Justification for

Revised Tornado Design Criteria

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1.0 Background

The current tornado design criteria for WNP-2 is considerably more conservative than that required by the NRC or by probabilistic considerations of tornado hazards at the Hanford Site. These conservatisms result in unnecessary costly designs to provide protection for the current design basis tornado. This document provides the basis for revising the tornado design criteria for new work or for re-evaluations of existing structures to more realistically reflect the tornado hazards at WNP-2.

The current NRC tornado design criteria applicable to WNP-2 are summarized in Section 2.0, the current WNP-2 criteria are summarized in Section 3.0, and the proposed revisions to the current WNP-2 criteria are presented in Section 4.0. The technical justifications for these revisions are provided in Section 5.0. The benefits of implementing these criteria revisions are summarized in Section 6.0.

2.0 NRC Tornado Design Criteria

NRC tornado design criteria are defined in Regulatory Guide 1.76 [1] and Standard Review Plan (SRP) Sections 3.3.2 [2] and 3.5.1.4 [3]. These criteria have been established to provide an annual probability of exceedance of design loads of 1×10^{-7}. To meet this objective, the NRC has defined in Regulatory Guide 1.76, three Tornado Intensity Regions which conservatively envelope the expected hazards within the respective regions. WNP-2 is in NRC Tornado Intensity Region III which has the least severe tornado loading requirements. A summary of NRC design requirements for Tornado Intensity Region III are provided in the following sub-sections.

2.1 Tornado Wind and Differential Pressure Loads

Regulatory Guide 1.76 specifies the following tornado wind and differential pressure loads for Tornado Intensity Region III:

- loads resulting from a rotational wind velocity of 190 mph and a translational wind velocity of 50 mph for a maximum horizontal velocity of 240 mph
- a differential pressure load resulting from an external pressure drop of 1.5 psi at a rate of 0.6 psi /sec.

2.2 Tornado Missile Loads

SRP Section 3.5.1.4 specifies that structures and equipment subjected to tornado effects are to be evaluated for resistance to damage from the following tornado generated missiles:

Missile	Weight (lbs)	Dimensions	Horizontal Impact Velocity for Tornado Intensity Region III (ft/sec)
Wood Plank	115	3.6" x 0.94' x 12' long	190
6" Sch 40 Pipe	287	6.6" dia x 15' long	33
1" Steel Rod	8.8	1" dia x 3' long	26
Utility Pole	1124	13.5" dia. x 35' long	85
12" Sch 40 Pipe	750	12.75" x 15' long	23
Automobile	3990	16.4' x 6.6' x 4.3'	134

These missiles are considered to strike surfaces in any direction. Vertical velocities are taken to be 70 percent of the horizontal velocities except the 1" steel rod which is assumed to have the same velocity in any direction. The utility pole and the automobile are considered to strike surfaces at any elevation up to a maximum elevation of 30 feet above the highest finished grade within 0.5 miles of the plant. All other missiles are considered to strike at any elevation above finished grade.

2.3 Load Combinations

Based on SRP Section 3.3.2, total tornado loads resulting from wind loads, differential pressure loads, and tornado generated missiles are established from the following equations:

$$W' = W_w$$
$$W' = W_p$$
$$W' = W_m$$
$$W' = W_w + 0.5\,W_p$$
$$W' = W_w + W_m$$
$$W' = W_w + 0.5\,W_p + W_m$$

where:

W' = Total tornado load
W_w = Tornado wind load
W_p = Tornado differential pressure load
W_m = Tornado-generated missile load

3.0 Current WNP-2 Tornado Design Criteria

Current WNP-2 tornado design criteria are considerably more conservative than required by the applicable NRC Regulatory Guides and Standard Review Plans. Current tornado wind speeds are based on NRC Regulatory Guide 1.76 [1] Tornado Intensity Region I requirements (where as noted above, WNP-2 is in Tornado Intensity Region III). In addition, the load combinations used to define the net loads resulting from wind loading and differential pressure are conservative with respect to those required by NRC SRP 3.3.2 [2]. A summary of the current WNP-2 tornado design criteria is provided in the following sub-sections.

