TORNADO MISSILE DESIGN FOR NUCLEAR POWER PLANTS

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Abstract

Nuclear power plants are designed to be capable of safely shutting-down in case of a large design-basis tornado or hurricane. The magnitude of the postulated design-basis tornado or hurricane is such that there is less than 1 in 10 million chance (1E-7) per year and per reactor that it would be exceeded. This probability governs the wind speeds, pressures, and missiles generated by the tornado and provide the engineers a basis for design of the plant structures, systems, and components.

In 2015, the US NRC issued Regulatory Issue Summary 2015-06 “Tornado Missile Protection” to remind licensees, as they implement post-Fukushima upgrades for natural phenomena hazards, of the need to conform to deterministic, site-specific licensing basis for tornado-generated missile protection.

This paper consists of three parts.

- Part 1 is an overview of the NRC regulations which govern tornado and hurricane design for nuclear power plants.
- Part 2 is a timeline of key developments in tornado design for nuclear power plants, which spans 70 years, with an emphasis on tornado missiles.
- Part 3 presents the analytical options to simulate the effects of tornado missiles on steel stack targets.

PART 1 - Road Map to Regulatory Requirements

General Design Criteria

The protection of nuclear power plants for the effects of tornadoes (or extreme winds from typhoons or hurricanes, depending on the locality) is required through 10CFR50 Appendix A, General Design Criterion 2 which requires that structures, systems, and components (SSCs) important to safety be designed to withstand the effects of natural phenomena such as tornadoes.

Standard Review Plan

The methods and criteria for the design of SSCs against the effects of tornadoes are addressed in the following Sections of NUREG-0800 (Standard Review Plan):

Section 2.3.1 addresses regional climatology. This Section refers to RG 1.76 for the postulated design-basis tornado parameters.

Section 3.3.2 addresses tornado loadings. This Section defines the three effects to be addressed:

- Tornado winds, considering translational and rotational wind speeds.

- Tornado-generated atmospheric pressure differentials across the interior and exterior of enclosed or partially-enclosed structures.

- Tornado missile impacts on exposed SSCs.

Regarding design rules, Section 3.3.2 refers to:

(a) ASCE-7 for calculating the wind pressure on SSCs.

(b) RG 1.76 and the textbook by Simiu and Scanlan for differential pressure loads.

(c) RG 1.76 and Section 3.5.3 for tornado missiles.

Section 3.5.1.4 addresses missiles generated by tornadoes and extreme winds. This Section refers to RG 1.76 for tornado missiles and to RG 1.221 for hurricane missiles.

Section 3.5.2 provides guidance to identify the SSCs that must be protected from externally-generated missiles.

Section 3.5.3 addresses the barrier design procedures. This Section points out the need to address local effects and overall response (global effects):

Local Effects

Local effects on concrete include penetration (crater) or perforation (full penetration), spalling (at the impact face) and scabbing (at the opposite face). This Section refers to the 1976 paper by R.P. Kennedy, the National Defense Research Committee (NDRC) formula, and it provides a Table of minimum concrete wall and roof thicknesses, by Tornado Region.

Local effects on steel include penetration (crater) or perforation (full penetration). This Section refers to the 1959 Stanford Research Institute (SRI) empirical formula (Zabel et. al., ORNL TID-4500, 1965), and the 1971 Ballistic Research Laboratory (BRL) empirical formula (Grabarek, BRL-MR-2134) if it leads to results comparable to SRI.

Global Effects

For global effects on concrete or steel, this Section refers to the 1973 paper by Williamson and Alvy, with ductility capacities from N-690-1994 with 2004 supplement.

Regulatory Guides

RG 1.76 provides three key design inputs: The tornado wind speeds, the differential atmospheric pressures, and the characteristics of tornado missiles.

RG 1.76 Tornado Wind Speed and Pressure Drop: The tornado intensity regions for the contiguous United States for exceedance probabilities of 10-7 per year. Three Regions are defined:

- Region I, central US, at 230 mph (1.2 psi atmospheric pressure drop)

- Region II, eastern US and great plains, at 200 mph (0.9 psi atmospheric pressure drop)

- Region III, western US, at 160 mph (0.6 psi atmospheric pressure drop)

In all three cases, the translational speed is 20% and the rotational speed is 80% of the total speed.

RG 1.76 Tornado Missiles - The tornado missiles are described as objects lying within the path of the tornado wind and debris of nearby damaged structures. The postulated types of missiles have changed over the years, as described in the Chronology below: Most plants were designed for a wooden plank, wooden telephone pole, two steel pipes, an automobile, and - for probing the potential for penetration - a 1 in. steel rod, see Figure 1. In 2007, the 6 missiles were replaced by 3 missiles.

RG 1.221 Design-Basis Hurricane and Hurricane Missiles for Nuclear Power Plants – This guidance applies to the United States, excluding sites located along the Pacific coast or in Alaska, Hawaii, or Puerto Rico. These would be evaluated on a case-by-case basis.

PART 2 - Roadmap to Methods and Criteria for the Analysis of Tornado Missiles

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1946

The National Defense Research Committee (NDRC) publishes the “Effects of Impact and Explosions” which contains empirical (test-based) formulas for the penetration of fragments. These formulas remain valid today for the analysis of the potential for missiles to penetrate nuclear power plant structures and components.

