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Wind/Tornado Guidelines Study

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WIND/TORNADO GUIDELINES STUDY*

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ABSTRACT

This report documents the strategy employed to develop recommended wind/tornado hazard design guidelines for a New Production Reactor (NPR) currently planned for either the Idaho National Engineering Laboratory (INEL) or the Savannah River (SR) site. The Wind/Tornado Working Group (WTWG), comprising six nationally recognized experts in structural engineering, wind engineering, and meteorology, formulated an independent set of guidelines based on site-specific wind/tornado hazard curves and state-of-the-art tornado missile technology. The basic philosophy was to select realistic wind and missile load specifications, and to meet performance goals by applying conservative structural response evaluation and acceptance criteria. Simplified probabilistic risk analyses (PRAs) for wind speeds and missile impact were performed to estimate annual damage risk frequencies for both the INEL and SR sites. These PRAs indicate that the guidelines will lead to facilities that meet the U.S. Department of Energy (DOE) design requirements and that the Nuclear Regulatory Commission guidelines adopted by the DOE for design are adequate to meet NPR safety goals.

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INTRODUCTION

A new production reactor (NPR) is currently planned for the Idaho National Engineering Laboratory (INEL) or the Savannah River (SR) site. The U.S. Department of Energy (DOE) has established specific requirements for the design of structures, systems, and components (SSCs) of NPR facilities for resisting all types of internal and external natural hazard events. The DOE Office of New Production Reactors has decided to adopt the wind/tornado design guidelines established by the Nuclear Regulatory Commission (NRC) for commercial nuclear power plants. However, the DOE-NPR office also commissioned Lawrence Livermore National Laboratory (LLNL) to perform this subject study to demonstrate the conservatism of NRC guidelines and for potential application of appropriate alternative criteria in cases where wind/tornado considerations control the design.

The Wind/Tornado Working Group (WTWG) at LLNL comprised six experts knowledgeable in the fields of structural engineering, wind/tornado engineering, and meteorology. They researched NPR facility design regarding the ability to withstand loading induced by wind/tornado hazards, utilizing the best technical knowledge and engineering judgement.

The WTWG reviewed the available wind/tornado hazard models for the specific sites, state-of-the-art tornado missile technology, structural response evaluation methods, and the acceptance criteria. Their work resulted in proposed design guidelines that have a high probability of achieving the desired safety goals. This report documents strategies employed to develop these guidelines.

DESIGN REQUIREMENTS

Public safety, worker safety, and environmental protection are among the primary considerations of the NPR design. The DOE design requirements document serves as the basis for design of the facilities. Contractors may propose methods which offer improvements over specified requirements, but are required to demonstrate the validity of resulting improvements.

The NPR wind/tornado design requirements are summarized below.

1. The design of NPR facilities shall meet the following annual safety goals for probable frequencies of occurrence:

   A. 5×10^{-7}/yr for an early fatality to an average individual assumed to be located within one mile of the reactor facility control perimeter.

   B. 2×10^{-6}/yr for a long-term fatality to plant workers or a member of the general public located within 10 miles of the reactor facility, but outside of the control perimeter.

   C. 1×10^{-6}/yr for a large release of radioactive materials from a reactor accident.

   D. 1×10^{-5}/yr for plant damage.

2. Contractors shall incorporate knowledge and experience in nuclear reactor design accumulated over many years.

3. Contractors shall make use of past regulatory compliance in commercial reactor design or demonstrate improvement over regulatory provisions.

The design requirements document stated that external events shall be addressed pro-actively in the design process in the context of the large-release goal. Demonstrating achievement of the large-release goal requires additional consideration of containment failure modes: direct, bypass, and penetration failures. It is more realistic to demonstrate achievement of the plant damage goal as an interim step, by wind/tornado risk assessment. The WTWG expects that the mean large release risk frequency will be at least an order of magnitude lower than the mean plant damage risk frequency, because it is unlikely that wind and missile effects will significantly contribute to breaching containment. Therefore, achieving the plant damage goal is believed to ensure achievement of the large release goal.

