UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

October 7, 2019

Mr. Daniel G. Stoddard
Senior Vice President and
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Millstone Power Station
Innsbrook Technical Center
5000 Dominion Boulevard
Glen Allen, VA 29060

SUBJECT: MILLSTONE POWER STATION, UNITS 2 AND 3 – SUPPLEMENT TO STAFF ASSESSMENT OF RESPONSE TO 10 CFR 50.54(f) INFORMATION REQUEST -- FLOOD-CAUSING MECHANISM REEVALUATION (EPID NOS. 000495\05000336\L-2015-JLD-0011 AND 000495\05000423\L-2015-JLD-0012)

Dear Mr. Stoddard:

The purpose of this letter is to transmit the supplement to the U.S. Nuclear Regulatory Commission (NRC) staff's assessment of Millstone Power Station, Units 2 and 3 (Millstone), reevaluated flood hazard information that was issued by letter dated October 3, 2018 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML18256A200). The supplement updates the original staff assessment by providing the staff's assessment of the reevaluated probabilistic storm surge mechanism including combined effects.

By letter dated March 12, 2012 (ADAMS Accession No. ML12053A340), the NRC issued a request for information pursuant to Title 10 of the *Code of Federal Regulations*, Section 50.54(f) (hereafter referred to as the 50.54(f) letter). The request was issued as part of implementing lessons learned from the accident at the Fukushima Dai-ichi nuclear power plant. Enclosure 2 to the 50.54(f) letter requested that licensees reevaluate flood-causing mechanisms using present-day methodologies and guidance. By letter dated March 12, 2015 (ADAMS Accession No. ML15078A204), Dominion Nuclear Connecticut, Inc. (Dominion, the licensee) responded to this request for Millstone by providing the flood hazard reevaluation report (FHRR).

By letter dated December 21, 2016 (ADAMS Accession No. ML16308A226), the NRC staff sent the licensee a summary of the staff's review of Millstone reevaluated flood-causing mechanisms. This letter did not include the staff's conclusions associated with the storm surge flood-causing mechanism and stated that the staff's evaluation of the storm surge analysis was ongoing. The December 21, 2016, letter stated that future correspondence documenting the results of the staff's review would follow. The October 3, 2018, letter provided the staff's assessment of flood mechanisms, other than storm surge, that supported the staff's conclusions summarized in the December 21, 2016, letter.

By letter dated January 4, 2019 (ADAMS Accession No. ML19011A110), Dominion supplemented the FHRR report with additional information related to the probabilistic storm surge reevaluated flood hazard. By letter dated April 3, 2019 (ADAMS Accession No. ML19070A217), the staff provided a summary of the staff's review of Millstone's probabilistic storm surge mechanism. The staff noted in the April 3, 2019, letter that the values for mechanisms considered to be not bounded by the current design basis, other than storm surge, remain unchanged from the NRC's December 21, 2016, letter. The enclosed staff assessment provides the documentation supporting the NRC staff's conclusions summarized in the April 3, 2019, letter for the probabilistic storm surge reevaluated flood hazard and supplements the documentation provided in the staff's assessment dated October 3, 2018.

If you have any questions, please contact me at (301) 415-1132 or by e-mail at Joseph.Sebrosky@nrc.gov.

Sincerely,

Joseph M. Sebrosky, Senior Project Manager
Beyond-Design-Basis Management Branch
Division of Licensing Projects
Office of Nuclear Reactor Regulation

Docket Nos. 50-336 and 50-423

Enclosure:
Supplement to Staff Assessment of Flood Hazard Reevaluation Report for Millstone

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SUPPLEMENT TO

STAFF ASSESSMENT BY THE OFFICE OF NUCLEAR REACTOR REGULATION

RELATED TO FLOODING HAZARD REEVALUATION REPORT

NEAR-TERM TASK FORCE RECOMMENDATION 2.1

MILLSTONE POWER STATION, UNITS 2 AND 3

DOCKET NOS. 50-336 AND 50-423

1.0 INTRODUCTION

By letter dated March 12, 2012 (NRC, 2012a), the U.S. Nuclear Regulatory Commission (NRC) issued a request for information to all power reactor licensees and holders of construction permits in active or deferred status, under Title 10 of the *Code of Federal Regulations* (10 CFR), Section 50.54(f) (hereafter referred to as the "50.54(f) letter"). The request was issued in connection with implementing lessons-learned from the 2011 accident at the Fukushima Dai-ichi nuclear power plant as documented in the Near-Term Task Force (NTTF) report (NRC, 2011a). Recommendation 2.1 of the NTTF report recommended that the NRC staff issue orders to all licensees to reevaluate seismic and flooding hazards for their sites against current NRC requirements and guidance. Subsequent staff requirements memoranda associated with SECY-11-0124 (NRC, 2011c) and SECY-11-0137 (NRC, 2011d), directed the NRC staff to issue requests for information to licensees pursuant to 10 CFR 50.54(f) to address this recommendation.

Enclosure 2 to the 50.54(f) letter (NRC, 2012a) requested that licensees reevaluate flood hazards for their respective sites using present-day methods and regulatory guidance used by the NRC staff when reviewing applications for early site permits (ESPs) and combined licenses (COLs). The required response section of Enclosure 2 specified that NRC staff would provide a prioritization plan indicating flood hazard reevaluation report (FHRR) deadlines for each plant. On May 11, 2012, the NRC staff issued its prioritization of the FHRRs (NRC, 2012c).

By letter dated March 12, 2015 (Dominion, 2015), Dominion Nuclear Connecticut, Inc. (Dominion, the licensee) provided an FHRR for Millstone Power Station, Units 2 and 3 (Millstone, MPS). On December 21, 2016 (NRC, 2016b), the NRC issued an interim staff response (ISR) letter to the licensee providing a summary of the staff's conclusions associated with flood mechanisms other than storm surge. As stated in the December 21, 2016, letter the licensee's FHRR included both deterministic and probabilistic storm surge analysis. The licensee informed the staff that it intended to use the probabilistic storm surge analysis to perform subsequent flooding evaluations. The staff stated in the December 21, 2016, letter that because of the complexity of the probabilistic storm surge review, the staff's conclusions associated with flood mechanisms, other than storm surge, were provided as part of the letter. The staff also stated that the staff's probabilistic storm surge review would be documented in future correspondence. On October 3, 2018 (NRC, 2018a), the NRC issued a staff assessment of flood mechanisms, other than storm surge, that supported the staff's conclusions summarized in the December 21, 2016, letter.

By letter dated January 4, 2019 (Dominion, 2019), Dominion supplemented the FHRR report with additional information related to the probabilistic storm surge reevaluated flood hazard. By letter dated April 3, 2019 (NRC, 2019a), the staff provided a summary of the staff's review of Millstone's probabilistic storm surge mechanism. The staff noted in the April 3, 2019, letter that the values for mechanisms considered to be not bounded by the current design basis, other than storm surge, remain unchanged from the NRC's December 21, 2016, ISR letter.

This enclosure is a supplement to the October 3, 2018, staff assessment and provides the documentation supporting the NRC staff's conclusions summarized in the April 3, 2019, letter for the probabilistic storm surge reevaluated flood hazard. Except for the reference section, this supplement only contains the sections that were changed to resolve issues associated with the Millstone probabilistic storm surge reevaluated hazard.

2.0 REGULATORY BACKGROUND

2.1 Applicable Regulatory Requirements

There are no changes or updates to this section of the NRC staff assessment.

2.2 Enclosure 2 to the 50.54(f) Letter

There are no changes or updates to this section of the NRC staff assessment.

2.2.1 Flood-Causing Mechanisms

There are no changes or updates to this section of the NRC staff assessment.

2.2.2 Associated Effects

There are no changes or updates to this section of the NRC staff assessment.

2.2.3 Combined Effects Flood

On January 4, 2019 (Dominion, 2019a), the licensee submitted a supplement to their FHRR documenting the reevaluated storm surge and combined effects flood analysis. The NRC staff's review is provided in Section 4.0 of this supplemental staff assessment.

2.2.4 Flood Event Duration

On January 4, 2019 (Dominion, 2019a), the licensee submitted a supplement to their FHRR documenting the reevaluated storm surge and combined effects flood analysis which included a discussion of flood event duration. The NRC staff's review is provided in section 4.0 of this supplemental staff assessment.

2.2.5 Actions Following the Flood Hazard Reevaluation Report

There are no changes or updates to this section of the NRC staff assessment.

3.0 SITE INFORMATION

There are no changes or updates to this section of the NRC staff assessment.

3.2 Detailed Site Information

Elevations in this supplemental staff assessment are given with respect to the National Oceanic and Atmospheric Administration (NOAA) National Geodetic Survey Mean Sea Level (MSL) datum, which the licensee has adopted as the Millstone site datum (Dominion, 2019). Table 3.1-1 provides the summary of controlling reevaluated flood-causing mechanisms the licensee computed to be higher than the site grade elevations.

3.3 Design-Basis Flood Hazards

The flood hazard levels described in the plant's CDB are summarized by flood-causing mechanism in Table 3.2-1 in this staff assessment. The NRC staff reviewed the information provided and determined that sufficient information was provided to be responsive to Enclosure 2 of the 50.54(f) letter (NRC, 2012a).

3.4 Flood-Related Changes to the Licensing Basis

There are no changes or updates to this section of the NRC staff assessment.

3.5 Changes to the Watershed and Local Area

There are no changes or updates to this section of the NRC staff assessment.

3.6 Current Licensing Basis Flood Protection and Pertinent Flood Mitigation Features

There are no changes or updates to this section of the NRC staff assessment.

3.7 Additional Site Details to Assess the Flood Hazard

By letter dated March 12, 2015 (Dominion, 2015), Dominion submitted the FHRR which included the storm surge analysis. Due to the complexity of the review associated with the estimated maximum storm surge level, the portion of the review associated with storm surge levels was extended. By letter dated January 4, 2019 (Dominion, 2019), Dominion submitted a supplement to their FHRR. This information provided in the January 4, 2019 (Dominion, 2019), submittal is evaluated in this supplement to the NRC staff assessment. Details regarding the NRC staff's independent analysis are contained in the Attachment to this supplemental NRC staff assessment.

4.0 TECHNICAL EVALUATION: STORM SURGE ANALYSIS

Both the licensee and the NRC staff performed the storm surge analysis in two parts: evaluating the stillwater storm surge and then evaluating the combined effects. In the analyses discussed below, stillwater storm surge flood level includes the effects of wind and wave setup, but not the effects of wave run-up. The combined effects analysis considers wave run-up combined with stillwater storm surge to obtain the total water level. The combined effects analysis also provides an estimate on the duration (Table 4.4-2, Figure 4.0-1) of flooding and significant wave overtopping. To assist NRC staff in evaluating the licensee's stillwater surge analysis, staff performed an independent stillwater surge analysis which is described in the Attachment to this document. Although there are differences in some details of the licensee and NRC staff analyses, the same overall approach was used, and a brief description of this approach is provided below.

The licensee's and NRC's stillwater storm surge analyses both used the Joint Probability Method (JPM) with optimal sampling to estimate the Annual Exceedance Probability (AEP) for a range of stillwater storm surge elevations. The JPM is recognized as the preferred probabilistic method for evaluating stillwater storm surge due to tropical cyclones. The main inputs into the JPM include the storm recurrence rate, probability distributions for storm surge parameters, and an error term to model the distribution of storm surge about the mean value.

The error term accounts for randomness or aleatory variability. Epistemic uncertainty is incorporated using a logic tree in the JPM analysis. The JPM involves quantifying the frequency of tropical cyclones that generate storm surge in the vicinity of the site of interest, the likelihood of observing storms with a specific set of storm parameters (e.g. central pressure deficit (CPD), forward speed, direction of storm, and radius of maximum winds), and the likelihood of exceeding a specific surge for a storm with a given set of storm parameters. The JPM utilizes coupled storm surge and wind wave numerical simulations to evaluate the mean stillwater storm surge by developing a response surface from a limited set of storm parameters. Interpolation and extrapolation methods are used with the response surface to evaluate the mean stillwater storm surge for combinations of storm parameters not included in the numerical simulations.

There are generally multiple technically valid models and/or modeling decisions used in a hazard analysis. Uncertainty associated with multiple models and modeling decisions is called epistemic uncertainty, and this uncertainty is typically incorporated into a hazard analysis using a logic tree. Branches of the logic tree are associated with methods/decisions, and weights are assigned to the branches. The JPM is used to evaluate hazard for each path through the logic tree, and the mean hazard is obtained by multiplying the JPM results at the end of each path by all weights along the path through the tree and then summing results from the end of each path. Greater weights are assigned to branches in the logic tree that use methods deemed to be more valid or more likely to be correct. Both the licensee and NRC staff used a logic tree to incorporate epistemic uncertainty into the stillwater storm surge hazard analysis.

The licensee determined the combined effects total water level at the site in a multi-step process. Inputs to the process included identification of the ground level and site conditions near the critical infrastructure, analysis of possible wave conditions near the site at 1E-4 AEP stillwater level, and development of the total water level including wave runup and overtopping at the critical infrastructure. Staff used relevant regulatory criteria based on present-day NRC methodologies and regulatory guidance and estimation methods when evaluating the combined effects. Details on the staff's combined effects analyses are provided in the Attachment to this document.

The sub-sections below describe the relevant methods and key assumptions used by the licensee for their stillwater storm surge and combined effects analyses, the NRC staff's evaluation of the analyses, and conclusions from the staff's evaluation.

- Section 4.1 describes the licensee's stillwater storm surge analysis.

- Section 4.2 summarizes NRC staff's evaluation of the licensee's stillwater storm surge analysis.

- Section 4.3 presents the staff's conclusions on the stillwater storm surge analysis.
- Section 4.4 describes the licensee's methods and assumptions for evaluating the combined effects flood analysis.
- Section 4.5 summarizes NRC staff's evaluation of the licensee's combined effects analysis.
- Section 4.6 presents staff's conclusions on the combined effects analysis.