1957

The BRL perforation formula is published by Jameson and Williams, "Velocity Losses of Cylindrical Steel Projectile Perforating Mild-Steel Plates," Report No. 1019, Ballistic Research Laboratories, July, 1957. As is the case with the NDRC formula, the BRL formulas remain valid today for the analysis of the potential for missiles to penetrate nuclear power plant structures and components.

1957

Hoecker publishes “Wind Speed and Air Flow Patterns in the Dallas Tornado of April 2, 1957”. This paper, which provides velocity field data and damage observations, will be referenced by the Oak Ridge and Texas Tech. reports in developing tornado missile for nuclear power plants (see below).

1960

"The Tornados at Dallas, Texas, April 2, 1957," Research Paper No. 41, US Weather Bureau, Washington, D.C., 1960

To that date, the most comprehensive observation of a tornado made to that date was that of the Dallas, Texas, tornado of 2 April 1957.

1960

"Wind Speed and Air Flow in the Dallas Tornado of April 2, 1957," Monthly Weather Review, 88, 5, 167, 1960 W. H. Hoecker, Jr.

Hoecker employed photogrammetric analysis of a large number of motion pictures of that storm to deduce the related low-level wind field.

1963

Ballistic Perforation Dynamics

R. F. Recht and T. W. Ipson, Denver Research Institute of The University of Denver, Transactions of the ASME September 1963

Analytical equations of the types required to define ballistic perforation dynamics are developed. These equations concern both blunt and sharp-nosed fragments, perforating plates normally and at oblique impact angles. Residual velocities are defined in terms of magnitude and direction. Analytical models and confirming experimental data, which are presented here, specifically concern the ballistic velocity-impact range to about 25 percent of the velocity of longitudinal sonic waves in the impacting materials.

This paper is referenced in Standard Review Plan Section 3.5.3 Barrier Design Procedures.

1965

Buckling of Thin-Walled Circular Cylinders, NASA, Space Vehicle Design Criteria (Structures), NASA SP-8007, September 1965 Revised August 1968

This monograph indicates current practices for predicting buckling of uniform stiffened and unstiffened circular cylindrical shells under various types of static loading, and suggests the procedures that yield estimates of static buckling loads considered to be conservative.

1965

US Reactor Containment Technology, A Compilation of Current Practice in Analysis, Design, Construction, Test, and Operation, ORNL-NSIC-5, August 1965, Wm. B. Cottrell and A. W. Savolainen, editors, Section 6.6 Shock and Missile Protection Missile generation: Shock-generated missile; self-propelled missile; jet-propelled missile; spalling.

Penetrability of shells: Penetration experiments.

Blast shielding: Theory; absorption mechanisms; criteria for ideal absorbers; reduction factors; materials; absorber thickness; composite design.

The resulting test-based penetration formulas are still referenced today in the NRC Standard Review Plan (SRP) Section 3.5.3 (2007).

1967

Tornado Design Considerations for Nuclear Power Plants, F. C. Bates (St. Louis U), A. E. Swanson (Black & Veatch), Transactions of the American Nuclear Society, Nov./Dec. 1967

A basis for the quantitative evaluation of possible missiles and their impact speeds can be established using the following information: 1) The vector wind distribution at the significant depth and radius; 2) The pressure distribution; 3) Missile injection methods; 4) Aerodynamic modes in which objects may exist in the tornadic flow; 5) Application of the above to a range of objects injected into a "maximum intensity" tornado. The paper addresses three modes in which objects can be injected upward into the flow field of the tornado, together with a suggested analytical relationship for the height of injection.

1968

Missile Generation and Protection in Light-Water -Cooled Power Reactor, R. C. Gwaltney, Oak Ridge National Laboratory, ORNL-NSIC-22, September 1968

The state of the then current technology of missile generation and protection in relation to the design of nuclear power plants is presented. Practices in other industries are discussed, and the available calculation techniques and their bases and deficiencies are described. A general description is also included of the cause and nature of shock waves, the various kinds of missiles that could be generated in the event of rupture of a primary system vessel, and the considerations involved in designing to protect against the harmful effects of shock waves and missiles. A summary of the current practice for nuclear power reactor de-signs is given, gaps in the relevant current technology are discussed, and recommendations are made for further research and development.

1969

Characteristics of Tornado Generated Missiles, D. F. Paddleford, Westinghouse, Pittsburgh, PA, April 1969, WCAP-7987

In this report, following the procedure suggested by Bates and Swanson (1967), the wind field of a tornado has been described using relations appearing in the technical literature and solutions of the trajectory of a spectrum of typical objects that could be postulated as potential tornado missile sources: A 3,940-lb automobile, a 35-ft long 14-in wooden diameter utility pole, a 12-ft long 8-in diameter wooden utility pole, an 18-ft long 4-in diameter wood fence post, a 10-ft long 4-in thick wood deck plank, a two-by-four, a 9-in brick, a 1/2-in diameter steel rod, a 2-in thick section of a concrete slab. The WCAP introduces the importance of the missile flight parameter CD A / W (CD = drag coefficient, A = area exposed to wind force, W = weight of missile).

1969

Structures to Resist the Effects of Accidental Explosions, Department of the Army, the Navy, and the Air Force, Tech Manual TM 5-1300 (June 1969).