DESIGN GUIDELINES DEVELOPMENT STRATEGY AND TECHNICAL SUPPORTING BASES

To ensure the safety of the plants, DOE-NPR requires that facility designs meet stringent safety goals, incorporate reactor experience, and comply with regulatory requirements. An effective approach to satisfy these requirements is to employ a panel of experts with proven technical knowledge, experience, and judgment resulting from years of research and service in this area. Thus, the WTWG was established to review existing wind/tornado design criteria and propose updated guidelines. The group consists of six nationally recognized technical experts, briefly profiled below.

Dr. Robert F. Abbey, Jr. is a well-known meteorologist currently serving as the Director of Marine Meteorology Research, Office of Naval Research. He specializes in probabilistic and statistical analyses of the occurrence of natural phenomena.

Dr. W. Lynn Beason is Associate Professor of Civil Engineering at Texas A&M University. His expertise is in windborne missile research, tornado risk analysis, and structural design.

Dr. T. Theodore Fujita is a world-known tornado assessment expert. Dr. Fujita developed the Fujita-scale (F-scale) for estimating the relative intensity of tornadoes, and the DAPPLE method for estimating the probability of tornado occurrence.

Dr. Dale C. Perry, Chairman of the WTWG, heads the Department of Construction Science at Texas A&M University. His expertise is in structural design and wind engineering. He has over twenty years of experience in post-disaster investigations.

Dr. John W. Reed, is an Associate at Jack R. Benjamin & Associates, Inc. in California. He has 25 years of experience in nuclear reactor design and probabilistic risk assessment (PRA) for seismic and wind hazards. Dr. Reed performed the preliminary wind speed PRA for this Project.

Dr. Lawrence A. Twisdale, Jr. is Senior Vice President of Applied Research Associates Inc., Southeast Division in North Carolina. He specializes in tornado missile simulation and design methodology for tornado hazard assessment. Dr. Twisdale performed the preliminary missile criteria PRA for this Project.

Dr. James McDonald is a professor and researcher at Texas Tech University. He specializes in wind hazard assessment and missile impact research. Dr. McDonald is a member of the Senior External Events Review Group (SEERG) for the NPR project. He provides guidance to the WTWG, and reviews reports produced by the group.

Shortly after formation of the WTWG and prior to their first meeting, the existing wind/tornado hazard assessment reports, Nuclear Regulatory Commission (NRC) provisions, design standards, and other references available for the site of interest, were distributed to the WTWG. The methodologies and data utilized in existing regional and site-specific hazard assessments were compared and discussed by the WTWG in a series of meetings. Then, using their cumulative technical knowledge and judgment in the wind/tornado field, the WTWG planned the development of wind/tornado design guidelines.

The six basic goals of the WTWG strategy are summarized below.

1. To build in a factor of conservatism by reducing wind/tornado goals to 1/10 of total project goals.

2. To specify design wind load specifications based on site-specific hazard frequency curves.

3. To specify design missile load specifications based on DOE guidelines and the EPRI NP-2005 report.

4. To define conservative structural response evaluation and acceptance criteria to substantiate the design guidelines.

5. To assure the conformance of design guidelines with safety goals by performing preliminary probabilistic risk assessments (PRAs).

6. To make use of nuclear industry standards, NRC provisions, and national codes and standards as benchmarks and references.

Plant design guidelines were developed for structures, systems, and components required to bring a plant to a safe shutdown and maintain this condition following a wind or tornado event. Guidelines were developed for production-related SSCs to maintain an annual plant capacity factor of at least 75% in a sustained, highly reliable manner, over any rolling five-rear period following a wind or tornado event. Ordinary (low hazard) SSCs must satisfy only UCRL-15910 wind/tornado design guidelines.

DEVELOPING WIND LOAD SPECIFICATIONS BASED ON SITE-SPECIFIC HAZARD FREQUENCY CURVES

In the 1970s, the NRC divided the U.S. into three geographical regions, and recommended Design Basis Tornado (DBT) wind speeds for each region in NRC R.G. 1.76 [1]. These DBT wind speeds are believed to be broadly conservative, due to coarse assumptions and to problems with the regional data sets employed.

More recently, the NRR position paper [2] divided the U.S. into four regions and recommended DBT wind speeds based on regional analyses. Recommendations based on regional analyses cannot provide a realistic portrayal of the risk associated with specific sites within the region.

