JUL 25 1991

DESIGN FOR CONTAINMENT OF HAZARDOUS MATERIALS

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This paper was prepared for submittal to the Tornado Symposium III
Norman, Oklahoma
April 2-5, 1991

March 1991

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Design for Containment of Hazardous Materials

Abstract

Department of Energy, (DOE), facilities across the United States, use wind and tornado design and evaluation criteria based on probabilistic performance goals. In addition, other programs such as Advanced Light Water Reactors, New Production Reactors, and Individual Plant Examinations for External Events for commercial nuclear power plants utilize design and evaluation criteria based on probabilistic performance goals. The use of probabilistic performance goals is a departure from design practice for commercial nuclear power plants which have traditionally been designed utilizing a conservative specification of wind and tornado loading combined with deterministic response evaluation methods and permissible behavior limits. Approaches which utilize probabilistic wind and tornado hazard curves for specification of loading and deterministic response evaluation methods and permissible behavior limits are discussed in this paper. Through the use of such design/evaluation approaches, it may be demonstrated that there is high likelihood that probabilistic performance goals can be achieved.

1. Introduction

Use of deterministic design and evaluation criteria to meet probabilistic performance goals is the approach used by DOE facilities across the United States as given in UCRL-15910, "Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards", (Kennedy, et al. 1990). An overview of the approach is presented in this paper.

In this paper, three types of winds are discussed: extreme (straight), hurricane, and tornado. Extreme (straight) winds are non-rotating such as those found in thunderstorm gust fronts. Wind circulating around high or low pressure systems are rotational in a global sense, but they are considered "straight" winds in the context of this paper. Tornadoes and hurricanes both have rotating winds. The diameter of rotating winds in a small hurricane is considerably larger than the diameter of a large tornado. However, most tornado diameters are relatively large compared to the dimensions of typical buildings. It is estimated that the diameter of 80 percent of all tornadoes is greater than 300 feet.

Wind pressures produced by extreme winds are studied in boundary layer wind tunnels. The results are generally considered reliable because they have been

verified by selected full-scale measurements. Investigations of damage produced by extreme winds tend to support the wind tunnel findings. Although the rotating nature of hurricane and tornado winds cannot easily be duplicated in a wind tunnel, damage investigations suggest that pressures produced on enclosed buildings and other structures by extreme, hurricane, and tornado winds are so similar that it is almost impossible to look at damage to an individual structure and tell which type of wind produced it. Thus, the approach for determining wind pressures on buildings and other structures proposed in this paper is considered to be independent of the type of windstorm. The recommended procedure is essentially the same for straight, hurricane, and tornado winds.

UCRL-15910 wind and tornado provisions use deterministic evaluation criteria with the hazard annual probability of exceedance specified to get design/evaluation wind speeds. The evaluation of response and structure or equipment capacities are performed using deterministic methods which are familiar to engineers. Wind speeds are developed from probabilistic hazard curves are used to meet performance goals for various building occupancies.

2. Performance Goals

Performance goals may be expressed in terms of annual probability of exceedance of some level of damage. Levels of damage can include that damage beyond which occupants are endangered, beyond which hazardous materials cannot be confined, beyond which a facility cannot safely shutdown, or beyond which a facility cannot continue its mission. The performance goal for the safety of Advanced Light Water Reactors is on the order of 1.0×10^{-5} annual probability of exceedance for external events induced core damage, (EPRI, 1990). Performance goals upon which design/evaluation guidelines are based for DOE facilities in UCRL-15910, are presented in Table 1.

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Usage Category	Performance Goal Description	Performance Goal (Annual Probability of Exceedance)
General Use	Maintain Occupant Safety	$\sim 10^{-3}$ of the onset of major component ⁽¹⁾ damage to the extent that occupants are endangered
Important or Low Hazard	Occupant Safety, Continued Operation with Minimal Interruption	$\sim 5 \times 10^{-4}$ of component damage to the extent that the component cannot perform its function
Moderate Hazard	Occupant Safety, Continued Function, Confinement	$\sim 10^{-4}$ of component damage to the extent that the component cannot perform its function
High Hazard	Occupant Safety, Continued Function, Very High Confidence of Confinement	$\sim 10^{-5}$ of component damage to the extent that the component cannot perform its function
Commercial Reactor	Beyond the scope of UCRL-15910	

⁽¹⁾ Component refers to structure, equipment, or distribution system.

Table 1. Performance Goals for Each Usage Category

For each performance goal there are separate wind and tornado design and evaluation criteria. DOE management categorize facilities or individual structures, systems, or components depending on the cost, mission importance, or hazard to people or the environment. For UCRL-15910, a DOE natural phenomena hazards panel selected reasonable and achievable performance goals, bounded by current practice.

