of the system. A transparent isometric view of the barrier system computational model is shown in Figure 4, where the ring-net panels, HSS support column baseplates and anchor rods, foundation block, and foundation block reinforcement can all be seen. Various impact scenarios involving the bolted wood decking missile were carried out. During all simulations, appropriate static and dynamic coefficients of friction for concrete-on-concrete sliding (ACI, 2006) were implemented in the contact algorithm for the base of the foundation block. From a global stability perspective, the Nexus Engineering design team determined via energy balance calculations that a direct impact near the base of an HSS support column created the most severe sliding and overturning demand. This finding was a result of the fact that a near-support impact does not promote appreciable flexural response (and hence flexurally driven plastic hinging) of the HSS column and it creates the largest dynamic shear demand to be resisted by the foundation block. Plan and elevation views of this impact scenario are computationally presented in Figure 5. Figure 6 shows the post-impact state of the bolted wood decking missile and perforated barrier system superimposed on a history plot of the missile's average horizontal velocity. It can be seen in Figure 6 that the perforated barrier system was able to arrest the bolted wood decking missile without suffering a global stability failure. Specifically, the barrier system foundation block experienced a peak horizontal velocity of less than 1-mph, a peak horizontal displacement of approximately 1-in., and peak vertical corner displacement of approximately 0.25-in. during this impact event.

In addition to the computational modelling of the perforated barrier, physical tests conducted by the ring-net manufacturer further confirmed that the ring-net design configuration used in this application was capable of arresting all three of the design-basis tornado missiles. However, because the size of the high-strength steel rings (~16-in. diameter) would allow passage of the cedar fence post missile, additional physical testing was performed by an independent laboratory to ensure the high-strength steel overlay mesh alone was capable of arresting the cedar fence post missile. The additional testing conclusively showed that the overlay mesh would stop the 33-lb cedar fence post traveling at 150-mph.

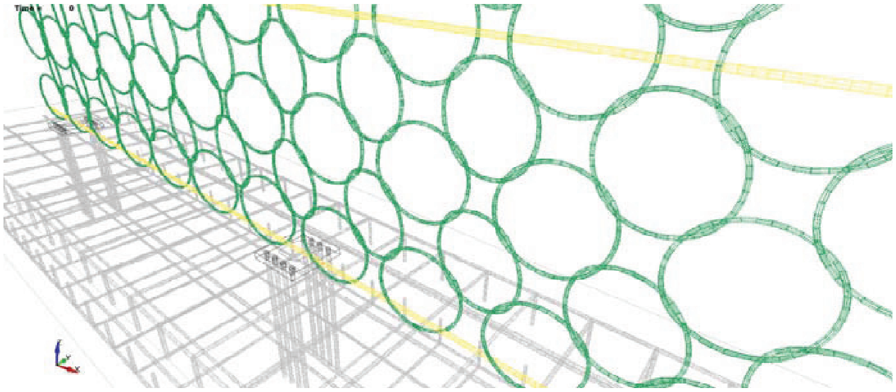
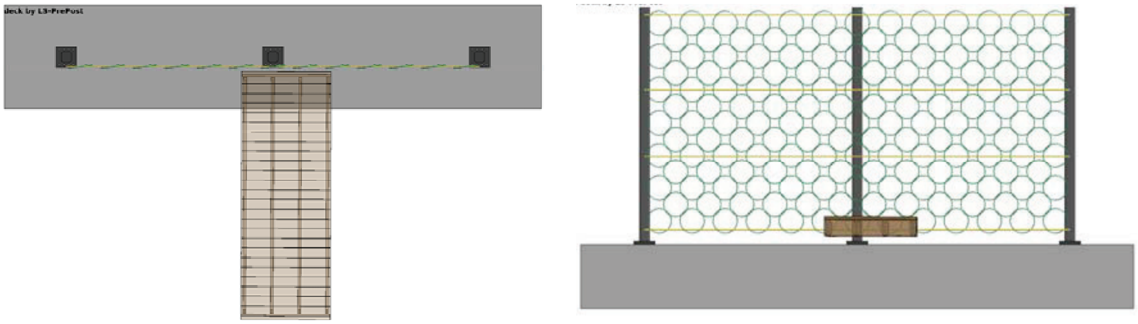