In 1979, two leading wind engineering experts, Drs. Fujita and McDonald, performed independent site-specific wind/tornado hazard assessments for 26 DOE facilities. Both NPR sites were among them. These analyses utilized advanced methodologies. Two of the most important improvements involved the use of wind speed gradations, both across the width and along the length of tornado damage paths. In addition, techniques were introduced to allow adjustments to be made to tornado data sets to account for unreported tornado events. Based on these hazard assessment results, the DOE-UCRL-15910 report [3] provided design and evaluation guidelines for hazard frequencies up to 2×10^{-5}/yr.

In 1985, a third site-specific hazard assessment for the SR site was performed by Dr. Twisdale. This analysis used computerized simulation techniques to estimate hazard probabilities, and accounted for building size effects.

In summary, wind assessment technology has evolved from broadly conservative regional analyses to realistic site-specific assessments. In this process, coarse assumptions have been refined by application of accumulated knowledge related to tornado hazard assessment. In addition, during the years since the introduction of NRC R.G. 1.76, more complete tornado occurrence data have been recorded, thus allowing more accurate assessments. The resulting site-specific analyses yielded improvements over earlier regional analyses. Therefore, the WTWG opted to incorporate site-specific hazard curves in the design guideline development. Figures 1 and 2 depict composite hazard curve plots for the SR and INEL sites, respectively.

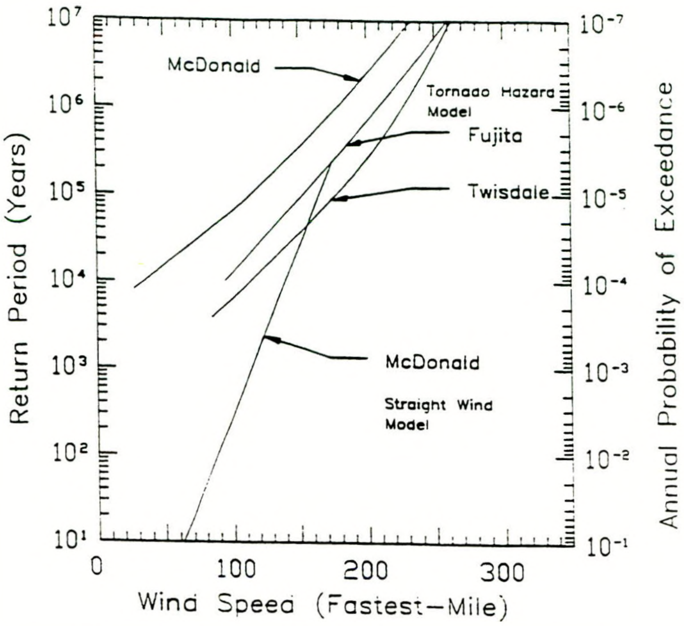

Figure 1. Wind/Tornado Hazard Curves for Savannah River Site

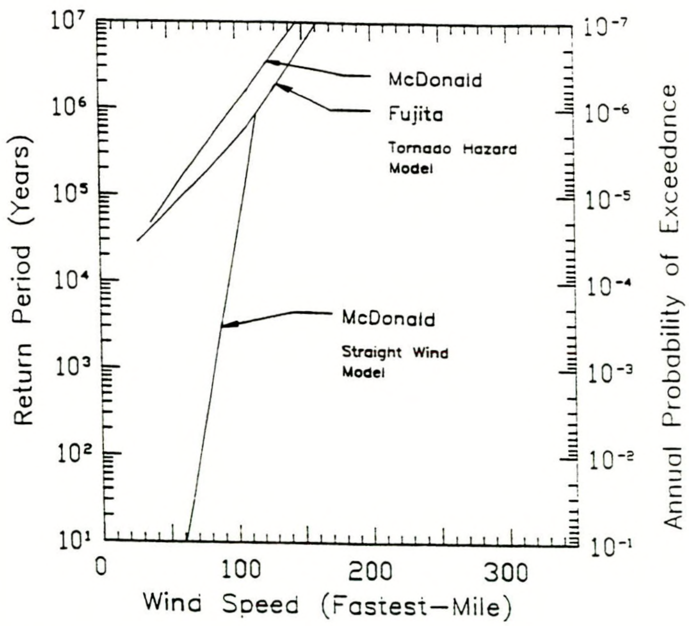

Figure 2. Wind/Tornado Hazard Curves for INEL Site

The proposed design guidance presented in this report represents a major improvement over NRC provisions. The suitability of these proposed trajectories. The velocity fractions for steel pipes generated by EPRI are slightly larger than SRP velocity fractions.