1971

Penetration of Armor by Steel and High Density Penetrators, C. Grabarek, Ballistic Research Laboratory BRL-MR-2134 (1971) AD 518394L.

1971

Tetsuya Fujita introduces the Fujita scale to rate tornadoes.

1972

ANSI A58.1 “Building Code Requirements for Minimum Design Loads in Buildings and Other Structures” provided wind load criteria based on probabilistically determined wind speed and tabulated forms of design load parameters. Later, these rules were moved to ASCE 7.

1972

Design Criteria for Missile Effects, B. Bedrosian, Burns & Roe memorandum, 1972

Provides missile penetration formula based on Navy “Design of Protective Structures” Technical publication NAVDOCKS P-51, 1953

1973

Bechtel issues BC-TOP-9 Rev.1. This is a systematic procedure for the analysis and qualification of concrete and steel targets to a tornado missile strike. In the period 1973-1975 similar reports are prepared by most Architect Engineers: Gilbert’s CAI-TR-102, TVA’s TVA-Tr74-1, Ebasco’s ETR-1003, Brown and Root’s U&R -001, Bechtel’s BC-TOP-9A, United Engineer’s UEC-TR-002-0, etc.

1973

Impact Effect of Fragments Striking Structural Elements, R. A. Williamson and R. R. Alvy, Holmes & Narver, Anaheim, CA, 1973

This paper is aimed directly at the effect of those fragments resulting from an explosion within a pressure vessel of a nuclear power reactor. The equations derived are applicable to any missile of known mass travelling at a specific velocity. An expression is derived for the required yield resistance of the beam in terms of the mass and velocity of the fragment, and the ductility factor and period of vibration of the beam.

This paper is referenced in Standard Review Plan Section 3.5.3 Barrier Design Procedures.

1973

Tornado Resistant Design, T. L. Anderson presentation

A slide presentation which provides the state-of-the-art in tornado design as of the early 1970's.

1973

Large Diameter Pipe under Combined Loading, J. G. Bouwkamp, and R. M. Stephen (U. of California Berkley), Transportation Engineering Journal, TE3, August 1973

The paper presents the results of a full-scale laboratory test of the structural behavior of the 48-in. dia. pipeline, under the combined effect of axial compression and lateral load, resulting in the wrinkling of the pipe wall, and the ultimate rupture of the pipe. The data can be used to benchmark the effect of tornado missile impact on pipes and steel stacks.

1974

Technical Basis for Interim Regional Tornado Criteria, US AEC Office of Regulation, May 1974, WASH 1300

The objective of this study was to determine a design basis tornado for the United States from an analysis of tornado data from the National Weather Service Offices. Three regions are defined with associated tornado severity, probable wind speed, upper bound pressure drop, and frequency of occurrence.

Defines the design basis tornado wind speeds and pressure drops (not missiles) for the three regions (approximately I east and central, II mountain, III pacific).

1974

Design Basis Tornado for Nuclear Power Plants, Regulatory Guide 1.76, U.S. Atomic Energy Commission (April 1974).

Provides the tornado wind speeds (based on WASH-1300), but does not specify tornado missiles. The NRC based this original version of RG 1.76 on WASH-1300 (see above) which determined that the probability that a tornado exceeding the design basis would occur to be on the order of 1E-7 per year per nuclear power plant.

1974

Tornado-Resistance Design of Nuclear Power Plant Structures, J. R. McDonald, K. C. Mehta, J. E. Minor (Texas Tech. U.)

The paper reviews the Atomic Energy Commission (AEC) design-basis tornado from Regulatory Guide 1.76 and the probable values of the tornado characteristics (maximum wind speed, rotational speed, translational speed, radius of maximum rotational wind, pressure drop, rate of pressure drop.) Tornado missiles are listed as the 4-in x 12-in x 12 ft long wood plank, 3-in sch.40 x 10 ft long pipe, 1-in dia. x 3 ft long steel rod, 6-in sch.40 x 15 ft long pipe, 12-in sch.40 x 15 ft long pipe, 13.5-in x 35 ft long utility pole, 4000 lb automobile. Recognizes Paddleford's missile flight parameter, but also that there are still questions related to the postulated tornado missiles.

1975

Development of a Design Basis Tornado and Structural Design Criteria for Lawrence Livermore Laboratory's Site 300, California, November 1975, J. R. McDonald, K. C. Mehta, J. E. Minor (Texas Tech. U.)

One of a series of reports prepared for the various US DOE facilities. The purpose of this document is to prescribe the tornado parameters, and to provide guidance for the evaluation of existing critical facilities to resist the effects of postulated tornadoes.

1975

Results of Missile Impact Tests on Reinforced Concrete, J. V. Rotz

Second Specialty Conference on Structural Design of Nuclear Plant Facilities, New Orleans, Louisiana, December 8-10 (1975).

1975

Missile Impact Testing of Reinforced Concrete Panel Calspan Corporation,, F. A. Vassallo, Bechtel, Buffalo, New York (January 1975).

The Calspan tests consisted of the following 8-in diameter missiles: (a) Wooden pole (200 lb), (b) Steel slug, (c) Steel pipe (132 lb). Missile velocities ranged from 100 ft/sec to 500 ft/sec. Reinforced concrete test panels were 9 by 9 ft and had thicknesses of 12, 18 and 24 in. The concrete strength ranged from 4400 to 5800 psi.