4.1 Description of the Licensee Stillwater Storm Surge Analysis

In the supplement to the FHRR, the licensee used JPM to calculate a storm surge mean stillwater elevation having an AEP of 1E-4. The JPM analysis only considers storm surge due to tropical cyclones so the licensee performed a separate analysis to consider the effect of extratropical storms on the 1E-4 AEP stillwater estimate. The key elements of the storm surge analysis are listed below noting the section where additional description of the licensee's approach is provided.

4.1.1 Summary of Data Sources and Datasets

Storm surge hazard calculations make use of tropical storm track information, associated storm parameters, and results from numerical storm surge simulations. The licensee used historic and synthetic storm tracks and associated storm parameters in their hazard evaluation. A record of historical tropical storm tracks and associated storm parameters is maintained by NOAA. This record is referred to as the HURDAT2 hurricane database (Landsea and Franklin, 2013) and contains data on Atlantic and Gulf of Mexico hurricanes from 1851 to the present. The synthetic storm tracks and storm parameters used by the licensee were developed by Wind Risk Tech (WRT) using a physics-based model described by Emanuel (Emanuel, 2006).

The licensee performed a set of storm surge simulations based on synthetic tracks and statistics from the WRT dataset (referred to as the MPS simulations). In addition, the licensee also used simulation results from the North Atlantic Coast Comprehensive Study (NACCS) (USACE [U.S. Army Corp of Engineers], 2015b), which are based on historical tracks and statistics from the HURDAT2 dataset (referred to as the NACCS simulations). The MPS grid has a resolution of approximately 100 feet (ft.) in the Millstone region and is refined to approximately 30 ft. near Units 2 and 3; whereas, the NACCS grid resolution is approximately 230 ft. Using a refined grid for the site-specific analysis may improve the accuracy of the mean stillwater surge estimates.

The MPS simulations are comprised of a coupled storm surge and wind wave simulation. The licensee used the Advanced Circulation (ADCIRC) Model for part of their analysis. The ADCIRC is a long-wave hydrodynamic model (Luettich, Jr. and Westerink, 1992) which solves time dependent, free surface circulation and transport problems in two and three dimensions using the finite element method on unstructured grids. The ADCIRC is widely used for simulating storm surge. The licensee also used the Simulating Waves Nearshore (SWAN) spectral wind wave model (Booij et al., 1999) for simulating nearshore waves. The corresponding NACCS simulations used ADCIRC and the STWAVE spectral wind wave model (USACE, 2015a).

4.1.2 Storm Surge Response Surface

A large number of storm parameter combinations are needed to estimate the mean stillwater storm surge using the JPM analysis. Interpolation and extrapolation of the ADCIRC simulation results is needed to obtain the mean stillwater storm surge elevations for storm parameter combinations not considered in the ADCIRC analyses. The combined ADCIRC and interpolated/extrapolated mean stillwater surge values is referred to as a response surface. The licensee used a combination of linear and second-order polynomial functions fit to the ADCIRC surge values to obtain the mean stillwater surge response surface. Storm parameter combinations not simulated in ADCIRC were interpolated from the response surface. The licensee created a response surface for both the MPS and NACCS simulations.

4.1.3 Logic tree and branch weights

The logic tree used by the licensee is illustrated in Figure 4.1-1.

4.1.3.1 Response Surfaces

The licensee's logic tree is divided into two equally weighted branches for the two response surfaces. The MPS branch uses the response surface developed from the MPS simulations and the NACCS branch uses the response surface developed from the NACCS simulations (see Section 4.1.2).

4.1.3.2 Storm Recurrence Rates

The licensee developed ranges for storm recurrence rate for both MPS and NACCS branches using the WRT synthetic tracks and the HURDAT2 tracks. The range of rates developed from the synthetic tracks were implemented in the MPS branches, and the range of rates developed from the HURDAT2-based tracks were used uses in the NACCS branches. The recurrence rates are shown in Table 4.1-1.

Aleatory variability of the antecedent water (Figure 4.1-1) level is shown as branches in the tree following storm recurrence rate. However, its quantification is included in the error term and as such will be discussed below in section 4.1.3.4.

4.1.3.3 Storm Parameters and Associated Probability Distributions

For the analysis at the 1E-4 AEP, the licensee used two approaches to evaluate the stillwater storm surge as described previously. The MPS branches of the logic tree included storm parameter distributions developed using the WRT synthetic storm database and data from HURDAT2. Within the MPS branches, the licensee assigned a value of 0.5 for both the total weight of the synthetic storms and the cumulative weight for the HURDAT2 data.

Within the NACCS branch of the logic tree, the likelihood of observing storms with a set of parameters and JPM analyses was only evaluated using historic data from the HURDAT2. Because the MPS branches used HURDAT2 data for half their JPM analyses and the NACCS branches used HURDAT2 data for all their JPM analyses as the basis for evaluating storm parameter probabilities, the total weight associated with HURDAT2 based storm parameter probabilities was 0.75; whereas a weight of 0.25 was assigned to the storm parameter probabilities developed using synthetic storms.

For both the HURDAT2 and the WRT subbranches described above, the licensee's logic tree included branches for the following storm parameters: forward direction (heading), forward speed, storm intensity, and radius of maximum winds. Storm heading dependency is included in the intensity metrics of maximum velocity and central pressure deficit.

The licensee considered the ranges and intervals for storm parameters shown in Table 4.1-2. The licensee used both parametric and non-parametric probability distributions to evaluate the likelihood of a storm track having a specific combination of storm parameters. For selected parameters, epistemic uncertainty was addressed by using multiple probability distributions with associated weights.

4.1.3.4 Error Term

The licensee used an error term to describe the distribution of the stillwater storm surge about the mean value obtained from ADCIRC analyses and the associated response surface. Within the JPM integral, the error term was used to determine the likelihood of exceeding the mean storm surge value given a set of storm parameters.

The licensee considered multiple sources that contribute to error in the mean estimate of stillwater storm surge. These sources included uncertainty due to coincidence of tide (low, mean, high) with the maximum storm surge, uncertainty in the numerical surge model, uncertainty due to sample variability, and uncertainties associated with wind speeds when using the 3M dataset. The licensee showed two branches in the logic tree associated with approaches used in evaluating the contribution of coincident tidal conditions (antecedent water level) with maximum storm surge. These two approaches resulted in different standard deviations for antecedent tidal conditions. Errors were considered for each branch of the logic tree based on the model and methods associated with the path through the logic tree resulting in a range of error terms considered in the licensee's analysis. Surge independent error values ranged from approximately 1.4 to 2.4, and surge dependent error ranged from approximately 0.05 to 0.28. The surge dependent and independent errors were combined to determine the total standard deviation associated with the calculated mean surge.

4.1.4 Extratropical Storms

The licensee examined the combined hazard curve for the tropical (TC) and extratropical (XC) cyclones to examine the influence on the XC on the storm surge hazard at the 1E-4 AEP. The licensee used available NACCS results obtained from the USACE Coastal Hazards System (USACE, 2015) at NACCS Save Point 756 located near the Millstone site of XC storms. The licensee concluded that the influence of XC at 1E-4 AEP is small to negligible, and they did not consider it further in their analyses.

4.2 NRC Review of the Stillwater Storm Surge Analysis

The NRC staff utilized regulatory guidance and considered multiple sources of information and data in reviewing the licensee's stillwater storm surge analysis. Staff reviewed the information contained in the licensee's submittal, data and methods in the scientific literature, applicable storm surge analyses performed by USACE and Federal Emergency Management Agency (FEMA), information provided during audits of the licensee's storm surge analysis, during which several interactions with the licensee occurred, and review of information on calculations provided in an electronic reading room. The audits were performed in accordance with the audit plan dated June 15, 2015 (NRC, 2015a). During the audits, the NRC staff reviewed the licensee's descriptions of its analyses and its rationale for the selected approaches to evaluating the stillwater storm surge elevation for a 1E-4 AEP and confirmed that the licensee's technical approach is consistent with current regulatory guidance, including guidance on conservatism in analysis.

The NRC staff examined the licensee's methods to verify that the JPM approach is reasonably implemented. This examination included independent evaluations on the development of the response surface using a dimensionless surge response function (SRF) as described in the Attachment to this document. The NRC staff also examined the storm recurrence rates developed by the licensee, the methods used to evaluate the likelihood of a storm track having a set of storm parameters, and the error term used to describe the distribution of storm surge about the mean value obtained from the response surface. The NRC staff performed an independent confirmatory stillwater storm surge analysis and used results from this analysis to evaluate the reasonableness of results developed by the licensee. See the Attachment for further details regarding the NRC staff's independent analysis.

A key observation by the NRC staff regarding the logic tree used by the licensee is that 75 percent of the storm surge analyses used to define the mean stillwater surge elevation with a 1E-4 AEP relied on HURDAT2 data to develop distributions describing the likelihood of observing sets of storm parameters; whereas 25 percent of the analyses were based on distributions developed using the synthetic WRT data. This was important because it demonstrated that the licensee placed significantly more confidence in the historical data for developing the likelihood of observing storm parameters for a storm track. The NRC staff performed an independent stillwater storm surge analyses using only the HURDAT2 data to evaluate the probabilities for observing a set of storm parameters.

Due to limited documentation on the development of the WRT synthetic data, the NRC staff did not focus their review on the theory and assumptions of the physics-based model, but instead, focused their review on the outcomes of that analysis such as the resulting storm recurrence rates and distribution of storm parameters in comparison with HURDAT2 historical data distributions.

The NRC staff compared the licensee's storm recurrence rates with those developed by the NRC staff and other government agencies for nearby sites. The NRC staff found that storm rates proposed by the licensee were consistent with NRC staff analysis results and results from applicable regional studies.

In reviewing the distribution of storm parameters from the synthetic data, the NRC staff found that distributions were generally consistent with the HURDAT2 data except for the distribution for radius to maximum winds which staff calculated based on a relationship to central pressure and latitudes of the HURDAT2 data (Vickery and Wadhera, 2008). The difference between the historical and synthetic data-based distributions for this parameter supported the decision to use less weight for the branches of the logic tree relying on synthetic storms for developing probabilities of observing a set of storm parameters. The NRC staff compared components of the licensee's error term with those developed from other regional studies and found them to be consistent.

The NRC staff reviewed the licensee's combined hazard curve for TC and XC and found that XC had a negligible influence at the 1E-4 AEP level, which is in alignment with accepted storm climatology in this region (storm surge at the 1E-4 AEP level is dominated by TC). As a confirmatory analysis, the NRC staff examined the NACCS TC and XC water level results for Station 756 (located near the Millstone site).

In addition to review of the components of the JPM analysis, the NRC staff compared the licensee's resulting stillwater storm surge hazard curve with results from the NRC staff's analysis. The mean surge hazard curves obtained from the licensee and the NRC staff evaluations are shown in Figure 4.2-1. These elevations included an increase in elevation due to sea level rise over the next 50 years. The licensee's stillwater surge elevation is approximately 5 percent greater than the stillwater surge elevation obtained by the NRC staff at the 1E-4 AEP. The NRC staff found this difference in results to be small for independently performed hazard studies and increases the NRC staff's confidence in the licensee's mean estimate of the stillwater storm surge hazard given the limitations in data, models, and methods available for performing this analysis.

4.3 NRC Staff Conclusions on Stillwater Storm Surge Analysis

The NRC staff reviewed the licensee's assumptions, approach, and methods. Additionally, the NRC staff augmented its review by performing independent calculations using the JPM and logic tree approach. Broadly, the NRC staff concluded the licensee's analysis of the storm surge mean stillwater water level applies reasonable approaches, methods, and assumptions. Details of the NRC staff's conclusions are described below.

The staff reviewed scientific literature (Toro et al. 2010, Hsu et al. 2018) and storm surge studies performed by other federal agencies such as USACE and FEMA. The NRC staff found that the JPM is the current state of practice for probabilistic evaluation of stillwater storm surge hazard. Therefore, the NRC staff found the licensee's use of the JPM acceptable for evaluating storm surge hazard at the Millstone site. The NRC staff performed independent calculations using a JPM and logic tree approach that are in general agreement with the licensee's results.

Applying the JPM involves evaluating storm track and storm parameter data to evaluate storm recurrence rate and the likelihood of observing a set of storm parameters for a storm track. The licensee evaluated historical HURDAT2 and synthetic WRT data for this purpose. The WRT simulation approach as described by Emmanuel (Emmanuel, 2006) has undergone peer review and the NRC staff considered this methodology to be reasonable and technically defensible. Therefore, the NRC staff found the inclusion of data from this method in the analysis to be acceptable.

The NRC staff found that the application of a logic tree by the licensee for the Millstone storm surge study to be acceptable. The use of logic trees to account for epistemic uncertainty is recommended in probabilistic seismic hazard studies (NRC, 2018b), and the Interagency Performance Evaluation Task Force study for New Orleans and Southeast Louisiana hurricane protection system (USACE, 2009) also incorporated epistemic uncertainty by using a logic tree. The NRC staff found weighting the two main branches equally with a weight of 0.5 to be acceptable. This weighting indicated that the licensee had equal confidence in the ADCIRC storm surge analyses specific to the Millstone site and those performed by the USACE for a nearby location. The logic tree weights resulted in 25 percent of the JPM analyses using the synthetic storm data for developing storm parameter probabilities and 75 percent used probabilities based on the HURDAT2 data. The NRC staff found the weighting of 25 percent for the WRT data and the weighting of 75 percent for the HURDAT2 data to be acceptable. The overall weighting was justified by a comparison of the licensee's mean hazard curve with the hazard curve from the NRC staff independent analyses, which produce similar results.