- For ordinary facilities, the performance goals are consistent with design according to conventional building code provisions.
- For high hazard facilities, the performance goals are comparable to performance reached by nuclear power plants as measured by probabilistic risk assessments (PRAs).^{*}

3. Performance Goal Achievement

Structure/equipment performance is a function of: (1) the likelihood of hazard occurrence and (2) the strength of the structure or equipment item. Therefore, design and evaluation criteria have been developed to attain performance goals by: (1) specification of hazard probability for definition of wind and tornado loadings and (2) specification of response evaluation methods, acceptance criteria, and design

^{*} Note that UCRL-15910 performance goals are related to individual component behavior while PRA results are in terms of core damage.

detailing requirements with controlled levels of conservatism. Acceptable performance can only be achieved by consistent specification of all design or evaluation criteria elements as shown below:

UCRL-15910 wind and tornado design and evaluation guidelines contain the following provisions:

- Lateral Force Provisions
- Damage Control Provisions
- Detailing Provisions
- Quality Assurance and Peer Review Provisions

Wind/tornado performance depends on the level of the hazard and on conservatism in the response evaluation and acceptance criteria. For example, a performance goal of 1×10^{-4} can be achieved either by: (1) a conservative evaluation/acceptance approach for a more frequent hazard probability, such as 1×10^{-3} or by: (2) a median centered evaluation/acceptance approach coupled with a less frequent 1×10^{-4} hazard

probability. UCRL-15910 uses the former approach because conservative evaluation/acceptance approaches are well established, extensively documented, and commonly practiced.

4. Design and Evaluation Criteria for Wind Load

A uniform approach to wind load determination that is applicable to the design of new facilities and the evaluation of existing facilities has been developed for DOE. A uniform treatment of wind loads is recommended to accommodate extreme, hurricane, and tornado winds. Buildings or facilities are first assigned appropriate usage categories. Criteria are recommended such that the performance goals for each category can be achieved. Procedures according to ASCE 7-88 (formerly ANSI A58.1) (ASCE, 1990), are recommended for determining wind loads produced by straight, hurricane, and tornado winds. The extreme wind/tornado hazard models developed for DOE sites were used to establish site-specific criteria for each of some 25 DOE sites, (Coats and Murray, 1985).

The performance goals established for General Use and Important or Low Hazard usage categories are met by conventional building codes or standards, see (ICBO, 1988). These criteria do not account for the possibility of tornado winds, because wind speeds associated with extreme winds typically are greater than those for tornadoes at exceedance probabilities greater than approximately 1×10^{-4} . For this reason, tornado design criteria are specified only for buildings and facilities in Moderate and High Hazard categories, where hazard exceedance probabilities are less than 1×10^{-4} .

The traditional approach for establishing tornado design criteria is to select extremely low exceedance probabilities. For example, the exceedance probability for design of commercial nuclear power plants is 1×10^{-7} , (NRC, 1974; Kimura and Budnitz, 1987; and Ravindra, 1990). There are reasons for departing from this traditional approach. The low exceedance value for commercial nuclear power plants was established circa 1960 when very little was known about tornadoes from an engineering perspective. Much has been learned about tornadoes since that time. Use of a low hazard probability is inconsistent with the practice relating to other natural hazards, such as earthquakes. There are many uncertainties in tornado hazard probability assessment, but they are not significantly greater than the uncertainties in earthquake probability assessment. The strongest argument against using low probability criteria is that a relatively short period of record (40 years) must be extrapolated to extremely small exceedance probabilities. For these reasons, an

alternative approach was used in the UCRL-15910 guidelines.

a. Establishment of Wind and Tornado Hazard Annual Probabilities

The rationale for establishing tornado criteria is described below. Figure 1 shows the tornado and straight wind hazard curves for two DOE sites (SLAC and ORNL). The wind speed at the intersection of the tornado and straight wind curves is defined for purposes of this discussion as the transition wind speed. An exceedance probability is associated with each transition wind speed. If the exceedance probability of the transition wind speed is less than 1×10^{-5} per year, tornadoes are not a viable threat to the site, because straight wind speeds are higher than tornadoes for a given return period. Thus, from Figure 1, tornadoes need not be considered at SLAC, but should be considered at ORNL.

Mean wind and tornado hazard curves were developed for each DOE site, along with the transition wind speed. Those sites with transition wind speed exceedance probabilities greater than 10^{-5} should be designed for tornadoes; others should be designed for extreme winds or hurricanes.