1975

Rev.0 of NRC SRP 3.5.1.4 “Missiles Generated by Tornadoes” is published. It contains two groups (spectra) of missiles:

Missile Spectrum A

- Wood plank; 4 in. x 12 in. x 12 ft.; weight 200 lb.; 0.8 fraction of total tornado velocity

- Steel pipe; 3 in. diameter, schedule 40 10 ft long; weight 78 lb.; 0.4

- Steel rod; 1 in. diameter x 3 ft long; weight 8 lb; 0.6

- Steel pipe; 6 in. diameter, schedule 40 15 ft long; weight 285 lb.; 0.4

- Steel pipe; 12 in. diameter, schedule 40 15 ft long; weight 743 lb.; 0.4

- Utility pole, 13-1/2 in. diameter 35 ft long; weight 1490 lb.; 0.4

- Automobile, frontal area 20 ft2; weight 4000 lb.; 0.2

Missile Spectrum B

- Wood plank; 4 in. x 12 in. x 12 ft.; weight 200 lb.; 368 ft/sec

- Steel pipe; 3 in. diameter, schedule 40; 15 ft long; weight 115 lb.; 268 ft/sec

- Steel Rod; 1 in. diameter x 3 ft long; weight 8 lb. 259 ft/sec

- Steel pipe; 6 in. diameter, schedule 40, 15 ft long; weight 285 lb.; 230 ft/sec

- Steel pipe; 12 in. diameter, schedule 40, 30 ft long; weight 1500 lb.

- Utility pole; 14 in. diameter, 35 ft long; weight 1500 lb.; 241 ft/sec

- Automobile; frontal area 20 ft2, weight 4000 lb., 100 ft/sec

These missiles are considered to be capable of striking in all directions with vertical velocities equal to 80% of the acceptable horizontal velocities. Missiles A, B, C, D, and E are to be considered at all elevations and missiles F and G at elevations up to 30 feet above all grade levels within 1/2 mile of the facility structures.

1976

Tornado-Born Missile Speeds, E. Simiu, Institute of Applied Technology, National Bureau of Standards, Washington DC., April, 1976, NBSIR 76-1050

The report proposes a model for the missile motion, and numerical analyses are carried out corresponding to various assumptions on the initial conditions of the missile motion, the structure of the tornado flow, and the aerodynamic properties of the missile. The vertical missile velocity is given as 2/3 the horizontal speed.

1976

A Review of Procedures for the Analysis and Design of Concrete Structures to Resist Missile Impact Effects, R. P. Kennedy, Holmes & Narver, Nuclear Engineering and Design. Volume 37, Number 2. 183-203. 1976.

The paper reviews several empirical equations, such as the modified National Defense Research Council (NDRC) formula to estimate missile penetration into concrete, and to help determine missile protection barrier thicknesses.

This paper is referenced in Standard Review Plan Section 3.5.3 Barrier Design Procedures.

1977

Twelve-inch Steel Pipe Impact Test of Three-Fourths-Foot Steel Test Panel, Calspan Company Report No. HC-5958-X-1, Buffalo, NY.

1977

Numerical Simulation of Tornado-Born Missile Impact, UCRL-52223, D. K. Tu, R. C. Murray, Lawrence Livermore National Laboratory, February 8, 1977

This study assesses the feasibility of using finite element analysis for the impact of an 8-in diameter non-deformable tornado-borne missile on a reinforced concrete barrier. The numerical results were then compared with experimental field tests and empirical formulas. In comparing the full-scale test results with empirical formulas, the Modified NDRC formula and the Bechtel formula were found to be valid. In predicting the scabbing threshold, the finite element method compared closer with the Modified NDRC formula than the Bechtel formula. The recommended 25% increase of Bechtel's formula in predicted scabbing threshold thickness brings the Bechtel formula in line with the predictions of the Modified NDRC formula and the finite element method.

1977

Full-Scale Tornado Missile Impact Tests, EPRI NP-440 (Research Project 399) (Sandia Report SAND77-1166), Final Report, July 1977

Poles, pipes, and rods were propelled into 12-in, 18-in, and 24-in thick, 15 ft2 reinforced concrete panels. The 1500-pound utility pole, 1-inch rod, and 3-inch pipe did not produce significant local and structural damage. The 12-inch pipes produced craters in the face of the tests. The 18-in thick wall is adequate to prevent back scabbing in the highest tornado-intensity region of the U.S., while 12-inch thick walls are adequate in other regions. Penetration depth and scabbing threshold for the 12-inch pipe impacts matched reasonably well the modified NDRC formula.

1978

Standardizing the Evaluation of Candidate Materials for High L/D Penetrators, E. L. Herr, C. Grabarek, US Army Armament Research and Development Command Memorandum Report ARBRL-MR-02860, September 1978

A procedure using penetration performance criteria for characterizing and evaluating the potential of candidate materials for use as kinetic energy penetrators has been developed. The report provides ballistic penetration formula.

1978

SRP 3.5.1.4 missiles generated by tornadoes Rev.1.

1979

Tornado Missile Transport Analysis, L. A. Twisdale, W. L. Dunn (N.C. State U., Raleigh), T. L. Davis, Nuclear Engineering and Design 51 (1979) 295-308, North-Holland Publishing Co.