The storm recurrence rates obtained by the licensee from the WRT and HURDAT2 datasets are in a range from 2.3E-4 to 7.1E-4 storms/yr/km. This rate is consistent with rates for nearby sites in the regions having a rate of approximately 4.3E-4 storms/yr/km as reported by USACE (USACE, 2015a, 2015b) and rates estimated by staff (2.5E-4 to 7.0E-4 storms/yr/km). The NRC staff found the storm recurrence rates used by the licensee to be acceptable due to consistency with storm recurrence rates evaluated by NRC staff and the USACE (USACE, 2015a, USACE, 2015b).

The NRC staff found that the probability distributions used by the licensee to evaluate the likelihood of specific storm parameter combinations to be reasonable because the distributions are consistent with the WRT and HURDAT2 data. Some of the branches considered the storm parameters to be uncorrelated, which is consistent with standard approaches used by the USACE. For branches that considered correlated storm parameters, the NRC staff found the approach used by the licensee to generate correlated storm parameter sets to be technically justifiable, and the sensitivity study performed by the NRC demonstrated that the licensee's approach was sufficient to produce stable estimates of the probabilities for each parameter set.

In addition, the licensee considered multiple probability distributions for storm parameters, when applicable, to account for epistemic uncertainty in how the storm data variability was modeled. In reviewing the weights assigned to the branches associated with the various density functions, the NRC staff found the weights were generally equally weighted, indicating no significant bias for a specific approach, methodology, or density function. Because there is not a known consensus in the scientific community for how weights should be assigned in storm surge evaluations, the NRC staff found this unbiased approach to be acceptable.

The error terms developed by the licensee are consistent with other studies reported by USACE (USACE, 2015a, USACE, 2015b). Because the licensee included the significant contributors to error in their analysis and their results are consistent with other applicable storm surge studies, the NRC staff found the licensee's evaluation of the error term to be acceptable.

The NRC staff confirmed the licensee's finding of a small to negligible influence of the Extratropical Cyclone (XC) events on the 1E-4 AEP water level by comparison to the NACCS data results. Overall, the NRC staff found the components of the licensee's analysis to be reasonable and that they produce results for the 1E-4 AEP stillwater storm surge that are consistent with the NRC staff's independent analysis. The NRC staff concludes the licensee's methodology and resulting 1E-4 AEP stillwater storm surge estimate to be reasonable and technically defensible.

4.4 Description of Licensee Combined Effects Flooding Analysis

Section 4 of the Supplemental FHRR (Dominion, 2019) provided a discussion of the methodology, results, and conclusions from a revised combined effects flood analysis corresponding to the 1E-4 AEP storm surge stillwater level.

4.4.1 Total Water Level Analysis

The total water level is not a standard output for current storm surge simulation software packages (coupled wave and surge models can estimate combined storm surge and wave setup but not wave runup or overtopping). Therefore, supplemental analyses are performed to estimate the total water level due to these effects.

The licensee determined the combined effects total water level at the site in a multi-step process summarized below. The process utilized identification of the ground level and site conditions near the critical infrastructure, analysis of possible wave conditions near the site coincident with 1E-4 AEP stillwater levels, development of the total water level including wave runup and overtopping at the critical infrastructure. The licensee's process included the following steps:

- Evaluate hurricane parameters that are representative for a tropical cyclone to induce a stillwater flood elevation consistent with the mean 1E-4 AEP flood;
- Develop a set of synthetic storms for hydrodynamic and wave numerical model simulation with storm parameter combinations that are likely to generate storm surge elevations in the vicinity of the 1E-4 AEP stillwater elevation;
- Perform hydrodynamic and wave numerical modeling and extract results to determine the storm surge response and coincident wave activity around the 1E-4 AEP stillwater elevation;
- Identify the storm that is most representative of the storm conditions that will likely produce the 1E-4 AEP stillwater elevation at Millstone;
- Calculate total water levels at Unit 2 and Unit 3 Intake Structures and Turbine Buildings including wave runup.

The licensee reviewed synthetic storm tracks to evaluate "average" hurricane parameters that are representative of the storm surge stillwater at 1E-4 AEP. A set of 10 parameter combinations representative of stillwater at 1E-4 AEP was compiled for further coupled storm surge and nearshore wave simulations (ADCIRC+SWAN) near the site. These are referred to as "CE" storms in the FHRR Supplement. The simulated peak stillwater elevations, maximum significant wave height, and time series of stillwater, current, wave characteristics, and wind speeds were modeled for the 10 storms (see Supplemental FHRR Table 2). The licensee identified Storm CE2 as a representative storm for evaluating combined effects associated with the stillwater level at AEP of 1E-4 at MPS. Stillwater elevations, current velocities, calculated wave runups and total water levels from the CE2 simulation are summarized at selected locations around MPS in Supplemental FHRR Table 3.

Wave runup (exceeded by 2 percent of the incoming waves) for Unit 3 Turbine Building was estimated using storm CE2 along a selected transect shown Supplemental FHRR Figure 8. For other locations, wave runup (exceeded by 2 percent of the incoming waves) was estimated as 1.93 times the CE2 deep water significant wave height using the European Overtopping Manual (EurOtop, 2016, 2018).

Table 4.4-1 contains values for the combined effects total water level (still water including setup plus runup) at the mean 1E-4 AEP level for several locations as reported in Supplemental FHRR Table 3. The licensee reported that the total water level analysis indicates the 1E-4 AEP combined effects flood elevations are bounded by the current design basis at Millstone, Unit 2 and Unit 3 except for the Unit 3 Intake Structure.

4.4.2 Wave Overtopping Analysis

As part of the combined event total water level analysis, the licensee applied a deterministic analysis to develop the overtopping estimates based on examination of additional storm simulations designed to produce stillwater levels near the 1E-4 AEP level.

The licensee's wave overtopping analysis applied the European Overtopping Manual (EurOtop, 2016) to calculate the wave runup and overtopping. The licensee's analysis assumed that siding is not present (e.g., due to wind or other effects), and that wave overtopping of the flood wall was due to intermittent wave splashing on the west wall of the Unit 2 Turbine Building. The licensee's analysis adopted a 3-stage approach based on wave crest and stillwater elevations. The three consecutive stages were (1) prior to foreshore inundation; (2) during foreshore inundation; and (3) post-inundation for a selected transect. The licensee's calculated cumulative overtopping volume during Stages 1 and 3 was 1,324 gallons and 2,655 gallons, respectively. The licensee's calculated overtopping volume during Stage 2 was estimated at 22 gallons (with obliquity) or 4,862 gallons (without obliquity). Therefore, the licensee stated that the total overtopping volume equals approximately 4,000 gallons inside the Unit 2 Turbine Building, with obliquity effects included and equals approximately 8,840 gallons inside Unit 2 Turbine Building, with obliquity effects conservatively ignored. Section 4 of the Supplemental FHRR indicates these overtopping volumes can reach up to 1.4 and 3.2 percent of the available storage (i.e., 280,000 gallons) inside the building, with and without obliquity considered, respectively.

The licensee also examined wave impacts with respect to the internal flooding level of the Unit 2 Intake Structure. Wave conditions associated with the CE2 storm were used to develop the boundary conditions for a computational fluid dynamics simulation that estimated the internal flooding level of the Intake Structure. The simulations were performed using GOTHIC Version 8.2 to estimate the ingress of water through the louvers into the Intake Structure (Dominion, 2018).

4.4.3 Wave Loading Analysis

The licensee conducted an analysis to calculate hydrostatic, hydrodynamic, debris impact, and wave loads at Units 2 and 3 Intake Structures and at the Unit 2 Turbine Building. The licensee identified synthetic storm track CE2 as a representative storm for evaluating wave loading on structures. The licensee applied equations from American Society of Civil Engineers (ASCE) 7-10 (ASCE, 2010) to develop the hydrostatic lateral forces with maximum pressure at the bottom from FEMA guidelines in FEMA P-259 (FEMA, 2012). The licensee calculated maximum flood loads against Units 2 and 3 Intake Structures and Unit 2 Turbine Building. The licensee applied debris loading equations and coefficients from ASCE 7-16 and FEMA P-55 (FEMA, 2011). The licensee applied two types of objects in the debris impact analysis: a 2,000-pound (lbs.) log or a 5,291-lbs. container, based on current velocity.

Supplemental FHRR Tables 4 and 5 summarize the different types of loads at various structures at MPS, based on significant wave height and maximum wave height, respectively.
Tables 4.4-3 and 4.4-4 provide a summary of the Supplemental FHRR information on wave and debris loads at the Unit 2 and Unit 3 structures based on significant wave height and maximum wave height, respectively.

4.4.4 Combined Flooding Duration Analysis

The licensee performed an analysis to estimate the duration of the combined event flooding at the site. Similar to the wave runup and overtopping analysis, the licensee identified synthetic storm track CE2 as a representative storm for evaluating combined flooding duration associated with the stillwater level at AEP of 1E-4 at the Millstone site. Based on the review of the Storm CE2 results, the licensee estimated the duration of significant flooding (including stillwater and wave runup) around the Intake Structures and Unit 2 Turbine Building to approach up to 4.5 to 5 hours. The total duration of significant wave overtopping at Unit 2 Turbine Building flood wall was estimated to be approximately 7 to 8 hours (Table 4.4-2).

4.5 NRC Staff Review of Licensee Combined Effects Flooding Analysis

The NRC staff reviewed the licensee's evaluation of combined effects flooding, using relevant regulatory criteria based on present-day NRC methodologies and regulatory guidance and estimation methods. The staff reviewed the licensee's assumptions, approach and methods. In some cases, the NRC staff performed confirmatory analyses, while in other cases, the NRC staff compared the licensee's results to the results of independent assessments performed by NRC staff.

4.5.1 Total Water Level Analysis

The NRC staff reviewed the licensee's calculation of the total water level to ensure that appropriate methods and proper input data were applied. Staff reviewed the information contained in the licensee's submittal, data and methods in the scientific literature and similar applicable analyses performed by USACE and FEMA.

The NRC staff reviewed development of the wave conditions representative of the 1E-4 stillwater storm surge. The method used to select the representative storm was reviewed, as well as the parameters associated with the selected storm (e.g., central pressure deficit, maximum wind speed, direction, forward speed, significant wave height). The staff also reviewed the methods used to calculate the runup from this storm at the Unit 3 Turbine building, and the resulting runup and total water level values. The staff compared these values to results of the staff's independent runup and total water level analysis (see the Attachment to this document). For other locations, the NRC staff reviewed the licensee's application of the European Overtopping Manual (EurOtop, 2016) method to develop the runup and total water level. The EurOtop manual methods are largely based on European research but is applicable to conditions worldwide and is increasingly used in U.S. coastal engineering practice.

4.5.2 Wave Overtopping Analysis

The NRC staff reviewed the licensee's overtopping analysis for water ingress into the Unit 2 Turbine Building and the Unit 2 Intake Structure. The NRC staff did not conduct an independent calculation of the overtopping results.

The NRC staff reviewed the licensee's combined event total water level analysis for the Unit 2 Turbine Building that applied a deterministic analysis based on EurOtop guidance to develop the overtopping estimates. The NRC staff also reviewed the licensee's additional storm simulations designed to produce stillwater levels near the 1E-4 AEP level. The NRC staff reviewed the information in the supplement to the FHRR to verify that the licensee selected the appropriate methods, based on the EurOtop guidance, to develop the overtopping near the critical infrastructure. The NRC staff also reviewed the application of the selected methods including the inputs, coefficients, equations, and assumptions.

The NRC staff also performed a high-level review of the licensee's overtopping analysis for the Unit 2 Intake Structure. The NRC staff reviewed the development of the boundary conditions (Dominion, 2018) used in the overtopping simulation. The oscillating water level boundary condition at the Unit 2 Intake Structure louver was developed from the CE2 storm wave characteristics. The NRC staff also reviewed the development of the GOTHIC model for the intake structure, including the volumes and flow paths (NRC, 2019b). The NRC staff has accepted the use of GOTHIC code for licensing basis safety analysis for containment and ventilation systems and has also developed models for performing confirmatory analysis. The staff considers GOTHIC code suitable and acceptable for the non-safety related flooding analysis in review. The NRC staff also reviewed the GOTHIC code output for the peak water level inside the Unit 2 Intake Structure.

4.5.3 Wave Loading Analysis

The NRC staff reviewed the licensee's selection of representative storms for the wave loading analysis. The NRC staff reviewed the licensee's use of industry standard guidance documents such as ASCE 7-10 (ASCE, 2010), FEMA P-259 (FEMA, 2012), ASCE 7-16 (ASCE, 2017), and FEMA P-55 (FEMA, 2011), including formulas applied to calculate hydrostatic, hydrodynamic, debris impact, and wave load forces. The NRC staff also developed independent calculations to confirm the calculations and conclusions of the licensee approach to estimate the hydrostatic, hydrodynamic, debris impact, and wave loads. The NRC staff's analysis applied the wave and water level conditions determined by the licensee along with appropriate coefficient and factors used in the equations to check the final loading values determined by the licensee.

4.5.4 Combined Flooding Duration Analysis

The NRC staff developed an independent estimate of the total water level duration. To develop an independent estimate of total water duration above specific levels near the Unit 2 and Unit 3 buildings, the NRC staff reviewed data from independent storm surge and wave model simulations conducted by NRC staff during the review of the licensee's original FHRR. The data review examined the independent storm surge simulations that produced stillwater levels near the NRC staff estimate of the 1E-4 AEP level discussed in Section 4.1 and determined the approximate duration of such water levels.

4.6 <u>NRC Staff Conclusions on Licensee Combined Effects Flooding Analysis</u>

Based on review of the licensee's assumptions, approach, and methods and augmented by selected confirmatory calculations and independent analyses, the NRC staff reached the conclusions described below.

4.6.1 Total Water Level Analysis

Based on the NRC staff review of the licensee's submittal and independent analyses, the NRC staff concluded the licensee's analysis of the combined effect water level applies a reasonable approach, methods, and assumptions.

The NRC staff review of the licensee's wave runup and total water level analysis for the Unit 3 Turbine Building indicates the licensee appropriately applied the input wave and water level conditions derived from the 1E-4 AEP stillwater level analysis and followed standard engineering practice to calculate runup.