3.1 Tornado Wind and Differential Pressure Loads

All Seismic Category I structures and equipment have been designed to withstand the effects of a design basis tornado defined by the following concurrent loads:

- loads resulting from a rotational wind velocity of 300 mph and a constant translational wind velocity of 60 mph for a maximum horizontal velocity of 360 mph
- a differential pressure load resulting from an external pressure drop of 3 psi at a rate of 1.0 psi /sec.

The tornado wind velocities are considered to act horizontally and to be invariant with height. Wind forces are modeled in terms of static pressures based on ASCE paper No. 3269 [4].

3.2 Tornado Missile Loads

All structures and equipment subjected to tornado effects are evaluated for resistance to damage from tornado generated missiles. Missiles which are considered consist of the following:

Missile	Weight (lbs)	Dimensions	Horizontal Impact Velocity (ft/sec)
Utility Pole	1600	14" dia. x 35 ft long	241
1" Steel Rod	8	1" dia x 3 ft long	259

These missiles are considered to strike surfaces in any direction. The utility pole is considered to strike surfaces at any level up to a maximum level of 30 feet above the highest finished grade within 0.5 miles of the plant. The steel rod is considered to strike at any level above finished grade.

An exception is made for the access door of the makeup water pump-house where the velocities of the above missiles are reduced to 85 ft/sec for the utility pole and 26 ft/sec for the steel rod. These velocities are consistent with those of Revision 2 of SRP Section 3.5.1.4 for Tornado Intensity Region III. These reduced velocities were incorporated to reduce the thickness of the door to facilitate equipment replacement while still providing adequate missile protection by virtue of the compliance to the SRP.

3.3 Load Combinations

The total tornado load resulting from wind loads, differential pressure loads, and tornado generated missiles is established as follows:

$$W' = W_w$$
$$W' = W_p$$
$$W' = W_m$$
$$W' = W_w + W_p$$
$$W' = W_w + W_m$$
$$W' = W_w + W_p + W_m$$

where all terms are defined in Section 2.3.

4.0 Proposed Revisions to the WNP-2 Tornado Design Criteria

This section presents proposed revisions to the WNP-2 tornado design criteria for new work or re-evaluations of existing structures. These criteria are based on extensive studies which define site specific tornado hazards for the Hanford area. These criteria reduce unnecessary conservatism in the original WNP-2 design criteria and in the NRC criteria (which conservatively envelopes tornado hazards within Tornado Intensity Region III) while maintaining an annual probability of exceedance of design loads of 1×10^{-7}. The technical justifications for these criteria are provided in the following section.

4.1 Tornado Wind and Differential Pressure Loads

The following tornado wind and differential pressure loads will form the design basis for new work or re-evaluations of existing structures at WNP-2.

- loads resulting from a rotational wind velocity of 135 mph and a translational wind velocity of 45 mph for a maximum horizontal velocity of 180 mph
- a differential pressure load resulting from an external pressure drop of 0.65 psi at a rate of 0.29 psi /sec.

4.2 Tornado Missile Loads

The following tornado generated missiles will form the design basis for new work or re-evaluations of existing structures at WNP-2:

Missile	Weight (lbs)	Dimensions	Horizontal Impact Velocity (ft/sec) (see discussion below)
Wood Plank	115	3.6" x 0.94' x 12' long	167
6" Sch 40 Pipe	287	6.6" dia x 15' long	17
1" Steel Rod	8.8	1" dia x 3' long	20
Utility Pole	1124	13.5" dia. x 35' long	- -
12" Sch 40 Pipe	750	12.75" x 15' long	13
Automobile	3990	16.4' x 6.6' x 4.3'	- -

The utility pole and the automobile are not considered to be credible missiles for wind velocities less than 200 mph for reasons presented in Section 5.2. The remaining missiles are considered to strike surfaces in any direction. Vertical velocities are taken to be 70 percent of the horizontal velocities except the 1" steel rod which is assumed to have the same velocity in any direction. All missiles are considered to strike at any elevation above finished grade. As noted in Section 5.2, the impact velocities of credible missiles are based on studies performed by EPRI [20] and are conservatively based on a maximum wind speed of 240 mph.