Figure 4. Transparent Isometric View of Perforated Barrier Computational Model



Plan View

Elevation View

Figure 5. Illustration of Controlling Impact Scenario for Global Stability

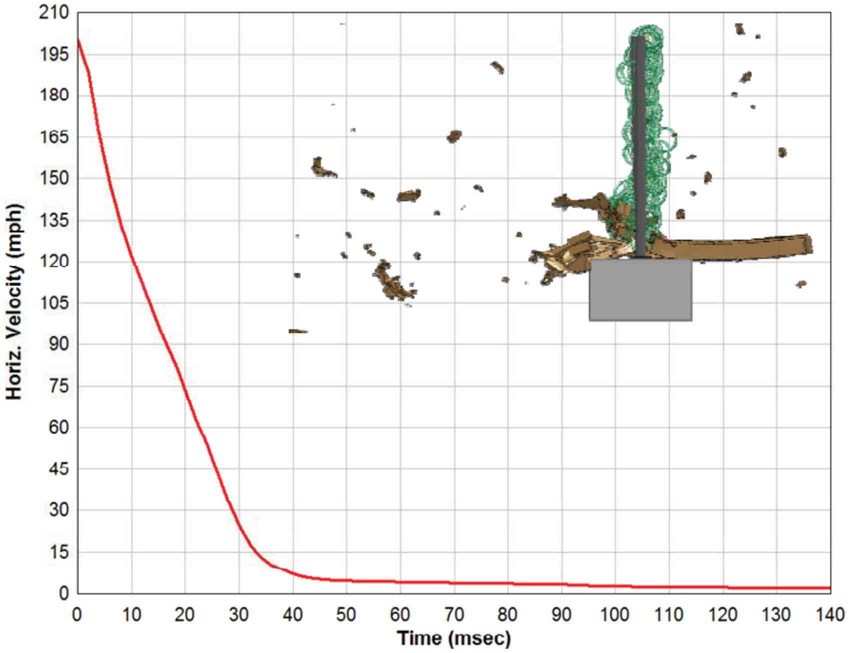


Figure 6. History Plot of Average Horizontal Tornado Missile Velocity

The modular nature of the foundation blocks provided excellent flexibility during installation. They were prefabricated offsite, which enabled the steel reinforcement to be placed within very tight tolerances. Additionally, the concrete was poured and cured in a controlled environment, protected from the effects of what became an unusually harsh winter at the Plant. Prefabrication also reduced the risk of delays from factors unique to nuclear construction, such as access and resource availability. Each foundation block was fabricated with two lifting lugs. The lugs were useful during fabrication, delivery, and installation. Also, if the foundation blocks need to be temporarily moved in the future, the lugs provide a lifting option that has been qualified and successfully implemented.

Prior to construction, the area around the CSTs was paved asphalt. No deliberate grading or drainage considerations were identified. Consequently, a cast-in-place concrete mud-mat of variable thickness up to 18 inches was designed to provide a stable and level location on which to place the perforated barrier system. The mud mat was designed such that the foundation blocks would all be at an equal elevation high enough to protect the minimum CST elevation. The mud-mat design included drainage channels to allow water to flow around individual foundation modules and prevent the area enclosed by the barrier system from filling with water during a heavy rainfall event. Following the mud-mat installation and placement of all modular foundation blocks, the support columns and ring-net panels were installed. Installation of these components was straightforward and was completed without any delays. The support columns were lifted onto the embedded anchor rods and fastened with nuts. The ring-net was then suspended from horizontal steel cables running between the support columns.

Construction was completed on time, with limited requests for information, and with no substantial design changes. The perforated barrier itself fits the aesthetic of a typical nuclear power plant and does not adversely impact day to day operations. An image of the completed missile barrier is shown in Figure 7.