The paper presents an algorithm to simulate the release and motion of objects transported by tornadoes. A probabilistic three-degree-of-freedom trajectory model which includes drag, lift, and side forces has been developed to simulate rigid body dynamics in turbulent tornado flow fields.

1980

Simulation of Tornado-Generated Missiles, D. A. Malaeb (Texas Tech. U.)

The thesis develops a procedure for the simulation of tornado-generated missiles on the basis of the wind field model (such as Bates and Swanson or Paddleford), the aerodynamic flight parameters (drag force, tumbling), the initial conditions (injection into the wind field), and the degrees of freedom of dynamic model. Results are compared to post-storm observations of missiles that were transported by the Bossier City (Louisiana) tornado of December 3, 1978.

1981

SRP 3.5.1.4 missiles generated by tornadoes Rev.2

Spectrum I missiles are defined as: An 1800 Kg automobile, a 125. Kg 8" armor piercing artillery shell, and a 1" solid steel sphere, all impacting at 35% of the maximum horizontal windspeed of the design basis tornado. The first two missiles are assumed to impact at normal incidence, the last to impinge upon barrier openings in the most damaging directions.

Alternately, Spectrum II missiles are defined as the missiles selected by the National Bureau of

Standards as representative of construction site debris in report NBSIR 76-1050. Tornado regions are defined in WASH-1300:

Missile; Mass (Kg); Dimensions (m); Velocity (m/sec) Region I / Region II / Region III:

- A Wood Plank; 52; .092 x .289 x 3.66; 83 / 70 / 58

- B 6" Sch 40 pipe; 130; .168 D X 4.58; 52 / 42 / 10

- C 1" Steel rod; 4; .0254D x .915; 51 / 40 / 8

- D Utility pole; 510; .343D x 10.68; 55 / 48 / 26

- E 12" Sch 40 pipe; 340; .320 x 4.58; 47 / 28 / 7

- F Automobile; 1810; 5 x 2 x 1.3; 59 / 52 / 41

Vertical velocities of 70% of the postulated horizontal velocities are acceptable in both spectra except for the small missile in Spectrum I or missile C above. These missiles, which are used to test barrier openings, should be assumed to have the same velocity in all directions. Missiles A, B, C, and E are to be considered at all elevations and missiles D and F at elevations up to 30 Feet above all grade levels within 1/2 mile of the facility structures.

1983

A Survey of Penetration Mechanics for Long Rods, T. W. Wright, Ballistic Research Laboratory, Aberdeen Proving Ground, MD. Some of the simpler methods in current use for analyzing ballistic impacts by long rod penetrators are reviewed and critiqued.

1983

The NRC approves TORMIS in a safety evaluation report (SER), dated October 26, 1983 (ML080870291) and staff position (ML080870287) for use "in lieu of the deterministic methodology when assessing the need for positive tornado missile protection for specific safety-related plant features …"

From this time forward, plants may evaluate non-protected SSCs using TORMIS and other probabilistic methodology, with approval of license amendment and change to the licensing bases.

1996

SRP 3.5.1.4 missiles generated by tornadoes Rev.3 draft.

1996

Information Notice (IN) 96-06 (ML031060290) - Design and Testing Deficiencies of Tornado Dampers at Nuclear Power Plants.

2006

Draft RG 1.76 Rev.1 Draft introduces tornado design-basis wind speeds corresponding to the exceedance frequency of 1E-7 per year are lower than those given in the original version of RG 1.76.

Three new missiles are introduced (see 2007 RG 1.76 below).

2006

SRP 3.5.1.4 missiles generated by tornadoes Rev.3 second draft: deletes the characteristics of the postulated missile, and refers back to RG 1.76.

2006

Regulatory Issue Summary (RIS) 2006-23 (ML061720371) - Post-tornado Operability of Ventilating and Air-conditioning Systems Housed in Emergency Diesel Generator Rooms.

2007

NUREG/CR-4461, Tornado Climatology of the Contiguous United States

This NUREG included data recorded for more than 46,800 tornado segments occurring from January 1, 1950, through August 31, 2003.

2007

The National Weather Service implements the Enhanced Fujita Scale, which is a revised assessment relating tornado damage to windspeed.

2007

SRP 3.5.1.4 missiles generated by tornadoes Rev.3.

2007

RG 1.76 “Design Basis Tornado and Tornado Missiles for Nuclear Power Plants”.

A new set of tornado missiles is introduced: A 6 in. pipe, the automobile, and a 1 in. solid steel sphere (bullet-like, instead of the previous rod).

The NRC considers the missiles listed in Table 2 to be capable of striking in all directions with horizontal velocities and at vertical velocities equal to 67 percent of the maximum horizontal velocity . Barrier design should be evaluated assuming a normal impact to the surface for the Schedule 40 pipe and automobile missiles.

The automobile missile is considered to impact at all altitudes less than 30 feet (9.14 meters) above all grade levels within 0.5 mile (0.8 kilometer) of the plant structures. Table 2 includes a different size and weight automobile for Region III than for Regions I and II. The heavier automobile used in the calculations for Regions I and II will have a lower kinetic energy in Region III. This effect is a consequence of the low maximum horizontal speed VMh of the heavier automobile in the Region III tornado wind field.

