A.15 ANALYSIS OF TORNADO MISSILE GENERATION AND IMPACT ON THE MORRIS OPERATION FUEL STORAGE BASIN

A.15.1 INTRODUCTION

Only those windborne objects which could have a significant downward velocity on entry into the water-filled basin have the potential for causing damage to basin contents. Such objects must have been at a significant elevation above ground level, prior to entry, to develop the required vertical velocity component to result in damage.

A.15.2 POTENTIAL MISSILES

Potential missiles can be classified in regard to their relative elevation, as follows:

1. Objects in the immediate area which, when the tornado strikes, are at elevations above the level of the basin surface (operating equipment and auxiliaries, components of the enclosing structure, etc.).

2. Objects in the general vicinity, which are of such shape and density that they become airborne by aerodynamic lift, are carried by the tornado for a distance and then are dropped into the basin (roofs, doors, etc.).

3. Objects in the general vicinity which are too heavy to be lifted by aerodynamic forces but which conceivably could be deflected upward into a ballistic trajectory after being accelerated by the tornado winds at ground level (small automobiles, boulders, etc.)

4. Objects in the general vicinity which are too heavy to be lifted but, when the tornado strikes, are already at a location above ground level (tops of telephone poles, etc.) so that they could be carried by the tornado and dropped into the basin.

Fuel handling tools and equipment, as well as building siding and roof decking, are of low mass and could not be accelerated over the distance required to achieve the potential velocity at which damage could occur, since they are located within the immediate vicinity of the basins. Heavier items, such as fuel shipping casks, are capable of withstanding tornado winds without displacement.

To become airborne by aerodynamic lift, objects in the second category must be relatively light and of large surface area. Thus, high impact velocities would be required to cause damage but deceleration would be rapid upon entry into the water. For these reasons, damage potential from such objects is not significant.

Although the likelihood of actual occurrence is very low, objects in the third category must be considered because they are relatively dense and conceivably could arrive at the basin location with a high downward velocity.

Objects in the fourth category do not have significant damage potential because of their limited initial elevation, except as they may be deflected upward, after initial acceleration, in which case they become similar to the missiles described in the third category. In summary, only dense objects which achieve significant elevations by the mechanism described for the third category appear to have potential for inflicting damage to the basins or fuel.

In recognition of the fact that sufficient data are not available on which exact characterization can be based, four different methods of calculating potential missile velocities are considered. Three of these are derived from sources in the literature and the fourth from discussions with U. S. Weather Bureau Personnel. These methods are then applied to two simple geometrical bodies typical of potentially damaging missile objects, as described above; viz., a 12 in. diameter by 20 ft. long section of telephone pole weighing 630 lb. and a small automobile, 5 ft. by 5 ft. by 8 ft. in dimension and weighing 1,800 lb.[1]. The most conservative conditions of acceleration and ramp deflection are used in evaluating potential missile effects, although the analysis is based on assumptions regarding missile behavior which have a very low probability of actual occurrence.

A.15.3 TORNADO WIND VELOCITIES

A tornado is a violent whirlwind usually accompanied by a funnel cloud produced by low pressure inside the storm. Estimates of wind speed within the tornado funnel have been made directly from the shape of the funnel cloud, moving and still pictures of funnels and debris, and the extent of damage and patterns on the ground resulting from flying debris. Estimates of tangential wind speeds from damage can be significantly in error due to the many assumptions which must be made. Studies by Fujita, et. al. indicate that minimum wind speeds ranging from 55 to 217 mph are required to effect the typical damage wrought by Midwestern tornadoes.

Measurements of the Fargo tornadoes show a maximum tangential wind speed of about 230 mph with a translational speed of about 30 mph. The Dallas tornado measurements show a maximum tangential velocity of 170 mph and an average translational speed of 27 mph. Goldman calculated vertical velocities of 126 mph at a 750 ft. radius and about 900 ft. above the ground in studies of the Illinois tornadoes of April 1963. The tangential speed along the funnel edge of a Texas tornado of March 1956 was computed as about 230 mph at a radius of 200 ft. and 2,700 ft. above the ground. Some old estimates of 500 mph have been largely discounted over the last few years as more knowledge has been compiled on the subject, and it can be concluded that a maximum tangential speed of 300 mph is a conservative speed to be used in design of nuclear power facilities[2].

A.15.4 ANALYTICAL CRITERIA

The analyses reported herein were based on the following criteria:

Maximum Wind Velocity - 300 mph

Missile No. 1 Telephone pole, 12 in. diameter x 20 ft., weight assumed as 40 lb./ft.[3]

Missile No. 2 Small automobile, 5 ft. x 5 ft. x 8 ft. long, weight assumed as 1,800 lb.

Drag Coefficient1.3

A.15.5 ANALYTICAL METHODS

In several of the analysis methods used the trajectory of the missiles is considered, while in other methods the energy produced in the missile is translated to velocity or height and combinations of both.