In summary, state-of-the-art missile simulation technology incorporating relevant databases and newly developed experimental results, is an improvement over technology used for NRC missile impact estimates in the 1970s. In the judgment of the WTWG, the recommended missile spectrum and maximum impact velocities guidelines should be formulated by modification of DOE UCRL-15910 guidelines. The modification consists of incorporating additional missiles and extrapolating from EPRI tornado missile simulation results.

After evaluating the SRP provisions, EPRI missile simulation results, and DOE-UCRL-15910 missile spectra, the WTWG formulated proposed missile guidelines based on the following:

1. Selection of missile types observed in past tornado damage investigations.

2. Modification of DOE-UCRL-15910 to extend the hazard frequency from 2×10^{-5}/yr to 1×10^{-6}/yr.

3. Extrapolation of the EPRI tornado missile simulation results.

As a result of this effort, the WTWG added an 8 in. diameter steel pipe to the DOE UCRL-15910 missile spectrum to extend the hazard frequency to 1×10^{-6}/yr. The horizontal impact velocity for the 8 in. steel pipe was obtained by extrapolating EPRI results for a 6 in. diameter steel pipe at the 90th percentile. This extrapolation included conversion from a maximum velocity of 300 mph to 200 mph. The vertical impact velocity was set at 2/3 of the horizontal impact velocity by the WTWG. Tables 3 and 4 present spectra of potential missiles with recommended impact velocities and corresponding effective heights for the SR and INEL sites, respectively.

STRUCTURAL RESPONSE EVALUATION AND ACCEPTANCE LEVELS

The WTWG incorporated conservative structural response evaluation methods and acceptance levels in the proposed guidelines as follows:

1. Accounted for the fact that the critical facility is a high hazard facility by increasing the importance factor to 1.35.

2. Used exposure C for tornado controlled designs by assuming that the facilities are located in open terrain with obstruction heights generally less than 30 feet. This assumption accounts for uncertainties in the characteristics of tornadoes.

3. Accounted for variability in structural resistance properties by using a load factor of 1.3 on design wind pressures.

4. Selected the velocity pressure exposure coefficient and the gust factor corresponding to the height of structures for both tornado- and straight-wind-controlled designs.

5. Accounted for uncertainty in missile impacts by making the 20% increase in calculated barrier thickness recommended in ACI 349-85.

6. Did not apply the load factor of 1.3 to missile loads, since a conservative missile spectrum and maximum tornado-generated impact velocities were selected for barrier design.

ASSURING CONFORMANCE OF DESIGN GUIDELINES BY PERFORMING PRELIMINARY PROBABILISTIC RISK ASSESSMENT

Probabilistic risk assessments (PRAs) were performed to estimate annual damage risk frequencies for NPR facilities on the basis of the recommended design guidelines. These wind damage risk frequencies are measures of achievement of the NPR goals. Independent preliminary PRAs were performed to evaluate both wind speed and missile impact.

Preliminary PRAs were performed during the conceptual design stage; hence, component and plant details were not available. More refined PRAs need to be undertaken in the preliminary and final design stages. The results reported for this study must be considered preliminary, due to the following simplifications built into the analyses.

For wind speed risk analyses:

1. Results from previous PRAs were used to make approximate estimates of the expected damage frequencies.

design guidelines for NPR design and/or assessment was confirmed by preliminary probabilistic risk assessments (PRA), described later in this report.

It must be noted that in wind hazard assessment, limitations of tornado intensity and occurrence data, F-scale wind speed assumptions, and processes incorporated in the hazard models result in assessment uncertainties.