The tornado wind speed is obtained by selecting the wind speed associated with an exceedance probability of 2×10^{-5} per year. The value of 2×10^{-5} is the largest one that can be used and still represent a point on the tornado hazard curve. For example, the tornado wind speed for the ORNL is 130 mph (peak gust at 10m).

A comparison of the slopes of the tornado hazard curves for the DOE sites reveals that the slopes are essentially the same even though the transition wind speeds are different. The criteria required to meet the performance goals of Moderate and High Hazard facilities can be met by using multipliers that are equivalent to an importance factor in the ASCE 7-88 design procedure. The multipliers are specified in lieu of two different exceedance probabilities for Moderate and High Hazard facilities. The value of the importance factor is selected to achieve lower probability of tornado damage for High Hazard facilities compared to Moderate Hazard facilities. The importance factors are then chosen to meet the performance goals.

In general, design criteria for each usage category include:

1. Annual hazard exceedance probability.
2. Importance factor.
3. Wind generated missile parameters for Moderate and High Hazard facilities.
4. Tornado parameters for Moderate and High Hazard facilities, if applicable.

Figure 1. Straight Wind and Tornado Regions of Wind Hazard Curves

The criteria are formulated in such a way that a uniform approach for determining design wind loads, per ASCE 7-88, can be used for extreme, hurricane, and tornado winds.

In order to apply the ASCE 7-88 procedure, tornado gust wind speeds must be converted to fastest-mile speeds. Appropriate gust response factors and velocity pressure exposure coefficients are utilized in the process of determining wind loads. Appropriate exposure categories also are considered in the wind load calculations. Open terrain (Exposure C) should always be assumed for tornado winds, regardless of the actual terrain conditions.

b. Criteria for Design of Facilities

The criteria presented herein are consistent with the performance goals described earlier. Buildings or facilities in each category have a different role and represent different levels of hazard to people and the environment. In addition, the degree of wind hazard varies geographically. Facilities in the same usage category, but at different geographical locations, will have different input loading specified to achieve the same performance goal.

The minimum wind design criteria for each of the four usage categories are summarized in Table 2. The recommended basic wind speeds for extreme wind,

	Building Category	General Use	Important or Low Hazard	Moderate Hazard	High Hazard
W i n d	Annual Probability of Exceedance	2×10^{-2}	2×10^{-2}	1×10^{-3}	1×10^{-4}
	Importance Factor*	1.0 (1.05)	1.07 (1.11)	1.0 (1.05)	1.0 (1.05)
	Missile Criteria			2x4 timber plank 15 lb @ 50 mph (horiz.); max. height 30 ft.	2x4 timber plank 15 lb @ 50 mph (horiz.); max. height 50 ft.
T o r n a d o	Annual Hazard Probability of Exceedance			2×10^{-5}	2×10^{-5}
	Importance Factor			1 = 1.0	1 = 1.35
	APC			40 psf @ 20 psf/sec	125 psf @ 50 psf/sec
				2x4 timber plank 15 lb @ 100 mph (horiz.); max. height 150 ft; 70 mph (vert.)	2x4 timber plank 15 lb @ 150 mph (horiz.); max. height 200 ft; 100 mph (vert.)
	Missile Criteria			3 in. dia. std. steel pipe, 75 lb @ 50 mph (horiz.); max. height 75 ft, 35 mph (vert.)	3 in. dia. std. steel pipe, 75 lb @ 75 mph (horiz.); max. height 100 ft, 50 mph (vert.) 3,000 lb automobile @ 25 mph, rolls and tumbles

*The first value represents the importance factor for sites 100 miles or more inland. The value in parenthesis should be used at the coastline. Linear interpolation between the two values should be used for sites within 100 miles of the coastline to account for hurricanes.

Table 2. Summary of Minimum Wind Design Criteria

hurricanes, and tornadoes are contained in Table 3. All wind speeds are fastest-mile. Minimum recommended basic wind speeds are also noted in the table.

c. General Use Facilities

The performance goals for General Use facilities are consistent with objectives of ASCE 7-88 Building Class 1, Ordinary Structures. The wind-force resisting structural system should not collapse under design load. Survival without collapse implies that occupants should be able to find an area of relative safety inside the building. Breach of the building envelope is acceptable, since confinement is not essential. Flow of air through the building and water damage are acceptable. Severe damage, including total loss, is acceptable, so long as the structure does not collapse.

The ASCE 7-88 standard calls for the basic wind speed to be based on an exceedance probability of 0.02 per year. The importance factor for this class of building is 1.0. For those sites within 100 miles of the Gulf of Mexico or Atlantic coastlines, a slightly higher importance factor is recommended to account for hurricanes.