At other locations (Unit 2 Turbine Building and Unit 2 and Unit 3 Intake Structures), the staff review found that the licensee appropriately applied the European Overtopping Manual (EurOtop, 2016) method to develop the runup and total water level. An independent calculation completed by NRC staff produced similar wave runup and total water level values at these locations. The NRC staff independent analysis applied a similar approach, but with different coupled surge and wave simulation inputs, and obtained similar results. For further discussion, see the Attachment to this document.

4.6.2 Wave Overtopping Analysis

Following the review, the NRC staff concluded the licensee's analysis of the wave runup and overtopping at the Unit 2 Turbine building applies a reasonable approach (following the EurOtop guidance), methods, and assumptions. The NRC staff concluded the wave condition inputs were appropriate and the licensee correctly applied the EurOtop guidance. The NRC staff also found the inputs, coefficients, equations, and assumptions to be reasonable based on standard engineering practice.

The NRC staff found the licensee's analysis of the Unit 2 Intake Structure using GOTHIC to be reasonable. The NRC staff has accepted the use of GOTHIC code for licensing basis safety analysis for containment and ventilation systems and has also developed models for performing confirmatory analysis. The staff considers GOTHIC code suitable and acceptable for the non-safety related flooding analysis in review.

Based on a high-level review of the wave conditions, oscillating water level boundary conditions, volumes and flow paths at the Unit 2 Intake Structure, the NRC staff found the licensee's analysis to be reasonable.

4.6.3 Wave Loading Analysis

The NRC staff review found that the licensee's methods and application of loading equations and coefficients are reasonable given current practices and available tools and equations. The NRC staff found that the guidance documents used, and the formulas applied provided suitable approaches to complete the wave loading analyses. The NRC staff found that the selection of representative wave conditions was reasonable. The NRC staff found that the licensee correctly applied the guidance and formulas. The NRC staff independent analysis produced results similar to the licensee's values, which provided confirmation that the licensee's calculations provide reasonable estimates of the loadings.

4.6.4 Combined Flooding Duration Analysis

The NRC staff review concluded that the licensee's approach and methods were reasonable. Independent analyses using storm and wave simulations developed by the NRC staff confirm the duration estimates of 4 to 8 hours for the Unit 2 and Unit 3 buildings developed by the licensee provide reasonable estimates for the duration of water levels above approximately 15 ft.

4.6.5 Overall Conclusion (Combined Effects Flooding)

The NRC staff reviewed the combined effects flooding information provided for the licensee and concluded that the analyses and results are reasonable. Based on its review of the licensee's information provided and independent analyses, the NRC staff agrees with the licensee's conclusion that the reevaluated storm surge combined effect hazard for the Unit 3 Intake Structure is not bounded by the CDB. Therefore, the combined effects flooding hazard mechanism needs to be analyzed in a focused evaluation or an integrated assessment.

5.0 SUMMARY

As stated in Section 1, the licensee determined that the reevaluated flood hazard results for the storm surge at the 1E-4 AEP were bounded by the current design basis at MPS Units 2 and 3, with the exception of the MPS Unit 3 Intake Structure, where the CDB was exceeded only by the combined effects flood elevation (stillwater plus wind wave/runup). Based on the NRC staff's review and independent analyses, the NRC staff concluded the licensee's results are reasonable.

Consistent with the 50.54(f) letter and amended by the process outlined in COMSECY-15-0019 (NRC, 2015b) and Japan Lessons-Learned Division (JLD) Interim Staff Guidance (ISG) JLD-ISG-2016-01, Revision 0 (NRC, 2016a), the NRC staff anticipates that the licensee will perform and document a focused evaluation (FE) or integrated assessment (IA) for storm surge that assesses the impact of the hazard on the site, and evaluates and implements any necessary programmatic, procedural or plant modifications to address this hazard exceedance.

6.0 REFERENCES

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Table 3.1-1. Summary of Controlling Flood-Causing Mechanisms

Reevaluated Flood-Causing Mechanisms and Associated Effects that May Exceed the Powerblock Elevation 14 ft. MSL for Unit 2 and 24 ft. MSL for Unit 3	ELEVATION, ft
Storm Surge[1]	
Unit 2	
Powerblock (East Side)	17.5 ft.
Powerblock (West Side)	19.8 ft.
Within Intake Structure (Standing Wave)	27.6 ft.
Unit 3	
Seaward Wall of Intake Structure	42.6 ft.
Powerblock	22.2 ft.

[1]The storm surge elevation includes the combined effects with wind-wave activity.

Table 3.2-1. Current Design Basis Flood Hazards[1,2]

Flooding Mechanism	Stillwater Elevation (ft. NGVD29)	Waves/Runup	Design Basis Hazard Elevation (ft. NGVD29)	Reference
Storm Surge				
Unit 2 within Intake Structure	26.5	Not applicable	26.5	FHRR Section 1.5 and 3.4
Unit 2 at the Powerblock	18.1	7.0	25.1	FHRR Section 3.9 and FHRR Tables 1.2-1 and 3.0-1
Unit 3 seaward wall of Intake Structure	19.7 ft	21.5	41.2 ft	FHRR Section 3.9
Unit 3 at Powerblock	19.7	4.1	23.8	FHRR Section 1.5 and FHRR Table 1.2-2

Note 1: Reported values are rounded to the nearest one-tenth of a foot.
Note 2: There are no changes or updates to this Table of the NRC staff assessment

Table 4.1-1 Storm Recurrence Rates

Branch	Upper estimate storms/yr/km **Weight 0.25**	Best Estimate storms/yr/km **Weight 0.5**	Lower Estimate storms/yr/km **Weight 0.25**
MPS	3.1E-4	5.1E-4	7.1E-4
NACCS	2.3 E-4	4.3E-4	6.3E-4

Table 4.1-2. Storm Parameters Considered by the Licensee

Parameter	Intervals	Range	
Heading direction	10 degree	-50 degrees	50 degrees
Rmax*	10 km	20 km	180 km
Forward speed	5 knots	15 knots	50 knots
Central pressure deficit	5 mb	23 mb	98 mb
Maximum Wind Speed	10 knots	70 knots	170 knots

** where Rmax is the radius to maximum winds*

Table 4.4-1. Reevaluated Hazard Elevations for Flood-Causing Mechanisms Not Bounded by the CDB

Flood-Causing Mechanism	Stillwater Elevation (ft.)	Waves/Runup (ft.)	Reevaluated Hazard Elevation (ft.)	Reference
Storm Surge				
Unit 2				ML19011A110 (Table 6)
Powerblock (East Side)	17.5 ft.	Negligible	17.5 ft.	
Powerblock (West Side)	17.5 ft.	2.4 ft.	19.8 ft.	
Within Intake Structure (Standing Wave)	16.9 ft. [1]	N/A	27.56 ft. [2]	
Unit 3				ML19011A110 (Table 7)
Seaward Wall of Intake Structure	17.1 ft.	25.5 ft	42.6 ft.	
Powerblock	17.7 ft.	4.5 ft.	22.2 ft.	

1. External reevaluated water levels at the Unit 2 intake structure were reported as 16.9 ft. for stillwater and 37.2 ft. for the external total water level (including wave runup of 20.3 ft.). However, the CDB is for service water pumps within the Unit 2 intake structure.

2. This reported value is the maximum water level from 4 cases evaluated for Unit 2 internal water levels using the GOTHIC code as presented in calculation package NAI-1996-001, which is referenced as "Zachry, 2018c" in the supplement to the FHRR.

Table 4.4-2. Flood Event Duration for Flood-Causing Mechanisms Not Bounded by the CDB

Flood-Causing Mechanism	Time Available for Preparation for Flood Event (hr)	Duration of Inundation of Site	Time for Water to Recede from Site	Reference
Storm Surge				
Unit 2 Intake	Not Provided	4.5 - 5 hours	Not Provided	ML19011A110
Unit 2 Turbine Building	Not Provided	7 - 8 hours	Not Provided	ML19011A110

Table 4.4-3. Flood Loads Results based on Significant Wave Height

Structure	Location	Hydrostatic Pressure (psf)[1]	Current Velocity Hydrodynamic Pressure (psf)	Standing Wave Pressure (psf)[3]	Composite Pressure (psf)[4]	Debris Load Considering a Log of 2,000-lb (lb)[3]	Debris Load Considering a Shipping Container of 5,291-lb (lb)[3]
Unit 2 Intake West Side	Stillwater Elevation	0	34	691	725	10,400	27,513
	Bottom of Structure[2]	2,995	34	442	3,471	0	0
Unit 2 Intake South Side	Stillwater Elevation	0	59	707	766	13,800	36,508
	Bottom of Structure[2]	3,002	59	467	3,528	0	0
Unit 3 Intake South Side	Stillwater Elevation	0	5	898	903	4,000	10,582
	Bottom of Structure[2]	3,002	5	570	3,577	0	0
Unit 3 Intake East Side	Stillwater Elevation	0	32	877	909	10,200	26,984
	Bottom of Structure[2]	3,014	32	556	3,602	0	0
Unit 2 Turbine Building West Side[5]	Stillwater Elevation	0	224	N/A	224	21,200	N/A
	Bottom of Structure[3]	224	224	N/A	448	0	N/A

Notes:
1) psf = pounds per square foot (lb/ft^2)
2) Toe Elevation at Unit 2 and Unit 3 intake structures = -30.0 ft. MSL. Toe Elevation at Unit 2 Turbine Building = 14 ft. MSL
3) Debris loads assumed to act at the maximum stillwater elevation. Standing wave pressures are based on significant wave height.
4) The composite pressure at a given location is the sum of the hydrostatic pressure, current velocity hydrodynamic pressure and standing wave pressure.
5) Flood loads except for hydrostatic load do not apply to other sides of Unit 2 Turbine Building and structures in the Unit 2 main site / power block

Table 4.4-4. Flood Loads Results based on Maximum Wave Height

Structure	Location	Hydrostatic Pressure (psf)[1]	Current Velocity Hydrodynamic Pressure (psf)	Standing Wave Pressure (psf)[3]	Composite Pressure (psf)[4]	Debris Load Considering a Log of 2,000-lb (lb)[3]	Debris Load Considering a Shipping Container of 5,291-lb (lb)[3]
Unit 2 Intake West Side	Stillwater Elevation	0	34	1,168	1,202	10,400	27,513
	Bottom of Structure[2]	2,995	34	738	3,767	0	0
Unit 2 Intake South Side	Stillwater Elevation	0	59	1,196	1,255	13,800	36,508
	Bottom of Structure[2]	3,002	59	781	3,842	0	0
Unit 3 Intake South Side	Stillwater Elevation	0	5	1,512	1,517	4,000	10,582
	Bottom of Structure[2]	3,002	5	953	3,960	0	0
Unit 3 Intake East Side	Stillwater Elevation	0	32	1,477	1,509	10,200	26,984
	Bottom of Structure[2]	3,014	32	929	3,975	0	0
Unit 2 Turbine Building West Side[5]	Stillwater Elevation	0	224	N/A	224	21,200	N/A
	Bottom of Structure[3]	224	224	N/A	448	0	N/A

Notes:
1) psf = pounds per square foot (lb/ft.^{2})
2) Toe Elevation at Unit 2 and Unit 3 intake structures = -30.0 ft. MSL. Toe Elevation at Unit 2 Turbine Building = 14 ft. MSL
3) Debris loads assumed to act at the maximum stillwater elevation. Standing wave pressures are based on significant wave height.
4) The composite pressure at a given location is the sum of the hydrostatic pressure, current velocity hydrodynamic pressure and standing wave pressure.
5) Flood loads except for hydrostatic load do not apply to other sides of Unit 2 Turbine Building and structures in the Unit 2 main site / power block