2008

RIS 2008-14 (ML080230578) - Use of TORMIS Computer Code for Assessment of Tornado Missile Protection.

2011

RG 1.221 “Design Basis Hurricanes and Hurricane Missiles for Nuclear Power Plants” Missile Type Dimensions Mass:

- Automobile 5 m × 2 m × 1.3 m (16.4 ft x 6.6 ft x 4.3 ft); 1,810 kg; (4,000 lb)

- Schedule 40 Pipe 0.168 m dia × 4.58 m long (6.625 in. dia × 15 ft long); 130 kg (287 lb)

- Solid Steel Sphere 25.4 mm (1 in.) diameter 0.0669 kg (0.147 lb)

2013

SRP 3.5.1.4 missiles generated by tornadoes Rev.4 draft.

2015

SRP 3.5.1.4 missiles generated by tornadoes Rev.4

Initiating frequency of tornado missiles is reported as 1E-7 per year or greater.

2015

NEI white paper HCVS-WP-04 Missile Evaluation of HCVS Components 30 ft Above Grade, August 2015

The purpose of this white paper is to provide a reasonable protection evaluation of the BWR Hardened Containment Vent System (HCVS) against the external hazard of wind-borne missiles that cause an Extended Loss of AC Power (ELAP) or a Loss of the Ultimate Heat Sink (LUHS).

2015

Impact Analysis of Reinforced Concrete Panels for Wind-Born Missiles, B. Terranova, A. Whittaker, L. Schwer, and A. J. Aref (U. of Buffalo, NY), Transactions, SMiRT-23, Manchester, UK - August 10-14, 2015

The classic empirical formulae as well as LS-DYNA models are used to predict penetration, scabbing and perforation for tornado missiles, and compared to the 1970s EPRI and Calspan tests.

2015

NRC Regulatory Issue Summary 2015-06 Tornado Missile Protection

The U.S. Nuclear Regulatory Commission (NRC) issued this regulatory issue summary (RIS) to (1) remind licensees of the need to conform with a plant's current, site-specific licensing basis for tornado-generated missile protection, (2) provide examples of failure to conform with a plant's tornado-generated missile licensing basis, and (3) remind licensees of the staff's position that a licensee's systematic evaluation program (SEP) and individual plant examination of external events (IPEEE) results do not constitute regulatory requirements and are not part of the plant-specific licensing basis unless the NRC or licensee took action to specifically amend the operating license.

2015

Enforcement Guidance Memorandum (EGM) 15-002 (ML15111A269) – Enforcement Discretion for Tornado-generated Missile Protection Noncompliance.

PART 3 – Methods of Analysis

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The targets for tornado missiles are typically structures, systems, and components that have to perform a function during or after the tornado strikes. These functions could be classified in four categories:

- A barrier function to prevent missile penetration, such as walls, roofs, and purpose-designed shields made of reinforced concrete, steel, or heavy grating.
- A passive pressure boundary function to prevent out-leakage, such as preventing the failure (puncture leak or tearing) of a steam line inside a building, by impact of the portion that is outside the building.
- A passive flow area function, such as maintaining a minimum flow cross-sectional area of a steel stack or pipe outside buildings.
- An active function, for active mechanical or electrical equipment, to permit the equipment to continue to operate after a tornado strike.

In this paper we limit ourselves to steel stack (or pipe) targets. There are basically four analytical tools to investigate the effects of tornado missiles on steel stacks:

- Empirical (test-based) methods to evaluate the local effects of missiles, in the form of penetration and perforation.
- Energy balance methods to estimate the deformation or an equivalent static load for the global structural response of targets.
- Hydrocodes to analyze the penetration of the target by a sharp missile, using for the ballistics.
- Explicit, strain-based, finite element methods to analyze the global effects (deformation and buckling), and local effects (penetration and tearing) of the steel target.

Empirical Formulas for Local Effects

As described in PART 1 of this paper, these formulas, first developed for ballistics research have been used in tornado missile design since the 1960’s. A commonly used solution is that developed by Christman and Gehring for the US Army Ballistic Research Laboratory, the BRL formula, for steel perforation thickness. References to the empirical formulas can be found in several places, including ASCE’s “Structural Analysis and Design of Nuclear Plant Facilities”, Chapter 6 “Design against Impulse and Impact Loads”. Some of the empirical formula are applicable to a limited range of missile characteristics.

Energy Balance Methods

These methods have been benchmarked against tests of impacts on pipe targets, mostly as part of pipe whip design for high energy line breaks. These tests include pipe to pipe impact tests by France’s CEA-CEN; pipe whip experiments involving impacts between pipes conducted jointly by Atomic Energy of Canada and Japan’s Electric Power Development; pipe on pipe impact tests by Westinghouse; pipe on pipe impact tests reported in WRC Bulletin 321; tests on cracked pipe targets by Siemens; and experimental studies of pipe whip impact by EPRI.

One energy balance method that is referenced in the Standard Review Plan is the 1973 report “Impact Effects of Fragments Striking Structural Elements”, by Alvy and Williamson, of Holmes and Narver, which uses ductility and equivalent static loads. The ductility approach is also addressed in ASCE’s “Structural Analysis and Design of Nuclear Plant Facilities”.

The energy balance method is useful in designing a barrier, but it cannot predict the deformed shape (and therefore flow area) of the target stack.