With the combined judgment of the hazard and risk assessments analysts, the following major factors were taken into account in wind speeds selection:

1. Conservatism embedded in assessment methodologies.
2. Uncertainties identified in the assessment.
3. Site-specific wind speeds in geographical areas of interest.
4. Site-specific wind speeds required to achieve risk frequency goals.
5. Wind speeds acceptable by the consensus of WTWG members.

After careful study of hazard frequency curves and examination of preliminary risk calculations, the WTWG selected wind speeds through an iterative process. These are presented in Table 1 for both NPR sites, with their corresponding probabilities of occurrence and risk frequencies. Table 2 provides tornado characteristics for the SR site.

A preliminary risk analysis on the production event indicates that straight wind controls the SR site design. Straight wind also controls plant damage and production events for the INEL site.

DEVELOPING MISSILE LOAD SPECIFICATIONS BASED ON DOE GUIDELINES AND THE EPRI TORNADO MISSILE SIMULATION REPORT

Standard Review Plan (SRP), NUREG-0800 [4], recommends a conservative spectrum of tornado-generated missiles and corresponding velocity fractions. No regional distinctions are made regarding SRP missile types and sizes. However, missile impact velocities vary based on regional DBT wind speeds. DOE-UCRL-15910 also recommends missile spectra for various categories of facilities, based in part on results of missile research performed at Texas Tech University. However, missile spectra were developed only for hazard frequencies to 2×10^{-5}/yr.

Table 1. Proposed wind speeds and corresponding hazard and risk frequencies

For the Savannah River site:

Wind Speed	Prob. of Occur	Risk Freq.
180 mph	$3x10^{-6}$	$1x10^{-6}$
130 mph	$2x10^{-4}$	$5x10^{-5}$

For the INEL site:

Wind Speed	Prob. of Occur.	Risk Freq.
125 mph	$2x10^{-7}$	$1x10^{-7}$
100 mph	$2x10^{-5}$	$5x10^{-6}$

Table 2. Proposed Tornado Characteristics for Savannah River Site

Tornado fastest-mile wind speed	180 mph
Rotational Speed	130 mph
Translational speed (min - max)	5 - 50 mph
Radius of maximum rotational speed	175 feet
Pressure drop	92 psf
Pressure drop rate	38 psf/sec

The Electric Power Research Institute (EPRI) sponsored development of a probabilistic tornado missile risk methodology for assessing potential tornado missile hazards to nuclear power plants. Results of this effort are presented in the EPRI NP-2005 report [5]. Missile impact velocities were estimated based on computer simulations of potential missile populations at nuclear power plants, and on computer generated missile

Table 3. Proposed Windborne Missiles Criteria for Savannah River Site

MISSILE	MISSILE CRITERIA	SAFETY	PRODUCTION
2 X 4 timber plank	Horizontal impact speed (mph)	150	115
12 ft. long, 15 lb.	Effective height (ft)	200	200
	Vertical impact speed (mph)	100	75
3"Ø standard steel pipe,	Horizontal impact speed (mph)	120	90
10 ft. long, 75 lb.	Effective height (ft)	150	150
	Vertical impact speed (mph)	80	60
8"Ø standard steel pipe,	Horizontal impact speed (mph)	100	75
15 ft. long, 430 lb.	Effective height (ft)	75	30
	Vertical impact speed (mph)	70	50
Automobile, 3000 lb.	Rolls/tumbles along ground (mph)	35	25
	Effective height (ft)	30	30
	Vertical impact speed (mph)	20	15

Notes: 1. Horizontal and vertical missile speeds are uncoupled and should not be combined.
2. Specific missiles represent a class of debris.
3. Effective heights are elevations above ground level.

Table 4. Proposed Windborne Missiles Criteria for INEL Site

MISSILE	MISSILE CRITERIA	SAFETY	PRODUCTION
2 X 4 timber plank	Horizontal impact speed (mph)	115	75
12 ft. long, 15 lb.	Effective height (ft)	200	150
	Vertical impact speed (mph)	75	50
3"Ø standard steel pipe,	Horizontal impact speed (mph)	90	60
10 ft. long, 75 lb.	Effective height (ft)	150	150
	Vertical impact speed (mph)	60	40
8"Ø standard steel pipe,	Horizontal impact speed (mph)	75	-
15 ft. long, 430 lb.	Effective height (ft)	30	-
	Vertical impact speed (mph)	50	-
Automobile, 3000 lb.	Rolls/tumbles along ground (mph)	25	-
	Effective height (ft)	30	-
	Vertical impact speed (mph)	15	-

Notes: 1. Horizontal and vertical missile speeds are uncoupled and should not be combined.
2. Specific missiles represent a class of debris.
3. Effective heights are elevations above ground level.