Terrain surrounding the facilities should be classified as Exposure B, C, or D, as appropriate. Gust response factors and velocity pressure exposure factors should be used according to rules of the ASCE 7-88 procedures.

Wind pressures are calculated on the walls and roofs of enclosed buildings by appropriate pressure coefficients specified in the ASCE 7-88 standard. Openings, either of necessity or created by wind forces or missiles, result in internal pressures that can increase wind forces on components and cladding. The worst cases of combined internal and external pressures should be considered, as required by the standard.

Structures in the General Use category may be designed by either allowable stress design (ASD) or strength design (SD) as appropriate for the material used in construction. Except when applicable codes provide otherwise, plausible load combinations shall be considered to determine the most unfavorable effect on the building, foundation, or structural member being considered. When using ASD methods, allowable stresses appropriate for the building material shall be

Building Category	Fastest-Mile Wind Speeds at 10m Height					
	General Use	Important or Low Hazard	Moderate Hazard		High Hazard	
	Wind	Wind	Wind	Tornado	Wind	Tornado
DOE PROJECT SITES						
Bendix Plant, MO	72	72	--	144	--	144
Los Alamos National Laboratory, NM	77	77	93	--	107	--
Mound Laboratory, OH	73	73	--	136	--	136
Pantex Plant, TX	78	78	--	132	--	132
Rocky Flats Plant, CO	109	109	138	(3)	161	(3)
Sandia National Laboratories, Albuquerque, NM	78	78	93	--	107	--
Sandia National Laboratories Livermore, CA	72	72	96	--	113	--
Pinellas Plant, FL	93	93	130	--	150	--
Argonne National Laboratory -- East, IL	70 ⁽¹⁾	70 ⁽¹⁾	--	142	--	142
Argonne National Laboratory -- West, ID	70 ⁽¹⁾	70 ⁽¹⁾	83	--	95	--
Brookhaven National Laboratory, NY	70 ⁽¹⁾	70 ⁽¹⁾	--	95 ⁽²⁾	--	95 ⁽²⁾
Princeton Plasma Physics Laboratory, NJ	70 ⁽¹⁾	70 ⁽¹⁾	--	103	--	103
Idaho National Engineering Laboratory, ID	70 ⁽¹⁾	70 ⁽¹⁾	84	--	95	--
Feed Materials Production Center, OH	70 ⁽¹⁾	70 ⁽¹⁾	--	139	--	139
Oak Ridge National Laboratory, X-10, K-25, and Y-12, TN	70 ⁽¹⁾	70 ⁽¹⁾	--	113	--	113
Paduach Gaseous Diffusion Plant, KY	70 ⁽¹⁾	70 ⁽¹⁾	--	144	--	144
Portsmouth Gaseous Diffusion Plant, OH	70 ⁽¹⁾	70 ⁽¹⁾	--	110	--	110
Nevada Test Site, NV	72	72	87	--	100	--
Hanford Project Site, WA	70 ⁽¹⁾	70 ⁽¹⁾	80 ⁽¹⁾	--	90 ⁽¹⁾	--
Lawrence Berkeley Laboratory, CA	72	72	95	--	111	--
Lawrence Livermore National Laboratory, CA	72	72	96	--	113	--
Lawrence Livermore National Laboratory, Site 300, CA	80	80	104	--	125	--
Energy Technology and Engineering Center, CA	70 ⁽¹⁾	70 ⁽¹⁾	--	95 ⁽²⁾	--	95 ⁽²⁾
Stanford Linear Accelerator Center, CA	72	72	95	--	112	--
Savannah River Plant, SC	78	78	--	137	--	137

NOTES:

(1) Minimum extreme wind speed.

(2) Minimum tornado speed.

(3) Although extreme winds govern at Rocky Flats, it is recommended that facilities be designed for the tornado missile criteria. APC need not be considered.

Table 3. Recommended Basic Wind Speeds for DOE Sites.

used with the following combinations that involve wind:

- (a) $DL + W$
- (b) $0.75(DL + W + LL)$

where

DL = dead load
LL = live load
W = wind load

When using SD methods, the following load combinations that involve wind are recommended:

- (a) $0.9DL + 1.3W$
- (b) $1.2DL + 0.5LL + 1.3W$

The SD method requires that the strength provided be greater than or equal to the strength required to carry the factored loads. Appropriate strength reduction factors must be applied to the nominal strength of the material being used.

d. Important or Low Hazard Facilities

Important or Low Hazard facilities are equivalent to essential facilities (Class II), as defined in ASCE 7-88. The structure's main wind-force resisting structural systems shall not collapse at design wind speeds. Complete integrity of the building envelope is not required because no significant quantities of toxic or radioactive materials are present. However, breach of the building envelope may not be acceptable if wind or water interfere with the facility function. If loss of facility function is caused by water damage to sensitive equipment, collapsed interior partitions, or excessive damage to HVAC ducts and equipment, then loss of cladding and missile perforation at the design wind speeds must be prevented.