Hydrocodes

The hydrocodes were developed for ballistic analysis, and can be used to predict the local penetration of the 1-in diameter rod in steel. These codes have been developed by the National Laboratories for the analysis of penetration of missiles into steel. Southwest Research Institute has developed a 1-dimensional code, BREAKOUT Code. Sandia National Laboratory has developed a high-velocity missile penetration code CTH. The code first models the material motion, and then fracture which is initiated based on principal stress criteria.

Finite Element Analysis

The target material properties: The elastic-plastic material model used for the pipe targets is based on the stress-strain curves defined by the equations in ASME VIII Division 2, Annex 3.D. ABAQUS evaluates strains beyond the stress-strain curve as perfectly plastic. The strain rate hardening used for the pipe targets can be based on data provided in WRC Bulletin 500.

Missile material properties: The missile can be modeled as rigid, or with its own stress-strain curves. An elastic-perfectly plastic material model can be used for the utility pole to simulate the crush strength of the wood.

Interaction target-missile: The interaction of the missiles with the vent piping and the wall is modeled using frictionless general contact. Self-contact of the vent piping is also included to properly analyze the vent pipe collapsing on itself.

Ductility damage: Implementing the strain limit damage computations from ASME VIII-2 Section 5.3.3.2 in ABAQUS is accomplished by using the Johnson-Cook damage material model specified in Section 24.2.2 of the ABAQUS Analysis User's Guide.

Benchmarking: The FEA models are benchmarked against experimental data of high-velocity impacts on pipes, as illustrated in Figures 2 and 3, to assess the adequacy of the model in predicting the deformed flow area.

Results: The results of the finite element analysis are in the form of (A) the shape of the deformed target, Figure 4, this permits to obtain the flow areas for each of the missiles and each direction of impact; and (B) the cumulative strain damage to determine whether the target pipe wall will tear.

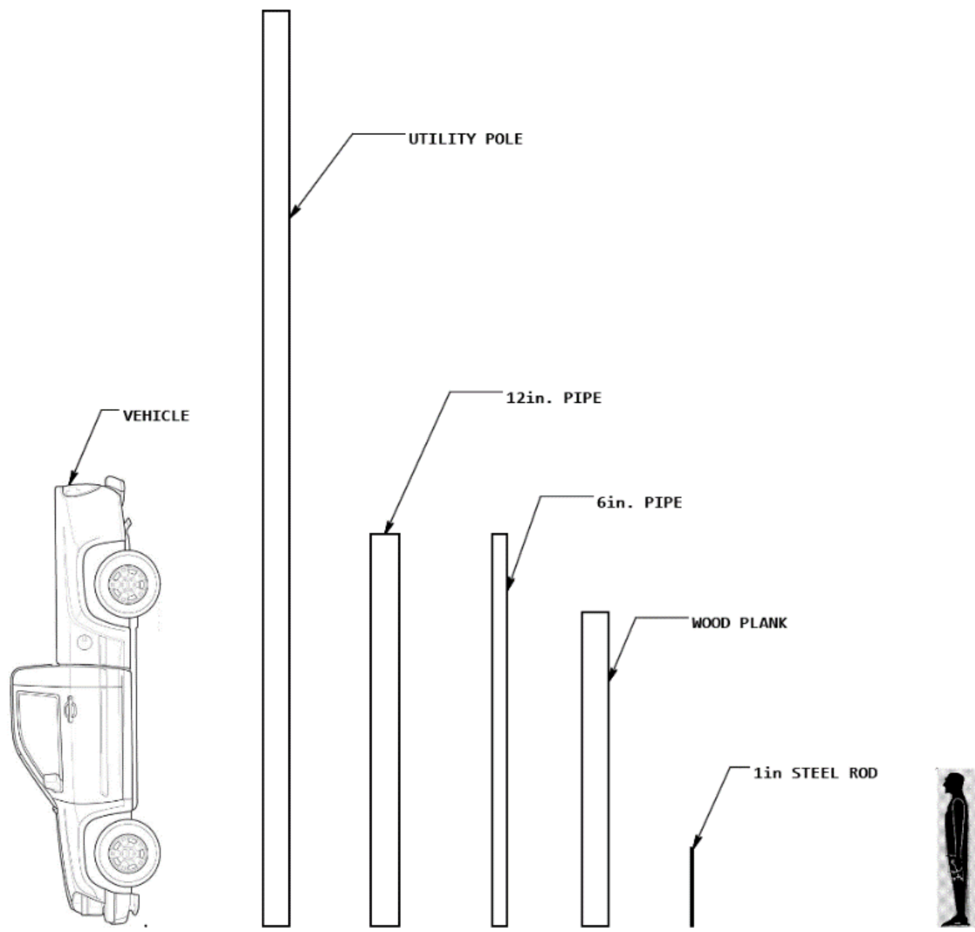


Figure 1 – The Six Common Tornado Missiles

(Some of the older plants only have three missiles: The vehicle, a pipe, and the 1-in rod)

The missiles can strike in any direction, with a specified horizontal and vertical downward velocity