2. Preliminary mean damage frequencies, representing damage within the 60 to 90 percent probability range, were used.

3. Mean damage fragility curves were inferred based on rules and procedures used in typical plant design processes. A more rigorous analysis would include performing detailed fragility analyses for every component, and combining the resulting mean component fragility curves through Boolean logic.

For missile criteria risk analyses:

1. Evaluation of damage was limited to exterior barriers for plant damage and production events.

2. Estimation of impact probabilities for vulnerable areas, such as doorways and vent openings, was not included in the analysis.

3. Failures of plant stacks due to high winds were not considered.

4. Missile generation contributions resulting from collapse and/or failure of tall structures were not included.

5. Non-linear relationships between numbers of missiles, wind speed, facility layout, and damage probabilities were not considered.

For plant damage events, reinforced concrete barriers were assumed to be damaged if the barriers suffered backface scabbing or worse from any single missile impact. As a first approximation, it was assumed that these minimum barrier thicknesses controlled plant design.

The sum of scabbing damage risk frequencies for minimum design requirements is 1.1×10^{-6}/yr. This value is slightly higher than the plant damage goal of 1×10^{-6}/yr. However, this damage criteria is very conservative, because even if backface scabbing occurs, a plant damage event is not very likely to occur. The WTWG believes that the plant damage risk frequency is at least one to two orders of magnitude less than the scabbing damage risk frequency, and that therefore the recommended missile criteria meet the plant damage goal by a significant margin.

At an impact velocity of 35 mph (the plant damage design guideline), the exceedance probability for automobile impact is 3.7×10^{-7}/yr. Thus, automobile results meet the plant damage performance goal.

PROPOSED GUIDELINES FOR NPR DESIGN

Separate wind and missile load specifications were proposed for NPR safety-related and production-related SSCs to meet corresponding plant damage and production requirements. The recommended response evaluation method and acceptance levels are similar for both safety-related and production-related SSCs. It is suggested that guidelines for other NPR SSCs which are not required to meet safety and production assurance requirements should be taken from guidelines provided by DOE UCRL-15910 for important or low-hazard facilities.

It is assumed that tornados and straight winds can occur from any direction. Hence the wind direction which causes the most critical situation shall control the design. Wind pressures induced by the winds shall be properly identified and computed for all wind-resisting structural components. The penetrating type missiles shall be designed assuming that local structural response controls the design. The missile load associated with an automobile shall be treated as an impulsive force applied to the entire structure.

PROPOSED DESIGN LOAD CALCULATION METHODOLOGY

Equivalent static wind pressures and forces shall be determined from recommended design load specifications for unenclosed main wind-force resisting systems, individual structural components, and cladding of buildings and other structures, following provisions of ASCE 7-88. Equation 1 gives the velocity pressure for a given basic fastest-mile tornado and straight wind speed at an elevation of 33 ft. above ground.

$$q_z = 0.00256\, K_z\, (IV_{33})^2 \qquad (1)$$

where:

q_z = velocity pressure from tornado or straight wind

K_z = velocity pressure exposure coefficient

V_{33} = recommended fastest-mile wind speed (mph)

I = importance factor; taken to be 1.35

Note that, for tornado controlled designs, the velocity pressure exposure coefficient (K_z), as well as gust response factors and/or internal pressure coefficients, shall be selected typical of exposure C, regardless of the actual exposure specification. All coefficients shall be selected according to the facility's true exposure category specification if the design is controlled by straight winds. In addition, the combination of internal and external pressures on the exterior wall shall be checked to determine the maximum pressure load.

The atmospheric pressure change (APC) load shall be considered for all sealed buildings designed to resist the effects of tornadoes. The net effect of APC is a positive pressure, W_p, inside the building. This pressure is considered to act outwardly on exterior walls.