An annual wind speed exceedance probability of 0.02 is specified, but the importance factor for important or Low Hazard category structures is 1.07. For those sites located within 100 miles of the Gulf of Mexico or Atlantic coastlines, a slightly higher importance factor is used to account for hurricane winds.

Once the design wind speeds are established and the importance factors applied, the determination of wind loads on Important or Low Hazard category structures is identical to that described for General Use category structures. Facilities in this category may be designed by ASD or SD methods, as appropriate, for the construction material. The load combinations described for General Use structures are the same for Important or Low Hazard structures. However, greater attention should be paid to connections and anchorages for main members and components, such that the integrity of the structure is maintained, see (McDonald, 1988).

e. Moderate Hazard Facilities

The performance goal for Moderate Hazard facilities requires more rigorous criteria than is provided by standard building codes. For some DOE sites, tornadoes must be considered.

Extreme Winds and Hurricanes

For those sites where tornadoes are not a viable threat, the recommended basic wind speed is based on an annual exceedance probability of 1×10^{-3} . The importance factor is 1.0. For those sites located within 100 miles of the Gulf of Mexico or Atlantic coastlines, a slightly higher importance factor is specified to account for hurricanes.

Once the basic wind speeds are established and the importance factors applied, determination of Moderate Hazard category wind loads is identical to that described for the General Use category. Facilities in this category may be designed by ASD or SD methods, as appropriate, for the material being used in construction. Plausible load combinations shall be considered to determine the most unfavorable effect on the building, foundation, or structural member being considered. When using ASD, allowable stresses appropriate for the building material shall be used with the following wind load combinations:

- (a) $0.9(DL + W)$
- (b) $0.67(DL + W + LL)$

The SD load combinations recommended for the Moderate Hazard category are:

- (a) $DL + 1.3W$
- (b) $1.1DL + 0.5LL + 1.2W$

Greater attention should be paid to connections and anchorages for main members and components, such that the integrity of the structure is maintained, see (McDonald, 1988).

A minimum missile criteria is specified to account for objects or debris that could be picked up by extreme winds, hurricane winds, or weak tornadoes. A 2x4-in. timber plank weighing 15 lbs. is the specified missile. Its impact speed is 50 mph at a maximum height of 30 ft above ground level. The missile will break glass; it will perforate sheet metal siding, wood siding up to 3/4 in. thick, or form board. The missile could pass through a window or a weak exterior wall and cause personal injury or damage to interior contents of a building. The specified missile will not perforate unreinforced masonry or brick veneer walls or other more substantial walls.

Tornadoes

For those sites requiring design for tornadoes, the criteria are based on site-specific studies. The basic wind speed is associated with an annual hazard probability of exceedance of 2×10^{-5} . The wind speed obtained from the tornado hazard model is converted to fastest-mile. The importance factor for the Moderate Hazard category is 1.0.

With the wind speed converted to fastest-mile wind and an importance factor of 1.0, equations in the ASCE standard should be used to obtain design wind pressures on the structure. Exposure Category C should always be used with tornado winds regardless of the actual terrain roughness. The velocity pressure exposure coefficient and the gust response factor are obtained from appropriate tables in the ASCE standard. External pressure coefficients are used to obtain tornado wind pressures on various surfaces of the structure. A distinction is made between the main wind-force resisting system and components and cladding.

If the building is not specifically sealed to maintain an internal negative pressure for confinement of hazardous materials, or, if openings greater than one square foot per 1000 cubic foot of volume are present, or, if openings of this size can be created by missile perforation, then the effects of internal pressure should be considered according to ASCE procedures. If the building is sealed, then atmospheric pressure change (APC) pressures associated with the tornado should be considered.

APC pressure is half its maximum value at the radius of maximum wind speed in a tornado. Thus, critical tornado loading will be one-half the maximum APC pressure plus the maximum tornado wind pressure. A loading condition of APC alone can occur on the roof of a buried tank or sand filter, if the roof is exposed at the ground surface. APC pressure always acts outward. The effect of rate of pressure change on ventilation systems should be analyzed to assure that it does not interrupt any function or processes carried out in the facility. Procedures and computer codes are available for such analyses.

Plausible load combinations shall be considered to determine the most unfavorable effect on the building, foundation, or structural member being considered. When using ASD methods, allowable stresses appropriate for the building materials shall be used with the following load combinations that involve tornado loading.