The wood plank, 6" Sch 40 pipe, and the 12" Sch 40 pipe were not considered in the original WNP-2 tornado missile evaluations. However, as a result of the substantially higher velocities (and weight of the utility pole missile), the damage potential of the original WNP-2 design basis missiles is substantially more severe than that for these missiles. Therefore, the introduction of these missiles does not necessitate a re-evaluation of existing structures.

4.3 Load Combinations

Load combinations for new work or evaluations of existing structures will be based on Standard Review Plan Section 3.3.2 [2] as summarized in Section 2.3. (Note that 1/2 of the tornado differential pressure load is combined with the tornado wind load as specified in the SRP.)

5.0 Technical Justification of Revisions in the Tornado Design Criteria

WNP-2 is located in an extremely low tornado hazard area. The State of Washington experiences, on the average, less than one tornado each year. Within a one hundred mile radius of WNP-2, there have been only 21 reported tornadoes in the period from 1916 to 1980 [5]. Within the 570 square mile Hanford Site there has been only one reported tornado.

A study of the tornadoes in Washington, Oregon, and Idaho area was performed by Fujita [6] which indicated that tornadoes occur primarily in "alleys". The location of these alleys with locations of reported tornadoes during the 20 year period from 1950 to 1969 is shown in Figure 5-1. Note that WNP-2 does not lie within any of the tornado alleys. These alleys are located in up-slope topography that we believe is necessary for tornado initiation within the Pasco Basin. The Hanford Site is essentially in a down slope region from the Rattlesnake ridge making tornado initiation unlikely.

One of the first attempts at quantifying tornado hazards was made by Thom [7]. By utilizing a simple geometric interpretation of probability, the probability of a tornado striking any given location is defined by the following equation:

$P(s) = a\,n / A$

where:

P(s)	=	the probability that a tornado will strike a given location
a	=	the mean tornado damage path area in square miles
n	=	the mean number of tornadoes per year
A	=	the area of the local region in which the mean number of tornadoes was reported in square miles

By assuming independence between tornado wind speed and tornado strike probabilities, Markee, Beckerley, and Sanders expanded upon the Thom model in Wash-1300 [8] to develop an interim regional tornado design criteria which currently forms the basis of Regulatory Guide 1.76. In their model, the probability of exceeding a given tornado wind speed is determined from the following equation:

$$P(v > V_o) = P_I(V_o)\,P(s)$$

where:

$P_I(V_o)$	= the probability of a tornado having wind speeds in excess of V_o. This probability is referred to as the tornado intensity distribution
P(s)	= the probability of a tornado strike as defined by the Thom model

Wash-1300 Methodology

The process employed in Wash-1300 to establish design tornado wind speeds for each Tornado Intensity Region is outlined below:

- Tornado strike probabilities were determined for each five degree square of latitude and longitude in the contiguous United States based on a mean tornado damage path area of 2.82 square miles established by Thom [7] for tornadoes occurring in a ten year period in Iowa. The mean number of tornadoes within each five-degree square was determined using 13 years of tornado occurrence records compiled by Pautz [9].

- Based on data developed by NOAA climatologists (Ref [10] and [11]) for tornadoes which occurred within the contiguous United States during 1971 and 1972, tornado wind speed exceedance probabilities ($P_I(V_o)$) were established independent of geographic location and tornado damage path area.

- For each five degree square of latitude and longitude, a tornado wind speed was selected to provide an annual probability of exceedance of 1×10^{-7}. Based on these wind speeds, design tornado wind speeds were established for each of the NRC's Tornado Intensity Regions.