Differential pressures can be generated on interior walls and ventilation systems of partially vented buildings that are subjected to the tornado-induced APC. Therefore, the interior walls and ventilation systems shall be designed for a minimum pressure of 5 psf. A lower pressure can be used provided it is justified through a rational analysis.

Roofs and walls of safety-related and production-related SSCs shall provide adequate protection to prevent perforation and scabbing. Scabbing of concrete could generate airborne missiles within a building that could damage equipment and piping systems attached to or residing near walls. When fragile equipment and small piping systems sensitive to scabbing damage are near walls and roofs, protection is required.

As provided in Tables 3 and 4, the angle of incidence of an impacting missile shall be assumed to be normal to the targeted plane with the longitudinal axis of the missile parallel to the line of flight, so that the area of contact between the missile and the targeted plane is minimized, and local impact force is maximized. The barrier thicknesses shall be calculated using equations 3 through 9 in the later subsection discussing local structural response evaluations.

Doors and other openings in the building envelope shall be protected from missile impacts by barriers to prevent perforation and scabbing, if the striking probability is greater than 1×10^{-5}/yr. If it can be shown through rational calculations that the annual probability of a missile striking an opening in a structure is less than 1×10^{-5}/yr, barriers are not required.

Unless a more rigorous procedure is employed, the following procedure shall be used to design barriers for overall damage caused by rolling and tumbling automobiles. In applying the impulse momentum procedure, barriers shall be designed assuming that the impact force, F, between an automobile and a barrier is constant over a 0.05 sec. interval, and that the barrier is perfectly rigid. The impact force is then given by equation 2.

$$F = 0.624\, W_a\, V \qquad (2)$$

where:

F = Force (lbs)
W_a = weight of automobile (lbs)
V = impact speed (fps)

The resulting load, F, shall be treated as a dynamic load with a 0.05 sec. duration. This impulse load shall be combined with the total wind pressure load as indicated by equations 13 through 21 in a later paragraph discussing load combination.

STRUCTURAL ELEMENTS CAPACITY EVALUATION

Design wind loads specified for NPR SSCs, shall be imposed on the structural elements. Walls and roofs shall be designed to withstand the total load created by external and internal pressures, to achieve adequate overall design margins to satisfy the probabilistic risk assessment requirements for the entire plant. Barriers shall be designed to protect openings from local and overall damage. The capacity of these elements shall be obtained from the national codes and standards given below:

1. ACI/ASCE 531 for masonry structures with a capacity factor to increase the working strength to ultimate strength.

2. ACI 349-85 and ACI 318-89 specifications for concrete structures (ultimate strength design).

3. AISC allowable stress design and plastic design specifications for structural steel buildings – chapter N for plastic design.

4. ASME service Levels D or C for ASME components (level D for safety-related SSCs and level C for production-related SSCs).

Local Structural Response Evaluation for Penetrating-Type Missiles

Reinforced concrete walls and roofs shall be protected from perforation and scabbing where equipment and piping systems in the immediate vicinity are sensitive to scabbing damage. Penetration thickness (used to calculate perforation and scabbing thicknesses), is calculated using equations 3, 4, and 5.

$$A = [K N (W / D_o) (V / 1000 D_o)^{1.8}]^{0.5} \quad (3)$$

$$Z = 2 A D_o; \text{ for } A \leq 1.0 \quad (4)$$

$$Z = (A^2 + 1) D_o; \text{ for } A \geq 1.0 \quad (5)$$

Barrier thicknesses required to resist both perforation and scabbing shall be checked using equations 6 through 9 . The larger barrier thickness shall control the design.