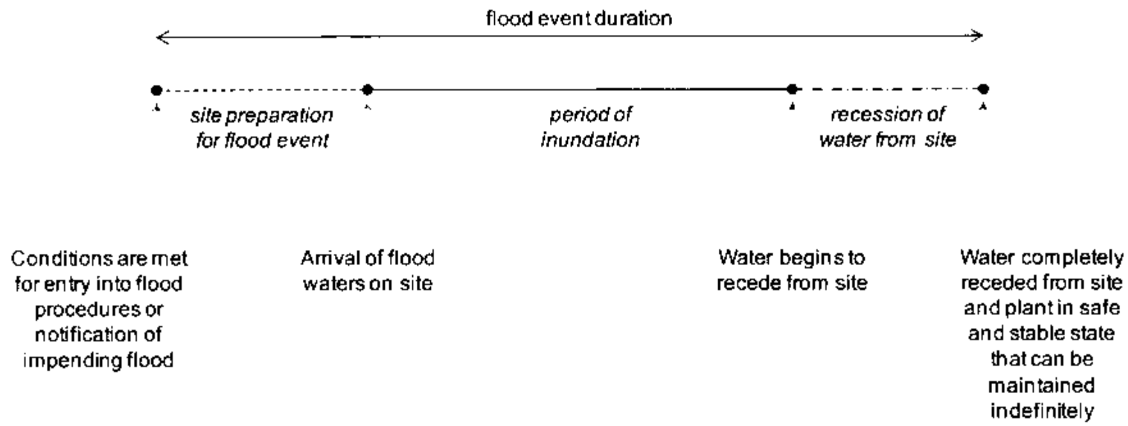

Figure 4.0-1. Flood Event Duration

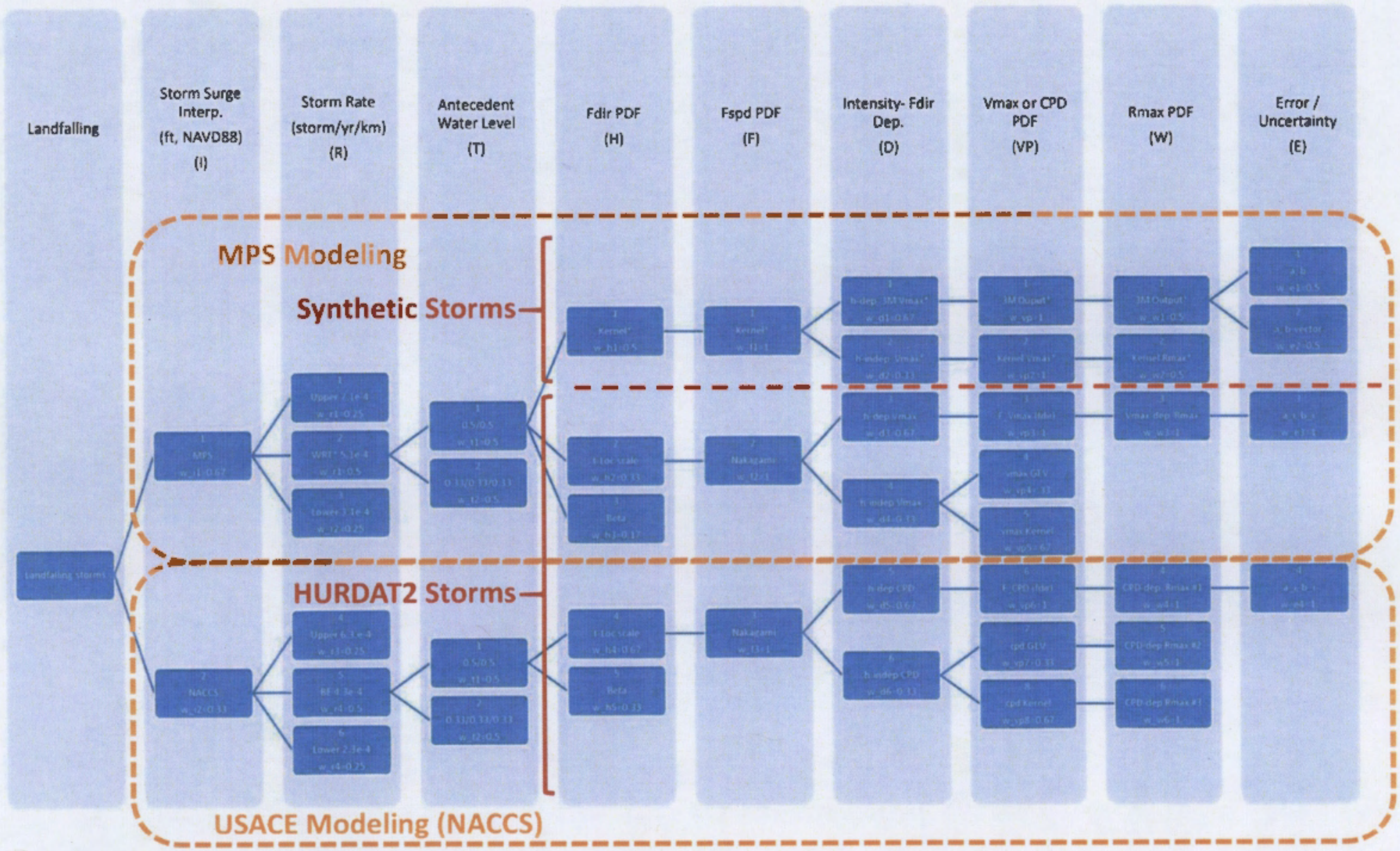

Figure 4.1-1. Annotated Version of Figure 1 from FHRR Supplement (ML19011A110)

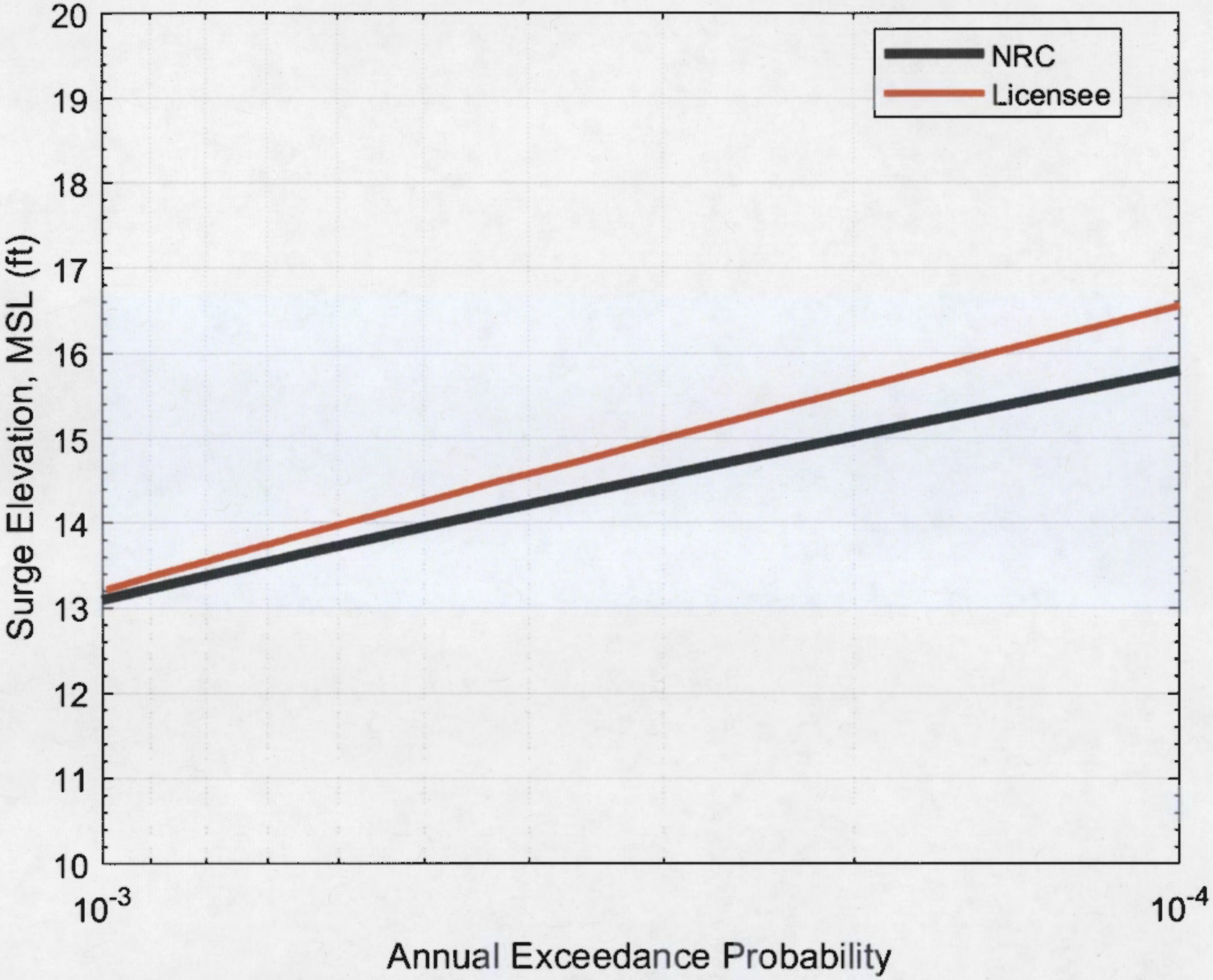

Figure 4.2-1. Mean Stillwater Surge Hazard Curves from Licensee and NRC Staff Evaluations.

STAFF'S INDEPENDENT ANALYSIS OF THE MILLSTONE STORM SURGE HAZARD INCLUDING COMBINED EFFECTS

1.0 INTRODUCTION

The purpose of this attachment is to document the staff's first independent application of a fully probabilistic methodology to the evaluation of a flooding mechanism at an operating nuclear power plant site. Based on the staff's experience and the use of an expert peer review process, the staff has confidence that the results may be used to confirm the licensee's evaluation (as presented in the staff assessment found in the Enclosure to this document). Further, the staff concludes that this methodology might be applied with confidence in future flooding reviews.

The NRC is employing this probabilistic approach to flood hazard reviews because it has used the approach successfully in other technical reviews across the agency, such as the Senior Seismic Hazard Analysis Committee (SSHAC) process for seismic hazards and the review process under 10 CFR 50.69, "Risk-Informed Categorization and Treatment of Structures, Systems and Components for Nuclear Power Reactors."

The NRC staff performed an independent analyses of storm surge flooding hazards for Millstone's probabilistic storm surge analysis to aid in reviewing the licensee's flood hazard reevaluation report (Dominion, 2015) and the associated supplement (Dominion, 2019). The staff's probabilistic analyses developed estimates of surge stillwater elevation for a range of Annual Exceedance Probabilities (AEPs) and surge total water level at an AEP of 1E-4.

The Millstone storm surge hazard independent confirmatory analysis performed by the staff is a fully Probabilistic Flood Hazard Assessment (PFHA). The analysis considered existing guidance described below in Section 5, and incorporated methodology primarily based on the PFHA Research Program technical bases research projects conducted by the Office of Research.

Based on discussions with the NRC staff regarding direction and methodology set forth for probabilistic evaluations in guidance in COMSECY-15-0019 (NRC, 2015), and interim staff guidance JLD-ISG-2016-01 (NRC, 2016), Dominion Energy agreed to submit a supplement to the FHRR which documented the evaluation of storm surge evaluation at an AEP of 1E-4. Nuclear Energy Institute (NEI) 16-05 (NEI, 2016) presents methods, which may be used to address flood scenarios and was endorsed by NRC with limited clarifications, which are described in JLD-ISG-16-01 (NRC, 2016). In the Closure Plan for Reevaluation of Flooding Hazards for Operating Nuclear Power Plants (COMSECY-15-0019 (NRC, 2015)), the staff clarified that, "...if a flooding hazard associated with a frequency of 10^{-4} per year cannot be defined in a timely and/or a technically defensible manner for a site...a surrogate (e.g., 10^{-3} plus a factor) consistent with the current state of practice may be developed to provide quantitative risk insights to augment the available qualitative risk insights".

The staff's application of probabilistic methodology for its confirmatory analysis is consistent with guidance in COMSECY-15-0019 (NRC, 2015) that directed staff to, "...develop probabilistic methods for assessing flooding hazards...to support the staff's assessments and regulatory decisions". The staff utilized a two-tiered approach for the PFHA review. First, project-specific technical review teams composed of subject matter experts from within and outside of the agency were established to perform the PFHA review. Second, the Senior Technical Review Board (STRB), a group of independent subject-matter experts, was constituted to perform a peer review of the PFHA review team's evaluations and analyses. The STRB peer review provided both technical and regulatory guidance for consistency with regulatory requirements. This PFHA methodology fully addresses the aleatory and epistemic uncertainties, and encompasses the center, body and range of different data, models, methods and approaches for analyzing storm surge.

1.1 Overview

In general, PFHA explores a set of potential flood scenarios for a flooding mechanism, such as storm surge. These scenarios include the parameters that may contribute to flooding and associate a probability to the resulting flood elevations for each scenario. For the Millstone PFHA, the staff performed several main steps to determine the potential range of stillwater flood elevations resulting from storm surge. In general, these steps were:

1) Selection of a probability method for use in the assessment that is appropriate for the site setting,

2) Identification of contributing parameters associated with the surge flood mechanism,

3) Discretization of flood related parameters into representative values using probability density functions (PDF),

4) Identification of the possible sources of uncertainty (epistemic and aleatory) that could affect the analysis using an error term and a logic tree,

5) Use of the logic tree to characterize and evaluate epistemic uncertainties (e.g. develop potential scenarios, or branches, and assign weights)

6) Calculation of hazard curves for each scenario/branch to determine the surge elevation for a range of return periods, and

7) Evaluation of the Confidence Interval (CI) associated with the results and development of a mean hazard curve.

In addition, the staff performed a separate evaluation to determine the wave runup and these results were combined with the stillwater results to determine the total water level for the AEP of 1E-4 surge event. Refer to Section 1.0 of this attachment.

The staff implemented the Joint Probability Method (JPM) (Ho and Meyers, 1975; Meyers 1975; Resio et al. 2009) to evaluate the stillwater storm surge hazard. The JPM approach was developed to account for the stochastic nature (i.e., natural variability) of storms and storm surge hazards and is widely used in coastal flood hazard studies performed by federal agencies such as the U.S. Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA). It is recognized as the preferred probabilistic method for evaluating storm surge due to tropical cyclones. The JPM requires quantifying the frequency of tropical cyclones that generate storm surge in the vicinity of the site of interest, the likelihood of observing storms with a specific set of storm parameters (e.g. central pressure deficit (CPD), forward speed, direction of storm, and radius of maximum winds), and the likelihood of exceeding a specific surge for a storm with a given set of storm parameters. This information is integrated to evaluate the AEP of a specific storm surge elevation.

Inputs for the staff analysis were derived from two sources. The staff evaluated tropical cyclone data contained in the hurricane database commonly referred to as HURDAT2 "Best tracks" database, developed by the National Oceanic and Atmospheric Administration's (NOAA) National Hurricane Center (NHC). "Best tracks" are the NHC post-storm analyses of the intensity[1], central pressure, position, and size of tropical and subtropical cyclones that have been observed in the North Atlantic since 1851[2] (Landsea, 2013). In addition to the storm information contained in the HURDAT2 database, the staff leveraged storm and surge response information developed in the USACE North Atlantic Coast Comprehensive Study (NACCS) (USACE, 2015b), which examined storm surge, tide, waves, wind, atmospheric pressure, and currents for the U.S. coastal region from Virginia to Maine. The NACCS included a dense spatial coverage of nearshore storm response for the region, high-fidelity computations, and comprehensive description of the natural variability of response from frequent storm events to very rare events (1E-4 AEP). The staff retrieved NACCS results (synthetic storms and surge responses) from the USACE Coastal Hazards System, a web-based coastal storm data resource (USACE, 2015b)[3].