Conservatisms in the Wash-1300 Methodology

The Wash-1300 tornado criteria is recognized as being conservative, and as is stated in Wash-1300, it was considered at the time of its development as an interim criteria until more realistic criteria could be developed. Major sources of conservatism of the Wash-1300 criteria as they relate to the Hanford area are as follows:

- The mean path area for tornadoes occurring within the Pacific Northwest is considerably less than the 2.82 square miles assumed in Wash-1300. As noted above, this path area was based on tornadoes occurring in Iowa. As an example, in a study performed for the Jersey Nuclear Fuel Facility (now referred to as the Advanced Nuclear Fuels Facility) in Richland WA, Jaech [12] determined that the mean path area for tornadoes occurring within Washington, Oregon, and Idaho during 1950 to 1969 to be 0.48 square miles.

- Tornado wind speeds within the Columbia Basin are considerably lower than the national average. For example, based on the data reported in [6] for the 20 year period from 1950 to 1969, within the region east of the Cascade Mountains and North of the 45th parallel, the highest reported tornado intensity was F2 (wind speeds 113 - 157 mph). During this period, there were only four reported F3 tornadoes (wind speeds 158 - 206) within Washington, Oregon and Idaho. Two of these tornadoes occurred in the Portland/ Vancouver area, one occurred in the Seattle/ Tacoma area, and the other occurred at the Oregon/ Idaho border near Ontario, Oregon.

- The Wash-1300 methodology assumed that the maximum wind speed of a tornado occurs uniformly over the entire damage area. However, wind speeds vary across and along the path of a tornado. For example, based on a simple Rankine vortex model of tornado winds and data obtained from the Super Outbreak of Tornadoes of April 3-5, 1974 [13], McDonald [14] established that for a F3 tornado, only 17 percent of the damage area experiences winds that are in F3 range.

Refined Tornado Hazard Models

Substantial refinements have been made by Abbey and Fujita [15] and by McDonald [14] in the methodology for predicting tornado hazards since the time the Wash-1300 study was performed. The refinements incorporated in these hazard models are summarized below:

- a larger database of reported tornadoes is available for statistical analyses than was available at the time the Wash-1300 study was performed
- estimates of the number of unreported tornadoes are made and are included in the hazard models based on population density and land use
- regionalized path area - intensity and occurrence frequency - intensity relationships are developed directly from reported data and estimated unreported tornadoes
- the variation of wind speed across and along the tornado path are explicitly accounted for in the revised models

The Department of Energy (DOE) through Lawerence Livermore National Laboratory contracted Fujita and McDonald to perform independent tornado hazard evaluations for the various DOE nuclear related sites using their tornado hazard models. The results of this effort were published in 1985 [16]. As a result of the low tornado hazard for the Hanford area, the maximum horizontal wind speeds derived independently by Fujita and McDonald were 179 mph and 177 mph respectively for an annual probability of exceedance of 1×10^{-7}. These evaluations form the basis for selecting the revised maximum wind speed of 180 mph for WNP-2.

In addition, the American National Standards Institute has proposed a "Standard for Tornado and Extreme Wind Characteristics at Nuclear Power Plant Sites" [24] which estimates tornado wind speeds of 180 mph corresponding to an annual probability of exceedance of 1×10^{-7} for the region west of the Rocky Mountains. This result provides additional support for the selection of a design maximum wind speed of 180 mph for WNP-2.

Pacific Northwest Laboratory Tornado Climatology Study

Pacific Northwest Laboratory (PNL) [22] compiled data on the characteristics of tornadoes occurring in the contiguous United States for the period from January 1, 1954, through December 31, 1983 based on reported tornadoes contained in the National Severe Storms Forecast Center tornado data base. Statistical analysis of these data were performed to estimate tornado wind speeds for each 5 degree square of latitude and longitude with 10^{-5}, 10^{-6}, and 10^{-7} probabilities of exceedance per year for both mean and 90 percentile confidence limits. Since design wind speeds have traditionally been based on a mean probability of exceedance of 10^{-7} (i.e.,WASH-1300 [8], McDonald [14], and the Department of Energy [16]), the results presented below are based on this value.