For perforation thickness:

$$e = 3.19 Z - 0.718 Z^2/D_e; \text{ for } Z/D_e \leq 1.35 \quad (6)$$

$$e = 1.32 D_e + 1.24 Z; \text{ for } 1.35 \leq Z/D_e \leq 13.5 \quad (7)$$

For scabbing thickness:

$$s = 7.91 Z - 5.06 Z^2/D_e; \text{ for } Z/D_e \leq 0.65 \quad (8)$$

$$s = 2.12 D_e + 1.36 Z; \text{ for } 0.65 \leq Z/D_e \leq 11.75 \quad (9)$$

where:

A = penetration variable
Z = penetration thickness
e = perforation thickness
s = scabbing thickness
V = missile strike velocity (fps)
N = shape factor of 0.72 for flat-nosed missiles
D_o = outside diameter of missile: rods and pipes (in)
D_e = $2.0 (A_s / P_i)^{0.5}$
A_s = contact area of rod or pipe (sq. in.)
P_i = 3.1416
W = weight of missile (lbs)
K = $180/(f'_c)^{0.5}$
f'_c = compressive strength of concrete (psi)

To ensure adequate protection, a minimum of 12 in. of reinforced concrete is required for all concrete barriers at elevations below 75 ft. from ground level, and a minimum of 8 in. of reinforced concrete is required for all concrete barriers at elevations above 75 ft. from ground level.

Steel plate barriers shall be designed to provide resistance to both penetration and perforation. For steel barrier designs, the Ballistic Research Laboratory formula shall be used, given in equation 10.

$$T = \frac{(M V_s^2 / 2.0)^{2/3}}{672 d_m} \quad (10)$$

where:

T = calculated thickness for incipient perforation of a steel plate
M = mass of missile (slugs)
V_s = velocity of missile (ft/sec)
d_m = diameter of missile (in)

For irregularly shaped missiles, an equivalent diameter shall be used. The equivalent diameter is taken to be the diameter of the circle with an area equal to the circumscribed contact, or projected frontal area of the non-circular missile. The thickness (T_p) to prevent perforation shall be as specified in equation 11.

$$T_p = 1.25 T \quad (11)$$

where:

T = calculated thickness for incipient perforation of a steel plate

To ensure adequate protection, a minimum of 1/2 inch of steel shall be required for all steel barriers, regardless of elevation.

Overall Structural Response Evaluation for Automobile Impact

The overall response of structural barriers to missile impact depends upon available ductility. It is acceptable to assume plastic collisions as long as the required ductility is within the allowable ratio. For concrete wall and roof slab designs which are controlled by flexure, the permissible ductility ratio (M_u), taken from ACI 349-85, Appendix C, is given in equation 12.

$$M_u = 0.05 / (p-p') \text{ or less than } 10.0 \qquad (12)$$

where:

M_u = ductility ratio
p = ratio of tension reinforcement
p' = ratio of compression reinforcement

Load Combination

The SSCs shall be designed for the most severe total wind load (W_t) weight. This is a combination of wind pressure (W_w), atmospheric pressure change (W_p), and missile impact loads (W_m). The load factor applies only to wind pressure and APC pressure, but not to missile loads. In addition, the APC pressure load is half of its maximum value at the radius of maximum wind speed in a tornado; therefore, only 0.5 W_p is combined with wind pressure and/or missile impact, as defined in equations 13 through 18.

$$W_t = 1.3\, W_w \qquad (13)$$
$$W_t = 1.3\, W_p \qquad (14)$$
$$W_t = W_m \qquad (15)$$
$$W_t = 1.3\, W_w + W_m \qquad (16)$$
$$W_t = 1.3\, W_w + 0.5 \times 1.3\, W_p \qquad (17)$$
$$W_t = 1.3\, W_w + 0.5 \times 1.3\, W_p + W_m \qquad (18)$$

For events controlled by straight wind, the APC pressure load does not exist. Load combinations for this case are defined in equations 19, 20, and 21.

$$W_t = 1.3\, W_w \qquad (19)$$
$$W_t = W_m \qquad (20)$$
$$W_t = 1.3\, W_w + W_m \qquad (21)$$

SUMMARY OF DESIGN GUIDELINES DEVELOPMENT

LLNL developed guidelines based on site-specific hazard assessments and EPRI report results, and on technological advancements and accumulated experience in wind engineering. The load specifications reflect enhancements to NRC regulations, and justification for these is provided in this report. Proposed structural response evaluation and acceptance criteria follow industry codes and standards with minor modifications. Design guidelines developed by the WTWG in this study provide a basis for verifying the conservatism and low risk inherent in the NRC criteria, and an indication of the margin in the design. However, this condensed paper should not be used for design without referring to the full report [6].

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