In addition to the natural variability addressed by the JPM approach, staff explicitly considered epistemic uncertainties (e.g., uncertainties in data, model structure and parameter distributions) in the storm surge hazard evaluation. Overall, the staff's review has focused on several areas which were needed to support the JPM and the analysis of epistemic uncertainty in determining the storm surge hazard levels for a range of frequencies. These staff review areas are listed below, with more detailed discussion in the following sections:

- Implementation of the Joint Probability Method (Section 2.2)
- Surge Response Functions (Section 2.3)
- Logic Tree Development Including Estimation of Branch Weights (Section 2.4)

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[1] Maximum 1-min-average wind associated with the tropical cyclone at an elevation of 10m with an unobstructed exposure.

[2] Although the database goes back to 1851, it is not considered complete and accurate for the entire century and a half. As one goes back further in time, uncertainties and biases in storm parameters and tropical cyclone frequencies become more pronounced. Some storms were missed and many intensities are too low in the pre-aircraft, reconnaissance era (1944 for the western half of the basin) and in the pre-satellite era (late-1960s for the entire basin). Even in the last decade or two, new technologies affect the best tracks in a non-trivial way because of generally improving ability to observe the frequency, intensity, and size of tropical cyclones.

[3] NAACS methods are described as "[Strategic selection of tropical storms]to characterize the regional storm hazard. CSTORM-MS was then applied with the wave generation and propagation model WAM, providing offshore, deep-water waves to apply as boundary conditions to the nearshore steady-state wave model STWAVE, ADCIRC to simulate the surge and circulation response to the storms, and STWAVE to provide nearshore wave conditions including local wind-generated waves." (USACE, 2015a). The Wave Model (WAM) is a 3rd generation wave model that solve the action balance equation and was developed by a consortium of modelers for weather prediction (Komen et al 1994). The Advanced CIRCulation (ADCIRC) model is a long-wave hydrodynamic model (Luettich et al 1992) which solves time dependent, free surface circulation and transport problems in two and three dimensions using the finite element method on unstructured grids. ADCIRC is commonly used for storm surge and flooding models. The nearshore wave model used is the Steady State spectral WAVE (STWAVE, Massey et al. 2011), "a steady-state, finite-difference, phase-averaged spectral wave model based on the wave action balance equation. STWAVE simulates nearshore wave transformation including depth- and current-induced refraction and shoaling, depth- and steepness-induced wave breaking, windwave generation and growth, and wave-wave interaction and whitecapping" (USACE, 2015a).

- Storm Recurrence Rate (Section 2.5)
- Storm Parameter Combinations and Associated Probability Distributions (Section 2.6)
- Error Term (Section 2.7)
- Stillwater Storm Surge Hazard Curve Development (Section 2.8)

The staff also evaluated the potential effect of wind-wave activity. To estimate the total water level near the site intake and turbine buildings, staff utilized wave data from the NACCS. This was combined with the stillwater storm surge to produce an estimate of the total water level for the site. This is discussed further in Section 3.0.

Elevations in this attachment are given with respect to the NOAA National Geodetic Survey Mean Sea Level (MSL) datum, which the licensee has adopted as the Millstone site datum (Dominion, 2019).

2.0 STAFF INDEPENDENT STILLWATER ANALYSIS

2.1 Summary of Approach

The staff performed an independent evaluation of the stillwater storm surge hazard for the site. The NRC calculations utilized data from the USACE NACCS (USACE, 2015a, USACE, 2015b) to take advantage of numerical model results required for developing estimates of storm surge for a range of storm parameter combinations. The staff used the NACCS results for save point SP0756 because it is the NACCS save point located closest (approximately 2,100 ft. from the Unit 2 Intake Building) to the site (Figure 2-1). The staff used the HURDAT2 NHC Data Archive to determine storm recurrence rates and probability distributions for storm parameters. The HURDAT2 database is updated periodically and the staff used a database that included storms from 1851 through 2013.

Aleatory variability and epistemic uncertainty are incorporated into the storm surge evaluation to account for natural variability that is not captured in the deterministic models and uncertainties associated with a range of acceptable modeling decisions. Probability density functions of storm parameters (PDFs) are used to represent the aleatory/natural variability of the parameters based on historical data and are used to estimate the probability of exceeding specified surge elevations. Storm surge estimates obtained from numerical models are assumed to be median values and have a normal distribution. The standard deviation for this normal distribution accounts for the aleatory variability in storm surge given a set of known storm parameters. A logic tree is used to incorporate epistemic uncertainty in the storm hazard analysis.

Figure 2-1 Location of NACCS save point in relation to Millstone (from Google Earth).

2.2 Implementation of the Joint Probability Method

Staff used the JPM optimal sampling (JPM-OS) method to evaluate storm surge hazard. Studies typically use one of two optimal sampling approaches, the response surface (RS) method (Irish et al. 2009) or the Bayesian Quadrature (BQ) method (Toro et al., 2010). Staff implemented the RS approach. This approach consists of using a limited set of storm surge simulations and interpolating to obtain storm surge for locations and storm parameter combinations that were not explicitly modeled in the simulations. The JPM integral in Eq. 1 was used to evaluate storm surge hazard.

$$\lambda_{\eta>\eta_0} = \lambda \int_{\underline{v}} P[\eta(\underline{v}) > \eta_0|\underline{v}] f_{\underline{v}}(\underline{v}) d\underline{v} \qquad \textbf{Eq. 1}$$

in which, $\lambda_{\eta>\eta_0}$ = AEP (1/yr); η_0 = an arbitrary elevation; η = surge elevation; λ = storm recurrence rate for the area of interest (1/yr); $\underline{v}$ = a set of storm parameters considered important drivers of surge elevation; $P[\eta(\underline{v}) > \eta_0|\underline{v}]$= probability of exceeding η_0 given $\underline{v}$; and $f_{\underline{v}}$ the density function for each storm parameter. The probability distribution of storm surge is considered to be a Gaussian distribution, so $P[\eta(\underline{v}) > \eta_0|\underline{v}]$ can be evaluated using a complimentary cumulative normal distribution.

For the evaluation of the surge elevation, η, staff used a dimensionless surge response function (SRF) described in the section below. This SRF provided storm surge for landfall locations spaced 10 kilometers (km) apart and for the range of storm parameters provided in Table 2-1.

Table 2-1 Storm parameters used for evaluating storm surge with the SRF.

Parameter	Intervals	Range	
Heading direction	20 degree	-60 degree	40 degree
Rmax*	10 km	25 km	175 km
Forward speed	7 m/s	3.3 m/s	24.3 m/s
Central pressure deficit	5 mb	28 mb	98 mb

** where Rmax is the radius to maximum winds*

2.3 Surge Response Functions

As part of the NACCS study, ADCIRC (see footnote 3) surge simulations were performed for 1050 tropical cyclone parameter combinations, a limited set due to the computational effort required for these analyses (USACE, 2015a, 2015b); simulated peak surge from the ADCIRC saved output location closest to the site are used. The NACCS parameters were heading, central pressure deficit, radius to maximum winds, forward speed and Holland *B*[4].

For the staff analysis surge response functions are used to interpolate median peak surge elevations for storm parameter combinations for which ADCIRC results are not available. For open-coast geographic locations characterized by position (x) and continental shelf width (L), maximum tropical cyclone surge height by landfalling storms (η) has been shown to scale with storm track parameters near landfall (e.g., Irish & Resio, 2010a, Irish et al., 2009): landfall position (x_o), CPD (Δp), storm radius (R), heading (θ), and forward speed (v_F). Using a hydrodynamics-based momentum conservation argument, and assuming wind surge is the dominant process and the aggregate influence of wind drag is taken to be proportional to CPD (Irish & Resio, 2010a), tropical cyclone surge height is expected to scale as follows:

$$\eta = \alpha \, \Delta p \, \psi_{\Delta p}(\Delta p) \, \psi_{x_o}\left(\frac{x - x_o}{R}\right) \psi_w\left(\frac{R}{L}\right) \psi_t\left(\frac{t}{t_\infty}\right) \psi_\theta(\theta) \qquad \textbf{Eq. 2}$$

where α is a dimensional location-specific constant and:

$\psi_{\Delta p}(\Delta p)$ is a dimensionless function representing additional wind drag effects not captured by the direct scaling with Δp.

$\psi_{x_o}\left(\frac{x-x_o}{R}\right)$ is a dimensionless function representing surge height dependence on relative proximity of the location of interest and landfall location. Surge tends to be highest about one storm radius from landfall.

$\psi_w\left(\frac{R}{L}\right)$ is a dimensionless function representing the relative importance of storm size on surge height. Surge height increases with increasing distance as winds blow over shallow water.

[4] A parameter used to characterize the pressure field (commonly referred to as the pressure profile parameter), (Holland, 2008).

Surge height is limited either by the storm's size or by the horizontal extent of the shallow water region, whichever is smaller.

$\psi_t\left(\frac{t}{t_\infty}\right) = f(v_f)$ is a dimensionless function representing the relative importance of storm duration on surge magnitude. Surge generation depends on duration of storm forcing, where the equilibrium steady-state maximum may not be achieved. The storm's duration over the continental shelf depends on its forward speed, among other factors.

$\psi_\theta(\theta)$ represents the relative importance of storm heading on surge magnitude. Considering an idealized tropical cyclone in the northern hemisphere, the strongest winds are in the forward right quadrant. Thus, storms approaching normal to the coast, or rotated counterclockwise from shore-normal, having predominantly onshore-directed winds will typically generate larger wind setup than storms rotated clockwise from shore-normal.

Though derived based on an open-coast argument, the above surge response form has been shown to hold in coastal locations farther inland (e.g., Taylor et al. 2015).

2.3.1 Application of SRF approach using NACCS ADCIRC simulations

The staff employed the leading order surge response scaling, where the influence of storm forward speed and heading were not considered. The two-dimensional, dimensionless surge response function (SRF) is then (Irish & Resio, 2010a, and Irish et al., 2009):

$$\eta' = f(x') \qquad \text{Eq. 3a}$$

$$\eta' = \frac{\gamma\zeta}{\Delta p} \qquad \text{Eq. 3b}$$

$$x' = \left(\frac{x - x_o}{R} - \lambda\right) \qquad \text{Eq. 3c}$$

where γ is seawater specific weight. The influence of heading and forward speed is not accounted for in this preliminary scaling (Eq. 3). Figure 2-2[5] shows the SRF performance for NACCS Station 756 using the ADCIRC-simulated NACCS "landfall" storm set (hereafter "NACCS SRF") based on leave-one-out analysis; standard deviation for all data is 1.00 ft. This degree of error is comparable to other SRF applications (Taylor et al., 2015).

[5] The left panel shows the SRF-predicted surge anomaly (NACCS SRF, Eq. 2) vs. ADCIRC-simulated surge anomaly for NACCS "landfall" storms. The right panel shows the associated surge residuals vs ADCIRC-simulated surge for NACCS "landfall" storms by leave-one-out analysis (right). Also shown (right) is binned mean (heavy red line and squares), one standard deviation (medium weight red lines), and two standard deviations (light weight red lines) of the surge residuals.

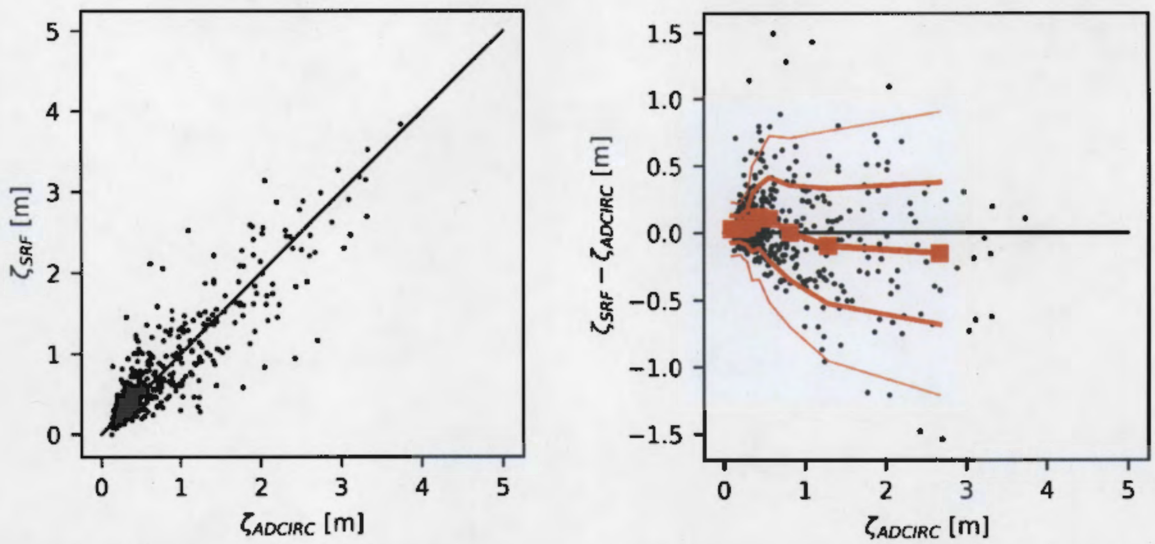

Figure 2-2 SRF vs. NACCS ADCIRC surge anomaly (left) and Associated surge residuals vs. NACCS ADCIRC surge by leave one out analysis at Station 756.

Using the SRF developed from the NACCS results, surges were estimated for JPM-OS SRF analysis by staff for the following storm track parameter ranges (parameter ranges for methodology case studies): storm CPD from 28 to 98 mb and storm radius from 25 to 175 km. Maximum SRF-predicted surge for the range of storm track parameters used by the staff in the JPM analysis is an extrapolated value of 15.7 ft. at NACCS Station 756, whereas the maximum ADCIRC-simulated surge in the NACCS storm set is 14.2 ft. at Station 756 (USACE, 2015a, and USACE, 2015b).