For an object to become a missile, it is necessary for it to be aerodynamically lifted and set in motion by the winds of the tornado. The three modes of injection are:

a. Explosive injection into the suddenly imposed pressure differential of the tornado. Here there must be a sufficient volume of air below the object injected to cause the explosion (for example, roofs on poorly vented building).

b. Aerodynamic injection of an object having some configuration which produces lift in the horizontal flow.

c. Ramp injection, where the object is accelerated horizontally and deflected upward.

Aerodynamically, it is impossible for a 300 mph wind to generate missiles approaching that speed because the object has to be accelerated and is subject to the influence of its shape, weight and friction relative to the air.

Four methods are used to determine the speed of the missiles under consideration. Method 1 assumes the object is accelerated and deflected upward at an angle of 45° while constantly exposing a maximum area perpendicular to the direction of the wind. Method 2 is similar to Method 1 in that the distance through which it is acted upon and the manner of acceleration are the same, but the object is considered to tumble as it travels with the tornado winds. In Method 3, an initial elevation is assumed and the missile is acted upon by simultaneous horizontal and vertical wind forces. In Method 4, a tumbling object is acted upon by the maximum winds over an average period of time.

A.15.5.1 Method 1

The following assumptions are made in this procedure[2]:

a. The velocity of the tornado winds at ground level is 300 mph.

b. The force associated with a 300 mph tornado acts on the object over a horizontal distance equal to a 90° chord of the diameter of the maximum velocity of the tornado. The linear horizontal distance (the chord) from the point at which the tornado picks up the object, to the point where it leaves the tornado, is 348 ft.

c. The maximum area of the missile remains perpendicular to the winds for the entire distance over which it is accelerated.

d. The object is deflected upward at an angle of 45° without loss of energy.

e. No drag force acts on the object once it leaves the tornado.

Horizontal acceleration may be expressed as:

$$\ddot{X}\left(\frac{W}{g}\right) = \frac{C_d A_m d\left(V_w - \dot{X}\right)^2}{2g}$$

and

$$\ddot{X} = \frac{C_d A_m d\left(V_w - \dot{X}\right)^2}{2W}$$

where

C_d = drag coefficient

A_m = maximum cross-sectional area of the object

d = density of air

V_w = wind velocity

$\dot{X}$ = horizontal velocity of object

W = weight of object

This equation can be solved for $\dot{X}$ as expressed in the following form:

$$\frac{V_W}{\left(V_W - \dot{X}\right)} - \log_e\left(V_W - \dot{X}\right) = \left(C_d A_m d\left(\frac{X}{2W}\right)\right) + 1$$

where X is the chord distance described in assumption b., above, Once the object has left the tornado area, it is acted upon by gravity only. The equations of motion are:

$$Y = \left(\frac{-gt^2}{2}\right) + \dot{X}_0 \sin 45° t$$

$\dot{Y} = -gt + \dot{X}_0 \sin 45°$

$X = \dot{X}_0 \sin 45° t$

$\dot{X} = \text{constant} = \dot{X}_0 \sin 45° =$ horizontal velocity after the object is deflected 45° upward

$\dot{X}_0 =$ horizontal velocity of object when leaving tornado

The vertical and horizontal velocities and displacements of the missile after it has left the tornado may be calculated using $\dot{X}_0$ and $\dot{X}_0 \sin 45°$ as initial conditions.

Several assumptions for this method are very conservative. A tangential wind velocity of 300 mph is a conservative maximum value and is common design practice[2]. Furthermore, maximum winds normally occur better than 100 ft. above the ground, so that a ground level assumption is very conservative. The distance over which the object is acted upon by maximum winds is also conservative. Since the momentum of the object will cause it to be hurled in a straight line, the distance over which an object would be accelerated by winds would necessarily be limited to something less than the assumed 90° chord. Furthermore, the object would most certainly bounce several times, thereby slowing the missile down. The assumption that the maximum area of the missile remains perpendicular to the winds for the entire distance over which it is accelerated is very conservative. Some objects, such as roofs and trees, can sail and soar in the winds, but objects which present the most serious potential hazards to the fuel in storage are not aerodynamically stable, and will turn in the wind.

A.15.5.2 <u>Method 2</u>

Method 1 assumes that the maximum area of an object remains constantly perpendicular to the wind. Method 2 is largely predicated on the same assumption as is Method 1, except the object is assumed to tumble in the wind, and its energy may be expressed as velocity or height or combinations of both. The force exerted by wind on an object is expressed as:

$$D_f = 0.5 C_d d \left(V_w - \dot{X}\right)^2 \left(A_+ \cos^2 a + A_= \sin^2 a\right)$$

where a is the angle of the wind with respect to an orthogonal axis of the object, A_+ is the cross-sectional area perpendicular to the wind, and $A_=$ is the cross-sectional area parallel to the wind.

Most frequently, the object tumbles in such a manner that the wind makes a random angle with respect to the orthogonal axes. The average values of $\cos^2 a$ and $\sin^2 a$ are therefore 1/4, obtained by squaring their values integrated over all angles from 0 to π, and the equation becomes:

$$F_{ave} = 0.125 C_d d \left(V_w - \dot{X}\right)^2 \left(A_+ + A_=\right)$$

Very short increments of time are used to determine the velocity of the object at any instant:

$$\dot{X}_i = \dot{X}_{i-1} + F_{ave} / M(dt)$$

A step-by-step integration is then used to determine the final velocity.