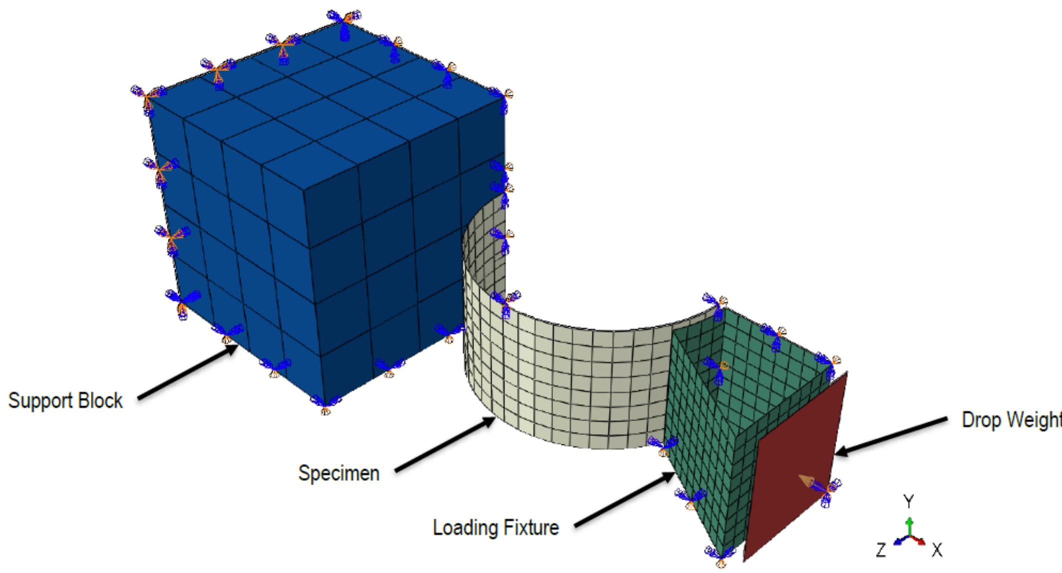
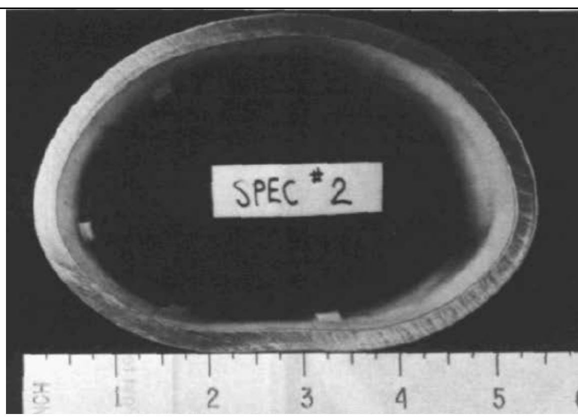
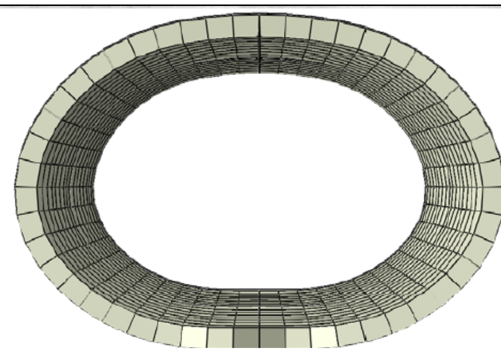


Figure 2 - Finite Element Model to Simulate Experimental Pipe Impact Tests



Experimental Data



Result from ABAQUS Simulation with Strain Hardening

Figure 3 – Benchmark of Finite Element Model against Experimental Pipe Impact Data

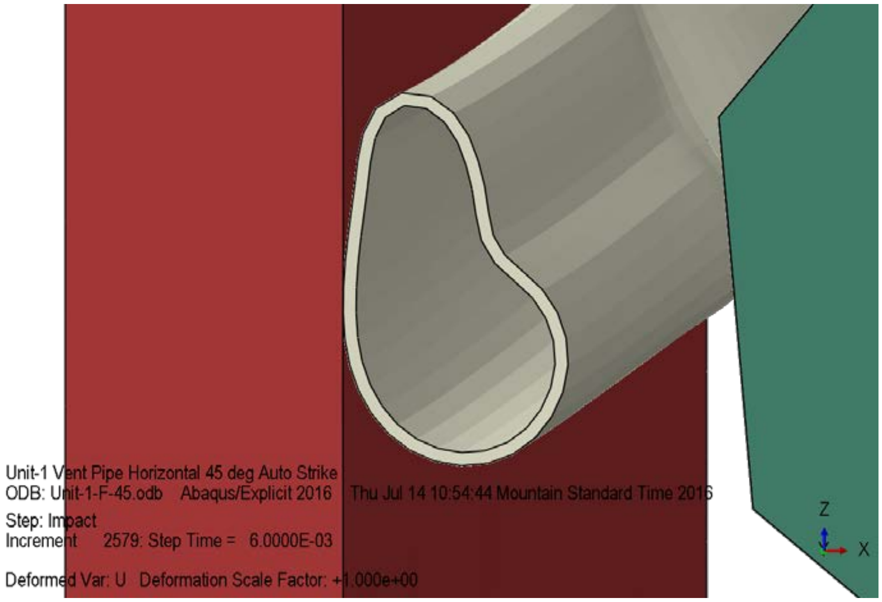


Figure 4 – Simulation of Impact of Pipe and Back Wall, with Missile Rebound