Figure 7. Photograph of Installed Perforated Barrier

CONCLUSION

When the post-Fukushima guidance was issued (NEI, 2012), an assumption was made by some U.S. nuclear power plants that if their existing equipment was not safety related, it would be unavailable for FLEX strategies. Unless these plants had a UHS that was highly accessible and clean, they seemed to be left with few options and prepared to spend a large portion of their budget on new clean-water storage tanks. These new tanks would be required to withstand the applicable BDBEEs, including seismic and high wind events. In addition to these stringent requirements, the tanks would be constructed on a nuclear site which typically increases cost significantly—a tank that would cost two to three dollars per gallon in non-nuclear industrial settings was estimated to cost thirty to thirty-five dollars per gallon on a nuclear site.

Once these budgets were understood, alternatives were discussed and some paradigm "busting" was undertaken. Data from seismic events around the world (EPRI, 2009) suggested that the tanks would likely survive a seismic BDBEE per the requirements specified by the site. This favourable probabilistic data somewhat contradicted generally accepted deterministic data often utilized in state-of-the-practice nuclear power plant seismic margin assessment methodologies (EPRI, 1991). There are certain conservatisms built into deterministic methods for safety related calculations that are required for design-basis safety related equipment. When dealing with events that are beyond design bases, a good understanding of the methodology allows certain conservatisms to be appropriately adjusted to be more realistic.

During this project, the aforementioned insight allowed for the creation of a realistic model that showed how robust the Plant's existing CSTs actually were and that they could withstand a seismic BDBEE. However, assessment of tornado missile impact effects revealed the potential for damage to certain external CST piping that would cause a loss of water inventory. Design of a missile barrier was initiated, but constraints soon led to escalating costs once again. The design team then came up with a simple cost-effective, movable missile barrier system using conventional materials originally intended for other uses. High-fidelity computational modelling and physical testing were conducted to demonstrate with a high level of confidence that the novel missile barrier design was capable of performing its intended function of protecting the CSTs and associated external piping from damage and associated loss of water inventory during a beyond-design-basis high wind event.

Building a new tank at this Plant was going to cost approximately $35,000,000. The use of alternative approaches and advanced analysis methodologies enabled the Plant to show that the existing equipment could meet the new post-Fukushima requirements with the addition of a cost-effective missile barrier. This freed up tens of millions of dollars in Plant budget that can now be used on other post-Fukushima modifications. This project highlighted the fact that innovative thinking and additional cost in advanced analysis and physical testing can yield tremendous value to a nuclear project.

Design-basis events need to be treated conservatively in order to ensure the health and safety of the public. "Sharpening the pencil" for extremely low-probability events that are beyond design bases, however, provides better control over the conservatism and allows the design to align more closely with real-world data and laboratory testing.

REFERENCES

American Concrete Institute (ACI) (2006). *Code Requirements for Nuclear Safety-Related Concrete Structures*, ACI Standard 349-06, Farmington Hills, MI.

Electric Power Research Institute (EPRI) (2012). *Severe Accident Management Guidance Technical Basis Report*, Report 1025295, Palo Alto, CA.

Electric Power Research Institute (EPRI) (2009). *Seismic Experience Database, Version 2.4*, Palo Alto, CA. <www.epriq.com/esqug/>

Electric Power Research Institute (EPRI) (1991). *A Methodology for Assessment of Nuclear Power Plant Seismic Margin*, Report NP-6041-SL, Palo Alto, CA.

Nuclear Energy Institute (NEI) (2012). *Diverse and Flexible Coping Strategies (FLEX) Implementation Guide, Revision 1*, Guide Document NEI 12-06, Washington, D.C.

U.S. Nuclear Regulatory Commission (NRC) (2012). "Issuance of Order to Modify Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events," Order EA-12-049, Washington, D.C.

U.S. Nuclear Regulatory Commission (NRC) (2000). "Pretest Analysis of a 1:4 Scale Prestressed Concrete Containment Vessel Model," NUREG/CR-6685, Washington, D.C.