The statistical models used in the PNL analysis were similar to those used in the WASH-1300 study with the following exceptions:

- rather than assuming a mean tornado path area of 2.82 square miles, the PNL study calculated expected mean tornado path areas in each 5 degree square by fitting a log-normal probability distribution to the recorded tornadoes within the square and integrating over the distribution to establish the expected mean path area. The computed expected mean values are generally substantially smaller than 2.82 square miles.

- in Wash-1300, tornado wind speed exceedance probabilities ($P_I(V_o)$) are established for the entire contiguous United States from the relative frequencies of each tornado intensity class (i.e., F-scale) and are assumed to be in the form of a log-normal probability distribution. In the PNL study, tornado wind speed exceedance probabilities are more realistically based on relative frequencies of the total affected area of each tornado intensity class and are based on a Weibull probability distribution. In addition, the PNL study develops independent tornado intensity distributions of western and eastern regions of the contiguous United States.

The PNL studies result in significantly lower tornado wind speeds than that predicted by WASH-1300. Tornado wind speeds for a probability of exceedance of 10^{-7} for the 5 degree square centered at 47.5° North, 122.5° West is 186 mph and for the 5 degree square centered at 47.5° North, 117.5° West is 192 mph (note that WNP-2 is located in the latter square adjacent to the border of these two squares). The slightly higher wind speeds developed by PNL than by Fujita and McDonald can be attributed to the differences in the methodology and the following conservatisms in the PNL approach:

- the PNL approach does not account for the variation of wind speed across and along the tornado path. As noted above, an F3 tornado will have only 17 percent of the damage area experiencing winds in the F3 range. It is estimated that approximately 36 percent of the path length and 48 percent of the path width will be in the F3 range. In the PNL study, it is reasoned that the conservatism of neglecting variations along the path length will offset potential miss-classification errors of violent tornadoes (i.e., reporting tornadoes with F-scales of 4 and 5 as having a lower intensity) as reported by Twisdale et al. [23]. This compensation should be overly conservative west of the Rocky Mountains since there have been only rare reports of violent tornadoes in this region. (Fujita [17] reports only 3 violent tornadoes in the period form 1916 to 1977 all of which were located in the Imperial Valley of southern California. No violent tornadoes were reported west of 105° west in the period from 1953 to 1983 [22]). In any case, neglecting variations across the path width as is performed in the PNL study will result in an over estimate of areas effected by peak tornado winds.

- expected tornado path areas are calculated by fitting a log-normal probability distribution to the recorded data and integrating over the distribution to establish the expected mean path area. This approach would provide a more accurate estimate of the mean than a simple arithmetic average provided that the probability distribution accurately models the data. As

noted in the PNL report, the accuracy of a log-normal distribution is open to question and a Weibull distribution may be a more accurate model. Based on data contained in Appendix A of the PNL report, the use of a log-normal distribution potentially results in a over prediction of the expected area by a factor of 1.5 to 2.0. For the Pacific Northwest, this would result in an over prediction of wind speeds by approximately 10 mph.

As a result of these considerations, the PNL study supports the proposed design tornado wind speed of 180 mph. The slightly higher wind speeds predicted by the PNL study are a result of the different methodologies and the above conservatisms.

5.1 Tornado Wind and Differential Pressure Design Parameters

Tornado wind and differential pressure design parameters can be established as a function of the maximum horizontal wind speed. For this purpose, the Fujita DBT-77 [17] tornado wind field model will be used. In this model, the translational and rotational wind velocities are determined as follows:

$$V_t = 1/4\, V_{max}$$
$$V_{ro} = 3/4\, V_{max}$$

where:

V_{ro} = Rotational Wind Velocity
V_{max} = Maximum Horizontal Wind Velocity
V_t = Translational Wind Velocity

Utilizing these equations and a maximum horizontal wind speed of 180 mph, the resulting rotational wind velocity is 135 mph and the resulting translational wind velocity is 45 mph.