- (a) $0.75(DL + W_t)$
- (b) $0.625(DL + W_t + LL)$

The SD load combinations recommended for the Moderate Hazard category are:

- (a) $DL + W_t$
- (b) $DL + LL + W_t$

where

W_t = tornado loading, including APC, as appropriate.

Two missiles are specified as minimum criteria for this usage category. The 2x4-in. timber plank weighing 15 lbs. is assumed to travel in a horizontal direction at a speed up to 100 mph. The horizontal speed is effective up to a height of 150 ft above ground level. If carried to a great height by the tornado winds, the timber plank could achieve a terminal vertical speed of 70 mph in falling to the ground. The horizontal and vertical speeds are assumed to be uncoupled and they should not be combined. The missile will perforate most conventional wall and roof cladding except reinforced masonry or concrete. The cells of concrete masonry walls must be filled with grout to prevent perforation by the timber missile. The second missile is a 3-in. diameter standard steel pipe, which weighs 75 lbs. It can achieve a horizontal impact speed of 50 mph and a vertical speed of 35 mph. Its horizontal speed could be effective to heights of 75 ft above ground level. The missile will perforate conventional metal siding, sandwich panels, wood and metal decking on roofs, and gypsum panels. In addition, it will perforate unreinforced concrete masonry and brick veneer walls, reinforced concrete masonry walls less than 8 in. thick, and reinforced concrete walls less than 6 in. thick. Although wind pressure, APC, and missile impact loads can act simultaneously in a tornado, the missile impact loads can be treated independently for design and evaluation purposes.

1. High Hazard Facilities

The performance goal can be achieved for this category if the main wind-force resisting members do not collapse, structural components do not fail, and the building envelope is not breached at the design wind loads. Loss of cladding, broken windows, collapsed doors, or significant missile perforations must be prevented. Strong air flow through the building or water damage cannot be tolerated.

Extreme Winds and Hurricanes

For those sites that do not require specific design for tornado resistance, the recommended basic wind speed is based on an annual hazard exceedance probability of 1×10^{-4} . The importance factor is 1.0. The wind speed is fastest-mile at an anemometer height of 10 meters above ground level.

Once the basic wind speeds are established and the importance factors applied, determination of High Hazard facility wind loads is identical to that described for the General Use category. Facilities in this category may be designed by ASD or SD methods, as appropriate, for the material being used in construction. Recommended wind load combinations are the same as for Moderate Hazard facilities. Greater attention should be paid to connections and anchorages for main members and components, such that the integrity of the structure is maintained, see (McDonald, 1988).

The missile criteria is the same as for the Moderate Hazard category, except that the maximum height achieved by the missile is 50 ft, instead of 30 ft.

Tornadoes

For those sites requiring design for tornado resistance, the criteria is based on site-specific studies. The recommended basic wind speed is associated with an annual hazard probability of exceedance of 2×10^{-5} (the same as the Moderate Hazard category). The wind speed obtained from the tornado hazard model is converted to fastest-mile. The importance factor for the High Hazard category is 1.35.

With the wind speed expressed as fastest-mile and an importance factor of 1.35, ASCE 7-88 equations should be used to obtain design wind pressures on the structure. Exposure Category C should always be used with tornado winds regardless of actual terrain roughness. The velocity pressure exposure coefficient and the gust response factor are obtained from appropriate tables in the ASCE standard. External pressure coefficients are used to obtain tornado wind pressures on various surfaces of the structure. A distinction is made between the main wind-force resisting system and components and cladding in determining wind pressures.

If the building is sealed to confine hazardous materials, the wind and APC load combinations specified for the Moderate Hazard usage category also should be used for this category. The effects of rate of pressure change on ventilating systems should be analyzed. Recommended tornado wind load combinations for Moderate Hazard facilities also apply to High Hazard facilities.

Three missiles are specified as minimum criteria for this usage category. The 2x4-in. timber plank weighs 15 lbs. is assumed to travel in a horizontal direction at speeds up to 150 mph. The horizontal missile is effective to a maximum height of 200 ft above ground level. If carried to a great height by the tornado winds, it could achieve a terminal speed in the vertical direction of 100 mph. The horizontal and vertical speeds are

uncoupled and should not be combined. The missile will perforate most conventional wall and roof cladding except reinforced masonry and concrete. Each cell of the concrete masonry shall contain a 1/2-in.-diameter rebar and be grouted to prevent perforation by the missile. The second missile is a 3-in.-diameter standard steel pipe, which weighs 75 lbs. It can achieve a horizontal impact speed of 75 mph and a vertical speed of 50 mph. The horizontal speed could be effective at heights up to 100 ft above ground level. This missile will perforate unreinforced concrete masonry and brick veneer walls, reinforced concrete masonry walls less than 12 in. thick, and reinforced concrete walls less than 8 in. thick. The third missile is a 3000-lb automobile that is assumed to roll and tumble on the ground and achieve an impact speed of 25 mph. Impact of an automobile can cause excessive structural response to columns, walls, and frames. Impact analyses should be performed to determine specific effects. Collapse of columns, walls, or frames may lead to further progressive collapse.