2.4 Logic Tree Development Including Estimation of Branch Weights

A logic tree was used to incorporate epistemic uncertainty into the storm surge hazard evaluation. The NRC staff considered epistemic uncertainty in the storm recurrence rate, selection of PDFs that describe the variability of storm parameters, the dependence of central pressure on the storm heading, and the aleatory variability in the storm surge error (See Section 2.7). When using logic trees, each branch is assigned a weight which is representative of a probability or degree of belief, and the weights for all branches for a given node must sum to 1. Additional details on development of the logic tree for this confirmatory analysis and weights assigned to each node are provided below.

2.4.1 Logic Tree Description

The logic tree implemented for this analysis is shown in Figure 2-3. The logic tree shows the landfall storms node, which is representative of storms that made landfall. Although there is only one node for the heading and forward speed PDFs, they are shown because epistemic uncertainty was evaluated for these density functions early in the analyses. Sensitivity tests performed on various density functions that fit the heading and forward speed data did not show significant variations in the calculated hazard. Therefore, these parameters were modeled without epistemic uncertainty.

A study by Resio and Irish (Resio et. al, 2015) showed that the central pressure is correlated with the storm heading relative to the coastline at landfall (storm heading). However, the NACCS did not explicitly consider heading dependence of the CPD PDF. Therefore, staff considered both heading dependent and heading independent distributions branches for CPD as shown in the logic tree (Figure 2-3). When using the heading dependent model, a single lognormal PDF was used by the NRC staff to characterize the CPD variability. In addition, four PDFs were used by the staff to characterize the heading-independent CPD variability. These are: generalized pareto distribution (GPD), lognormal distribution, gamma distribution, and normal distribution. These PDFs were selected using Bayesian information criterion (BIC) (Schwarz 1978) so that PDFs with the lower BIC values that fit the data better were selected over PDFs with higher BIC values. The BIC is a function of a maximum likelihood function of the PDF parameters and the number of data points used in developing the fit of the density function. The BIC values were also used by the staff to determine the weight that should be assigned to each PDF in the logic tree, as described below in Section 2.4.2.

The ADCIRC numerical model results were assumed to represent a median peak surge response. Aleatory variability in the surge response is incorporated using surge independent and surge dependent standard deviations. There is some epistemic uncertainty associated with the selection of the standard deviation value, and there are branches in the logic tree for various standard deviations and these branches are labeled as error terms.

Information about the radius of maximum winds is not shown in the logic tree. Rather, staff implemented relationships proposed by Vickery and Wadhera (Vickery, 2008) to evaluate the median radius of maximum winds and its distribution based on the central pressure and latitudes (see equations 6a and 6b below).

Some additional details pertaining to the storm recurrence rate, parameter PDFs, and error are provided below.

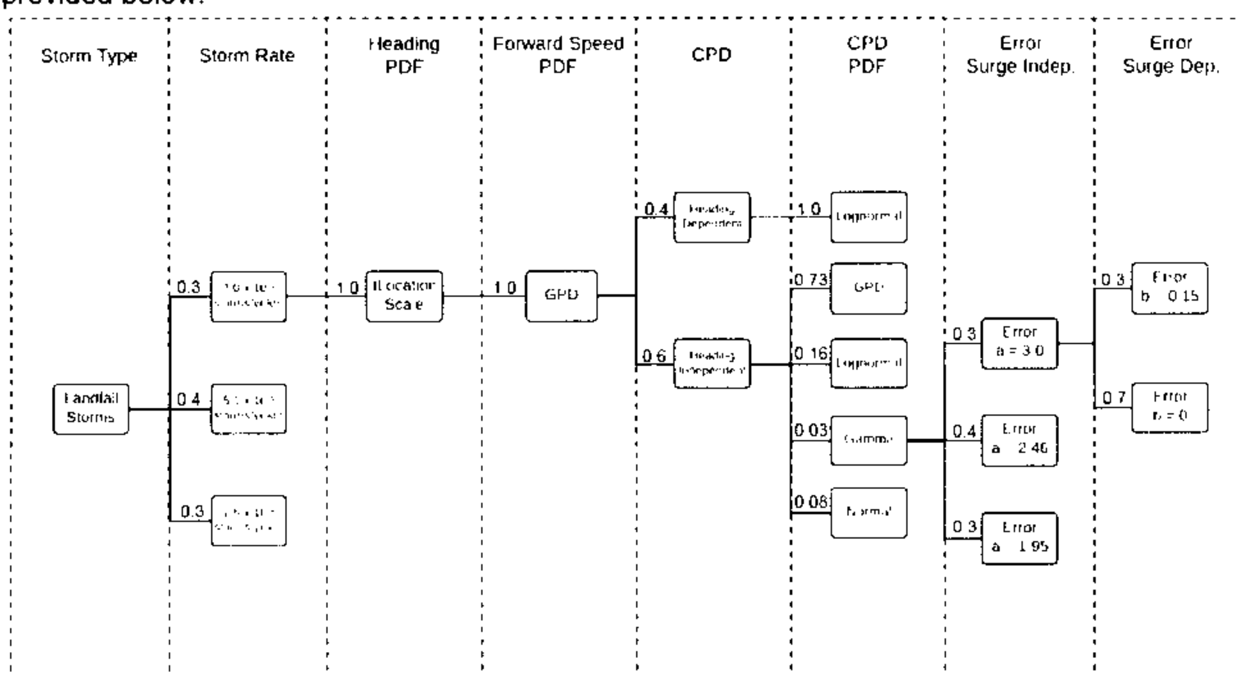

Figure 2-3 NRC staff's Logic tree used for storm surge calculations (numbers in front of each box are the weights assigned to that branch of the logic tree).

2.4.2 Estimation of Branch Weights

Staff used statistical evaluations and judgement to estimate weights for each branch of the logic tree. The three storm recurrence rates shown in the logic tree (Figure 2-3) were assumed to represent the 10th percentile, median, and 90th percentiles (fractiles). Weights of 0.3, 0.4, and 0.3 are used for these fractiles. The NRC staff used engineering judgement to assign weights of 0.4 for heading dependent and 0.6 for heading independent CPD distributions. The relationship used to develop the heading dependent CPD median value was based on a very limited data set. In addition, the standard deviation selected for the heading dependent CPD lognormal distribution was based on a visual check of the distribution compared to the data. For these reasons, less weight was placed by the staff on the heading dependent CPD distribution. When evaluating the heading independent CPD distributions, staff used BIC to develop weights using the following equation.

$$w_m = \frac{exp\left(-\frac{1}{2}BIC_m\right)}{\sum exp\left(-\frac{1}{2}BIC\right)} \qquad \text{Eq. 4}$$

Where w_m is the weight assigned to density function m.

For the surge-independent error term, the median value (best estimate) was developed using values reported in the NACCS report with an additional term to account for random tidal conditions. The lower and upper values of error were assumed to be equivalent to 10^{th} and 90^{th} percentile values. Therefore, weights of 0.3, 0.4, and 0.3 were assigned to these branches.

For the surge-dependent error term, staff assumed the best estimate is zero and assigned a weight of 0.7 to this branch. The upper surge dependent error term was assumed to be representative of a 90^{th} percentile value and thus given a weight of 0.3.

2.5 Storm Recurrence Rate

The storm recurrence rate was evaluated by weighting storms using a kernel density function and a defined capture zone. Storms having wind speed less than 40 knots were removed from the data set prior to evaluating recurrence rate. Storm recurrence rates for the site vary between 2.5E-4 to 7.0E-4 storms/year/km as shown in Table 2-2. The staff implemented each of these storm recurrence rates in the hazard logic tree shown in Figure 2-3. These rates were applied to all landfalling storms regardless of landfall location. Using a uniform rate term for all landfalling locations is acceptable because only storms near Millstone significantly contribute to the hazard at this location. When using the SRFs to interpolate surge elevations, landfall locations were spaced 10 km apart, and this distance was used to obtain the storm rate in storms/yr.

Table 2-2 Storm Recurrence Rates as a Function of Capture Zone on the Atlantic Coast.

Method	Capture Zone Radius/Kernel Width (km)	Storm Recurrence Rate (Storms/yr/km)
Capture Zone	100	6.3E-4
Capture Zone	200	7.0E-4
Normal Kernel	100	3.2E-4
Normal Kernel	200	2.5E-4

2.6 Storm Parameter Combinations and Associated Probability Distributions

Data from storms that entered a 300 km radius capture zone centered on the Millstone site (latitude 41° 18' 43", longitude -72° 10' 07"), made landfall within the capture zone, and had wind speeds greater than or equal to 40 knots were used to determine univariate distributions for the storm parameters. Staff examined various PDFs for each of the storm parameters. As stated earlier, BIC were used to select the CPD heading independent distributions. In the cases in which only one distribution is listed, sensitivity analysis showed little variation in the hazard curve when examining multiple distribution. For the cases where only one distribution is implemented, it is the PDF with the best BIC. The parametric distributions and their parameters are provided in Table 2-3.

Table 2-3 Probability distributions for storm parameters and the parameters of the distributions.

Storm Parameter	**Distributions**	**Distribution Parameters**
Heading Direction	tLocationScale	$\mu = 21.9925$, $\sigma = 13.0658$, $\nu = 1.7014$
Forward Speed	Generalized Pareto	$k = -1.0577$, $\sigma = 63.3342$, $\theta = 17.6781$
Heading Dependent CPD	Lognormal	$\mu = \ln(f(\text{Heading}))$, $\sigma = 0.3$
Heading Independent CPD	Generalized Pareto	$k = -1.0577$, $\sigma = 59.7274$, $\theta = 23.0$
	Lognormal	$\mu = 3.7718$, $\sigma = 0.4005$
	Gamma	$a = 6.851$, $b = 6.8369$
	Normal	$\mu = 46.833$, $\sigma = 18.7471$

Where μ is the location parameter, σ is the scale parameter for the tLocationScale, Lognormal and Normal distribution. v is the shape parameter for the tLocationScale distribution. For the Generalized Pareto distribution, k is the shape parameter, σ is the scale parameter and θ is the threshold parameter. a is the location parameter and b the scale parameter for the Gamma distribution.

The function (f) in Table 2-3 was used to determine the heading dependent median CPD or $\hat{x}$ in Eq. 5.

$$\hat{x} = -0.3625 \times Heading(deg) + 53.625 \quad \text{Eq. 5}$$

where $\hat{x}$ is the median CPD and the lognormal mean is defined as $\mu = \ln \hat{x}$.

The relationship proposed by Vickery and Wadhera (Vickery, 2008) for hurricanes in the Atlantic and the Gulf of Mexico as shown in Eq. 6 was used to evaluate the median radius of maximum winds and the standard deviation for a lognormal distribution.

$$\ln R_{max} = 3.015 - 6.291 \times 10^{-5} \Delta p^2 + 0.0337\psi \quad \text{Eq. 6a}$$

$$\sigma_{\ln R_{max}} = 0.441 \quad \text{Eq. 6b}$$

where R_{max} is the radius of maximum winds (km), Δp is the CPD (hPa) and ψ is latitude (deg).

2.7 Error Term

The NACCS reports the standard deviation of the error term due to hydrodynamic modeling, meteorological modeling, storm track variation, and Holland B. The Holland B uncertainty is surge elevation dependent; whereas, the other error terms are independent of surge elevation. Discrete values were listed for each standard deviation of the error term with exception of the Holland B uncertainty, which is listed as not applicable. The surge independent standard deviation of the error term is obtained using the square root sum of the squares and a value of 2.17 ft. is obtained. This value neglects the effect of random tides. A standard deviation for random tides of 1.16 ft. was incorporated into the error term to obtain a standard deviation[6] of 2.46 ft. The upper and lower surge independent error terms were estimated based on the uncertainty range from previous studies reported in the NACCS.

While the NACCS did not implement a surge dependent error term, both FEMA (FEMA, 2008) and USACE (USACE, 2011) adopted a surge dependent factor of 0.15 to estimate the surge dependent standard deviation. The staff includes a surge dependent error term and characterized it using the NACCS, FEMA and USACE studies. Consistent with the NACCS study, staff adopted a surge dependent factor of 0 for the best estimate and lower range estimate corresponding to a median and 10th percentile, respectively. A value of 0.15 which is consistent with other studies was assumed to be representative of a 90th percentile value. Similar to previous weighting, the 10th and 90th percentile were each weighted as 0.3 and the median as 0.4 resulting in a surge dependent error of 0 with 0.7 weight and 0.15 with 0.3 weight.

The mean error or bias for ADCIRC surge values, which is not included in the logic tree, is reported by the USACE in the NACCS report as -0.623 ft. This value was added to the peak ADCIRC surge and interpolated values to obtain an unbiased median peak stillwater surge.

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[6] Using square root sum of squares, $\sqrt{(2.17\,ft)^2 + (1.16\,ft)^2} = 2.46\,ft$

2.8 Summary of Staff Independent Stillwater Storm Surge and Hazard Curve Development

The storm surge hazard at the site is evaluated for each unique path through the logic tree and is compared to NACCS results at save point (SP0756), as shown in Figure 2-4. Weights from each branch are used by the staff to arrive at a weight for the hazard curve corresponding to that unique path, and then these weighted curves are summed to obtain the mean storm surge hazard. The mean hazard curve, 84th percentile and 95th percentile hazard curves are also shown in Figure 2-4. Results are compared to the USACE NACCS hazard curve where the USACE hazard includes the effects of random tides. The stillwater surge associated with the 1E-4 AEP from the NRC analysis is 15.2 ft. The USACE NACCS surge elevation with random tidal effects included is 14.9 ft. A comparison of mean hazard curves shows that the USACE and NRC analyses produce similar surge elevations for the range of annual frequencies of exceedance between 1E-2 and 1E-4.