The maximum differential pressure is established based on the rotational component of the wind velocity from the following equation:

$$p = \rho\, V^2_{ro}$$

where

ρ = mass density of air

For a maximum rotational wind velocity of 135 mph, the above equations result in a maximum differential pressure of 0.65 psi. The rate of pressure change is established from the following equation:

$$dp/dt = \rho\, V^2_{ro}\,(V_t / R_o)$$

where

R_o = radius of maximum winds

Based on Regulatory Guide 1.76 [1], R_o is assumed to be 150 ft (note, this value is conservative with respect to the Fujita DBT-77 model). Utilizing this value, the rate of pressure change is 0.29 psi/sec. Note that these values appear to be very conservative considering the almost total lack of damage from northwestern tornadoes.

5.2 Tornado Missiles

The tornado missile velocities incorporated in the revised WNP-2 tornado design criteria are based on the extensive research sponsored by EPRI ([20] and [21]) to establish more realistic tornado missile criteria. Original NRC tornado missile criteria were developed by the National Bureau of Standards (NBS) [19]. Major improvements in the EPRI tornado missile analysis methodology are outlined below:

- The EPRI tornado wind field model more realistically considers near ground tornado winds and models variations of wind velocities as a function of height. The NBS evaluations assume a simple Rankine vortex model of tornado winds which defines wind speeds strictly as function of radius from the center of the tornado. In the NBS evaluations, the missiles are conservatively assumed to be introduced into the wind field at an initial elevation of 40 meters. As a result, during their free fall, the missiles are subject to tornado winds which are invariant with height. The missile velocities in the revised WNP-2 criteria are also based on the conservative assumption of an initial height of 40 meters. However, using the more refined EPRI wind field model, the forcing function applied to the missiles considers expected variations with height which reduces in magnitude as the missile approaches the ground.

- The NBS flight model assumes that the missile is acted on strictly by drag forces. Lift and tumbling effects are neglected. Drag - Area coefficients are assumed to be an average of the analytically derived coefficients for three orthogonal directions of the missile. In the EPRI flight model, all 6 degrees of freedom of missile flight are explicitly included in the model. Flight parameters and drag coefficients were experimentally determined from wind tunnel testing.

The tornado missile velocities incorporated in the revised WNP-2 tornado design criteria are conservatively based on a maximum wind speed of 240 mph using the EPRI wind field and flight models. Similar to the NBS evaluations, the initial height of the missiles is conservatively assumed to be 40 meters.

An exception is made for the automobile and utility pole missiles. Based on analyses performed using the Institute for Disaster Research (IDR) TMTC computer program [18] reported in [16], these missiles will not be picked-up or sustained by the wind if the wind speed is less than 200 mph.

5.3 Load Combinations

The load combinations specified in the revised criteria are identical to those in SRP Section 3.3.2. These load combinations recognize the fact that peak wind and pressure differential loads do not occur simultaneously as was conservatively assumed in the original WNP-2 criteria.

6.0 Benefits of Implementing the Revised Tornado Design Criteria

By implementing the proposed revisions, the tornado design criteria will more realistically reflect the tornado hazards at WNP-2 while maintaining the NRC's objective of providing an annual probability of exceedance of design loads of 1×10^{-7}. These revisions will result in more realistic wind velocities, differential pressure loads, missile velocities, and load combinations. These revisions are an integral part of the Supply System's efforts of hard bolting the Reactor Building roof to improve its reliability

for differential pressure and straight wind loads [25]. The revised criteria may also benefit in the resolution of a concern regarding the potential hazard of a tornado missile induced failure of the nitrogen tank used to provide containment inerting [26]. The proposed revisions will also benefit the design of exterior structures and components which must consider postulated tornado effects.

7.0 References

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FIGURE 5-1

LOCATION OF TORNADO ALLEYS WITH REPORTED TORNADOES FROM 1950 TO 1969
Reference WNP-2 FSAR