g. Tornado Missile Impact Tests

Wall barrier specimens have been tested at the Tornado Missile Impact Facility at Texas Tech University. The facility has an air activated tornado missile cannon capable of firing 2x4 timber planks weighing 12 pounds up to 150 mph and 3 in. dia. steel pipes weighing 75 pounds at speeds to 75 mph.

Wall barriers tested to date include reinforced concrete walls from 4 in. to 10 in. thick; 8 in. and 12 in. walls of reinforced Concrete Masonry Units (CMU); and two other masonry wall configurations consisting of an 8 in. CMU and 4 in. clay brick veneer; and a 10 in. composite wall having two wythes of 4 in. clay brick.

The impact test series was designed to determine the impact speed to produce backface spall of each wall barrier. A set of 15 wall sections have been constructed and tested at this time. Preliminary findings suggest that all cells of CMU walls must be grouted to prevent missile penetration. Results of these impact test as well as previous available test data will be compared with existing impact formulas. In particular, the Rotz Equation and the Modified NDRC formula are being examined. A new impact formula for CMU walls is being developed. Results of this study are being assembled into a report which should be available in summer 1991.

h. Comments on Load Combinations

The ratios of hazard probabilities to performance goal probabilities for the usage categories as shown in Table 4 are an approximate measure of the conservatism required in the design to achieve the performance goals. The most conservatism is needed in the response evaluation and acceptance criteria for design

of General Use and Important or Low Hazard facilities. Somewhat less conservatism is needed for Moderate and High Hazard facilities. The hazard probabilities specified for tornadoes are less than the performance goal probabilities. Hence, the performance goals are theoretically met with no added conservatism in the design.

Conservatism can be achieved in designs by specifying factors of safety for Allowable Stress Design (ASD) and load factors for Strength Design (SD). Consistent with the ratios in Table 4, the loading conditions recommended for design for DOE facilities are summarized in Table 5.

plants as given in ACI 349 for concrete and ANSI/AISC N690 (AISC, 1984) for steel.

Additional background material on wind and tornado effects can be found in (McDonald, 1985a; McDonald, 1985b). A commentary on the design criteria summarized there is also included in Appendix B of (Kennedy et al. 1990).

5. Summary and Conclusions

UCRL-15910 is an example of deterministic design/evaluation criteria developed to achieve

Usage Category	Performance Goals	Wind/Tornado Hazard Probability	Ratio of Hazard Probability to Performance Goal
Extreme Winds			
General Use	10^{-3}	2×10^{-2}	20
Important or Low Hazard	5×10^{-4}	$10^{-2(1)}$	20
Moderate Hazard	10^{-4}	10^{-3}	10
High Hazard	10^{-5}	10^{-4}	10
Tornadoes			
Moderate Hazard	10^{-4}	2×10^{-5}	<1
High Hazard	10^{-5}	$3 \times 10^{-6(2)}$	<1

(1) 2×10^{-2} with $I = 1.07 \sim 10^{-2}$

(2) 2×10^{-5} with $I = 1.35 \sim 3 \times 10^{-6}$

Table 4. Ratio of Hazard Probability to Performance Goal

Since the ratio of extreme wind hazard probability to performance goal probability for General Use and Important or Low Hazard facilities are the largest, 20, designs for these categories should be the most conservative in terms of factors of safety for ASD and load factors SD. The recommended combinations are essentially those given in ASCE 7-88, (ASCE, 1990). The recommended load combination for Moderate and High Hazard facilities are slightly less conservative than for the General Use and Important or Low Hazard categories, because the ratio of extreme wind hazard probability to performance goal probability is less (10). The load factor coefficients have been reduced by approximately 10 percent.

The tornado hazard probabilities for both Moderate and High Hazard facilities are less than the performance goal probabilities. The tornado load combinations for both ASD and SD recognize that the performance goals are theoretically met and no added conservatism in the load combination is required. This approach is consistent with criteria for commercial nuclear power

probabilistic performance goals. UCRL-15910 also covers seismic and flood as well as wind and tornado criteria as discussed in this paper. The criteria developed is consistent with the consensus standard ASCE 7-88 and required by DOE General Design Criteria, (DOE, 1989). Conservatism is specified which is sufficient to achieve the performance goals. This conservatism increases from general use to high hazard usage category.