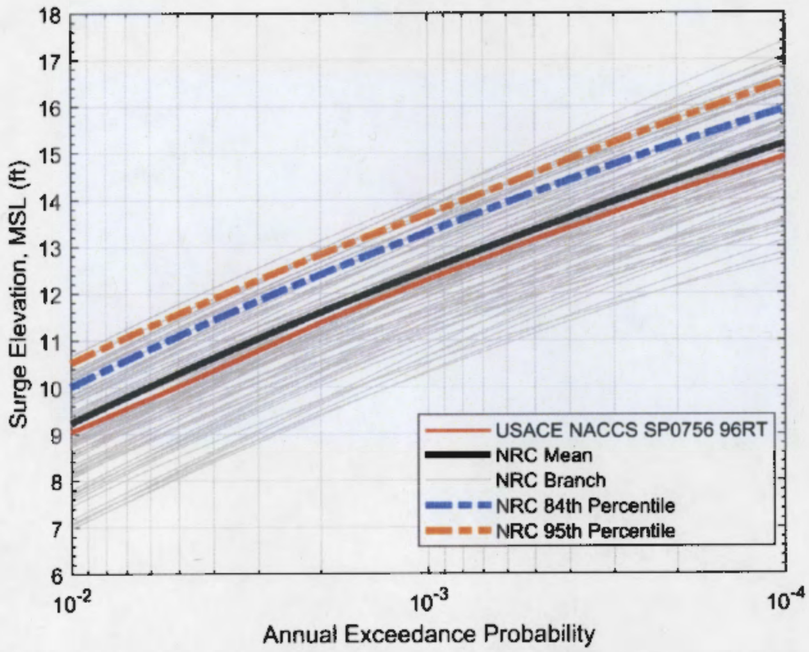

Figure 2-4 Stillwater storm surge hazard, with consideration for initial random tide conditions (96RT) for SP0756.

3.0 STAFF'S INDEPENDENT ANALYSIS OF TOTAL WATER LEVEL

The NRC staff estimated the total water level that can occur near the site during storm forcing conditions that produce a 1E-4 AEP stillwater level. The total water level estimate accounted for the effects of wave runup near Millstone that would elevate the water level above the stillwater condition during strong storm forcing that produces large nearshore waves. The total water level is not a standard output of the current state-of-the-practice coupled hydrodynamic and nearshore wave models. Recent applications of the ADCIRC hydrodynamic model coupled with a nearshore wave model (SWAN[7] for the Millstone analyses) do include the effect of wave breaking on the stillwater level (regional wave setup), but do not account for wave runup due to

[7] Simulating Waves Nearshore (SWAN) "is a third-generation wave model, developed at Delft University of Technology, that computes random, short-crested wind-generated waves in coastal regions and inland waters" (http://swanmodel.sourceforge.net/).

individual waves nor account for wave setup at local structures that are not refined within the coupled SWAN+ADCIRC model mesh.

To estimate the total water level at a specific AEP stillwater level, staff followed standard practice (when water level and wave results are available) to review the individual storm results (water level and wave) from the storm suite applied to develop the stillwater level vs AEP curve. The wave conditions that occur during the storms that produce water levels near the 1E-4 AEP (target level by the licensee) provide estimates of the wave conditions (height, period, and direction) that will elevate the total water level during runup and overtopping processes. The staff analysis to develop the total water level near the site included several steps as detailed below:

1. Determine 1E-4 AEP stillwater level near the site. This 1E-4 AEP stillwater level was developed from an independent Staff estimate of the stillwater level vs AEP curve.

2. Obtain and analyze the NACCS ADCIRC and STWAVE model datasets. The analysis included examination of the ADCIRC maximum stillwater level data (including tide effects, if possible) for each of the 1,050 synthetic storms executed as part of NACCS storm suite. Review of the NACCS output data stations indicated that data from ADCIRC Station 756 (co-located with STWAVE Station 433) provides suitable data for the Millstone analysis (Figure 3-1).

3. Review the NACCS data to determine the wave conditions (STWAVE Station 433) that occur for the five NACCS storms that produce the maximum stillwater levels (ADCIRC Station 756) closest to the staff estimate of the 1E-4 AEP stillwater level.

4. For the five identified storms, perform a total water level analysis including wave runup at the site. The wave runup and total water level analysis are performed at both the Millstone intake buildings (at the shoreline, not protected from open water waves) and the Millstone turbine buildings (located 200-300 feet (ft.) inland of shoreline and protected from open water waves).

Figure 3-1 Location map for NACCS ADCIRC output stations with Millstone location shown. Note that the STWAVE Station 433 is co-located with ADCIRC Station 756.

The NRC staff completed Steps 1 to 4 to estimate the total water level near the Millstone intake and turbine buildings. The staff estimate for the 1E-4 AEP stillwater level, depending on uncertainty treatment and tide influence, equals approximately 15.8 ft. including an estimated 0.6 ft. of sea level rise over the next 50 years[8]. Review of the NACCS results (not including uncertainty) indicates that the maximum stillwater produced at ADCIRC output Station 756 equals 11.0 ft. Thus, the NACCS storm suite does not produce water levels near the site that equal the NRC estimate of the 1E-4 AEP stillwater level (including uncertainty). However, examination of the NACCS storms that produces the highest water levels near the site does provide estimates of wave conditions that can occur during the NACCS storms that produce the highest water levels near the site. Review of the wave conditions for the storms with the top-five water levels indicates significant wave heights range from 10 to 12.5 ft. with mean periods near 8 seconds.

Application of these wave parameter values allows calculation of the total water level near the Millstone intake structures and turbine buildings. Wave conditions differ dramatically at the Millstone intake structures and turbine buildings due to the difference in water depth near each structure with 1E-4 AEP water levels. Therefore, the total water level analyses are discussed in two parts.

The Millstone intake buildings reside at the shoreline and can face open-water wave conditions. The NACCS modeling results indicate that waves with significant wave heights near 12.5 ft. can occur at NACCS STWAVE output Station 433. These waves could develop into non-breaking waves that interact with the vertical walls of the Millstone Unit 2 and Unit 3 intake structures and produce reflected wave conditions. Millstone FHRR Figures 2.9-1 and 2.9-2 provide layouts of the Millstone intake structures and show the vertical faces of the structures that could face the standing waves. The NRC staff estimate that given the water depth at the intake structures, the total water level could approach 35.4 ft. inclusive of the 15.8 ft. 1E-4 AEP stillwater level allowing for 14 ft. significant wave heights at the vertical walls of the intake structures where wave reflection can occur [15.8 ft. + 0.7 * (2 * 14 ft. wave height)]. The 0.7 factor accounts for the non-linearity of the wave crest height above stillwater level near the shoreline and the factor of two accounts for the maximum wave reflection.

The Millstone turbine buildings are located over 200 ft. inland from the shoreline. As listed in the Millstone FHRR, the Millstone Unit 3 turbine building has a ground floor elevation near 24 ft., which places the building well above the staff estimate of the 1E-4 AEP stillwater level. The Millstone FHRR lists the Millstone Unit 2 turbine building ground floor elevation near 14.0 ft., which means a 1E-4 AEP stillwater level near 16.0 ft. could cause wave conditions that produce wave runup at the structure. The ground elevation near the Millstone, Unit 2 turbine will only support relatively small waves due to the shallow water depth (~2 ft). Therefore, staff estimated a wave height of 1.4 ft. and a wave crest height of 1 ft. above the stillwater elevation with the wave reflected (and doubling in height) at the Millstone, Unit 2 turbine building wall. Therefore, the total water level including the wave runup caused by the reflected wave equals 17.8 ft. [15.8 ft. + 0.7*(2 * 1.4 ft. wave height)].

4.0 SUMMARY

The NRC staff performed an independent confirmatory analyses of storm surge flooding hazards for Millstone to aid in reviewing the licensee's FHRR (ADAMS Accession No.

[8] Value is based on Sea Level Trend at Montauk, NY (Closest NOAA station to Millstone with NOAA SLR calculation based on long data record).

ML15078A203) and the associated supplement (ADAMS Accession No. ML19011A110). The staff's probabilistic analyses developed estimates of surge stillwater elevation for a range of AEPs and surge total water level at an AEP of 1E-4.

The NRC staff applied the JPM-OS approach to evaluate storm surge hazards. The NRC staff used NOAA's HURDAT2 Atlantic hurricane database to develop probability models for storm recurrence rates and storm parameters. The response surface method was used to implement the optimal sampling approach. A surge response function was developed by leveraging ADCIRC surge simulations performed for the NACCS (see Section 2.3). Peak surge at the NACCS grid point closest to the site (save point SP0765) was extracted for each of 1050 tropical cyclones simulated using the ADCIRC hydrodynamic model plus coupled STWAVE wind wave mode. The NACCS simulated surge results (and subsequent staff stillwater estimates) incorporated wave setup, but not runup.

The NRC staff implemented a logic tree approach to incorporate epistemic uncertainties in the storm surge estimates, including epistemic uncertainty in the storm recurrence rate, storm parameter probability distributions, and dependence of storm intensity on heading. The staff's logic tree with branch weights are discussed in Section 2.4 and shown in Figure 2-3. Aleatory variability was incorporated via the storm recurrence rate model and a surge model error term. The NACCS-reported ADCIRC surge bias was used to adjust all stillwater surge elevation results.

The NRC staff-evaluated stillwater storm surge hazard results are summarized in Figure 2-4. Mean, 84th percentile and 95th percentile hazard curves are compared to the NACCS results for AEPs from 1E-2 to 1E-4. Note that the NACCS results include the effects of random tides. The NRC and NACCS mean hazard curves are very similar over the entire range of AEPs considered. At 1E-4 AEP, the staff stillwater surge estimate is 15.2 ft.

The NRC staff estimated the total water level that can occur near the site during storm conditions that produce a 1E-4 AEP stillwater level. The total water level estimate accounted for the effects of wave runup near Millstone that would elevate the water level above the stillwater condition during strong storms that produce large nearshore waves (i.e., runup due to individual waves and wave setup at local structures that is not resolved within the coupled surge-wave model).

The NRC staff reviewed the NACCS simulation outputs to determine the wave conditions that occur for the five NACCS storms that produce the maximum stillwater levels closest to the staff estimate of the 1E-4 AEP stillwater level. Review of the wave conditions for these storms indicates significant wave heights range from 10 to 12.5 ft. with mean periods near 8 seconds. For the five identified storms, staff performed a wave runup and total water level analysis for Millstone, Unit 2 and Unit 3 intake buildings (at the shoreline, not protected from open water waves) and the Millstone, Unit 2 turbine building (located 200-300 feet (ft.) inland of shoreline and protected from open water waves).

As shown below, staff estimated that the total water level at the intake structures could approach 35.4 ft. and at the Unit 2 Turbine Building could approach 17.8 ft.

- Total Water Level of 35.4 ft. at Intake Structure resulting from;
    - 15.2 ft. stillwater at 1E-4 AEP
    - 0.6 ft. SLR

    - o 19.6 ft. wind-wave (due to 14 ft. significant wave reflection on structure)

- Total Water Level of 17.8 ft. at Unit 2 Turbine Building resulting from;
    - o 15.2 ft. stillwater at 1E-4 AEP
    - o 0.6 ft. SLR
    - o 2 ft. wind-wave (due to 1.4 ft. significant wave reflection on structure)

5.0 CONCLUSION

In the wake of the March 2011 accident at the Fukushima Dai-ichi nuclear power plant, the NRC established the Near-Term Task Force (NTTF) to evaluate and recommend actions that might be taken to strengthen the regulatory framework for protection against natural phenomena. The NTTF Recommendation 2.1 specifically directed staff to develop guidance to outline acceptable approaches for reevaluation of flooding hazards.

The guidance developed by staff includes COMSECY-15-0019 (NRC, 2015), which describes the closure plan for the reevaluation of flooding hazards at nuclear power plants. This process specifies that a probabilistic flood hazard analysis (PFHA) methodology should be integral to the reevaluated flooding analyses. This process is consistent with the NRC's risk-informed decision-making goals. The NRC has previously applied probabilistic methodologies to seismic hazard analyses. However, the Millstone probabilistic storm surge analysis, documented here, exemplifies the first application of fully probabilistic methodology to a flooding mechanism for NRC reviews. The NRC staff completed this review in a fully risk-informed and efficient manner, as directed by the Commission in the staff requirements memorandum for COMSECY-14-0037 (NRC, 2014).

As part of this and other semi-probabilistic reviews, the NRC staff has utilized a Senior Technical Review Board (STRB) for peer reviews of staff's work. The STRB is composed of a small group of experts guiding the application of probabilistic methods for analyzing and evaluating external hazards. The STRB has provided technical and regulatory guidance to the individual PFHA review teams and ensured consistency across each project and throughout the various review processes. The approach has been used successfully in other technical reviews across the agency, such as the SSHAC process for seismic hazards and the review process under 10 CFR 50.69, "Risk-Informed Categorization and Treatment of Structures, Systems and Components (SSCs)for Nuclear Power Reactors."

As stated previously, the purpose of this attachment is to document the NRC staff's first independent application of a fully probabilistic methodology for analyzing and evaluating hurricane storm surge flooding mechanisms at an operating nuclear power plant site. Based on the NRC staff's experience and the use of expert peer review processes, the staff concludes that PFHA methodology was appropriately applied to this flooding review and that the staff has confidence in the regulatory review of the licensee's analyses (as presented in the staff assessment found in the Enclosure to this document). The PFHA process is consistent with the NRC's risk-informed decision-making goals. Moreover, the PFHA results, which generate true hazard curves for hurricane storm surge analyses, are a more realistic representation of the flooding hazard than traditional deterministic methods used to demonstrate margin.

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SUBJECT: MILLSTONE POWER STATION UNITS 2 AND 3 – SUPPLEMENT TO STAFF ASSESSMENT OF RESPONSE TO 10 CFR 50.54(f) INFORMATION REQUEST -- FLOOD-CAUSING MECHANISM REEVALUATION (EPID NOS. 000495\05000336\L-2015-JLD-0011 AND 000495\05000423\L-2015-JLD-0012) DATED: OCTOBER 7, 2019

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