The UCRL-15910 wind/tornado design and evaluation guidelines follow the philosophy of: (1) gradual reduction in hazard annual exceedance probability; and (2) gradual increase in conservatism of evaluation procedure as one goes from a General Use to a High Hazard facility. Four separate sets of design/evaluation criteria have been presented in UCRL-15910, each with a different performance goal. In all these criteria, loading is selected from hazard curves on a probabilistic basis but response evaluation methods and acceptable behavior limits are deterministic approaches with which design engineers are familiar.

Facility		General Use	Important or Low Hazard	Moderate Hazard	High Hazard
ASD	Extreme Winds	$DL + W$ $0.75(DL + LL + W)$	$DL + W$ $0.75(DL + LL + W)$	$0.9(DL + W)$ $0.67(DL + LL + W)$	$0.9(DL + W)$ $0.67(DL + LL + W)$
	Tornadoes			$0.75(DL + W_t)$ $0.63(DL + LL + W_t)$	$0.75(DL + W_t)$ $0.63(DL + LL + W_t)$
SD	Extreme Winds	$0.9DL + 1.3W$ $1.2DL + 0.5LL + 1.3W$	$0.9DL + 1.3W$ $1.2DL + 0.5LL + 1.3W$	$DL + 1.3W$ $1.1DL + 0.5LL + 1.2W$	$DL + 1.3W$ $1.1DL + 0.5LL + 1.2W$
	Tornadoes			$DL + W_t$ $DL + LL + W_t$	$DL + W_t$ $DL + LL + W_t$

ASD = Allowable Strength Design

Use allowable stress appropriate for building material

SD = Strength Design

Use ϕ factors appropriate for building material

DL = Dead Load

LL = Live load

W = Extreme wind load

W_t = Tornado load, including APC if appropriate

Table 5. Summary of recommended wind and tornado load combinations.

6. References

American Concrete Institute, 1985: Code Requirements for Nuclear Safety-Related Concrete Structures (ACI 349-85) and Commentary-ACI 349R-85, Detroit, Michigan.

American Institute of Steel Construction, Inc., 1984: Nuclear Facilities-Steel Safety-Related Structuring for Design, Fabrication, and Erection, ANSI/AISC N690, Chicago, Illinois.

ASCE, 1990: Minimum Design Loads for Building and Other Structures, ASCE 7-88 (formerly ANSI A58.1), American Society of Civil Engineers.

Coats, D.W. and R.C. Murray, 1985: Natural Phenomena Hazards Modeling Project: Extreme Wind/Tornado Hazard Models for Department of Energy Sites, Lawrence Livermore National Laboratory, Report UCRL-53526 Rev. 1.

DOE, 1989: U.S. Department of Energy, General Design Criteria, DOE Order 430.1A, Washington, D.C.

EPRI, 1990: Advanced Light Water Reactor Requirements Document, Volume 1, ALWR Policy and Summary of Top-Tier Requirements, Final Draft for Review, Electric Power Research Institute, Palo Alto, California.

ICBO, 1988: Uniform Building Code, 1988 Edition, International Conference of Building Officials, Whittier, California.

Kennedy, R.P., S.A. Short, J.R. McDonald, M.W. McCann, R.C. Murray, and J.R. Hill, 1990: Design and Evaluation Guidelines For Department of Energy Facilities Subjected to Natural Phenomena Hazards, Lawrence Livermore National Laboratory, Report UCRL-15910.

Kimura, C. Y. and R. J. Budnitz, 1987: Evaluation of External Hazards to Nuclear Power Plants in the United States, NUREG/CR-5042, Lawrence Livermore National Laboratory, Report UCID-21223.

McDonald, J.R., 1985a: Extreme Winds and Tornadoes: An Overview, Lawrence Livermore National Laboratory, Report UCRL-15745.

McDonald, J.R., 1985b: Extreme Winds and Tornadoes: Design and Evaluation of Buildings and Structures, Lawrence Livermore National Laboratory, Report UCRL-15747.

McDonald, J.R., 1988: Structural Details for Wind Design, Lawrence Livermore National Laboratory, Report UCRL-21131.

NRC, 1974: Regulatory Guide 1.76, U.S. Nuclear Regulatory Commission, Washington, D.C.

Ravindra, M. K. and A. M. Na'day, 1990: State-of-the-Art and Current Research Activities in Extreme Winds Relating to Design and Evaluation of Nuclear Power Plant B, NUREG/CR-5497.