A.15.5.3 Method 3

This method was presented by Bates and Swanson[3], and later included in a paper by Doan[4]. As in the previous method, tumbling of the object is assumed. The average force on the object is assumed to act for an average time of application, and the difference in velocities between the wind and the missile is not considered. The force acting on the object is approximately:

$$F_d = q\, C_d\, (A_+ \cos^2 a + A_= \sin^2 a)$$

where:

$$q = 1/2\, d\, V_w^2$$

Again, the values of $\cos^2 a$ and $\sin^2 a$ are determined to be 1/4, and the equation becomes:

$$F_{ave} = 1/4\, C_d\, q\, (A_+ + A_=)$$

The speed and kinetic energy of the missile are:

$$\dot{X} = F_{ave} t_{ave} / M$$

$$E = F_{ave}^2 t_{ave}^2 / 2M$$

where t_{ave} is the average time of force application. This average is estimated to be on the order of 0.2 second.

If all of the energy acquired is used to lift the object vertically, the maximum height attained is:

$$H_{\max} = \frac{F_{ave}^2 t_{ave}^2}{2Mg}$$

Bates and Swanson observe that the force exerted on a fixed object (conserved angle of attack) is of short duration because by the time the aerodynamic force has increased to a value sufficient to lift most objects, the moments which produce tumbling are also large. The mean time interval of action is estimated as 0.2 second. Doan does not discuss the merits of his time interval for a tumbling object, but simply estimates it as 0.2 second. The relatively low values obtained from this method reflects this short period of time.

A.15.5.4 Method 4

This method was developed after discussions by telephone with several offices of the Weather Bureau concerned with tornadoes and is based on the following assumptions:

a. The object is acted upon by the maximum winds for a distance equal to the radius of the tornado.

b. A maximum horizontal wind of 300 mph and a maximum vertical wind of 300 sin 45° mph act constantly on the vertical and horizontal faces of the object.

c. Since vertical velocities are small at the ground surface, it is assumed that the object is initially at a height of 30 feet above the ground.

The two basic equations of motion for objects within the tornado are:

$$M\ddot{Y}_1 = F_y - Mg$$

$$M\ddot{X}_1 = F_x$$

where $\ddot{Y}_1$ and $\ddot{X}_1$ are the accelerations within the tornado; F_y and F_x are the forces due to the tornado-induced pressures in the vertical and horizontal directions, respectively. The initial motion of the object when encountered by the tornado is zero. Upon leaving the tornado area, the missile is acted upon by gravitational force alone, and the equations become:

$$M\ddot{Y}_2 = -Mg$$

$$M\ddot{X}_2 = 0$$

Here, the initial velocity conditions are the maximum attained within the tornado.

A.15.6 Discussion and Results

Results of these analyses are listed in Table A.15-1, and applied in Section 8. Method 1 proved the most severe, the second being Method 2. Principal differences of all of the methods are: a. constant exposure of maximum missile area to wind versus a tumbling action, and b. the duration of time of wind acting on object. While the time element of Method 3 or 4 may be more nearly correct, the lack of pertinent information on the effective time of attack rules in favor of Methods 1 and 2. Of these, method 2 is more realistic but impact analyses were performed for velocities calculated by Method 1 to be more conservative.

Table A.15-1
RESULTS OF WIND ANALYSES

Missile	Telephone Pole 12-in. Diameter x 20 in. (630 lb)				Automobile 5 ft x 5 ft x 8 ft long (1,800 lb)			
	Maximum Velocity (ft/sec)		Maximum Distance (feet)		Maximum Velocity (ft/sec)		Maximum Distance (feet)	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Method 1	264[a]	187	2174	543	242[a]	171	1820	455
Method 2	171[a]	121	899	228	187[a]	132	1083	271
Method 3	16	-	6	4	17.5	-	7	5
Method 4	71	53.5	195	44	49	50.5	112	36

a Horizontal velocity before the object is deflected upward at 45°

A.15.6.1 Impact Analysis

For analysis of impact effect within the water-filled basins, it is further assumed that the object enters the water vertically at the velocities calculated from the above assumptions (187 ft./sec. for the telephone pole and 171 ft./sec. for the automobile), as shown in Table A.15-1, in an "end on" orientation.

Upon entering the basin water, forces acting on a missile are:

(1) Mass inertia $(m\dot{x})$

(2) Weight of the missile (mg)

(3) Buoyancy (ρvg)

(4) Drag $\left(\frac{C_d A\dot{x}^2}{2}\right)$

where:

m = mass of the missile

v = submerged volume of the missile

A = area of the missile perpendicular to the direction of movement

C_d = drag coefficient (assumed in all cased to be 1.0)

$\ddot{x}$ = missile acceleration at time t

$\dot{x}$ = missile velocity at time t

ρ = mass per unit volume of the basin water

For passage of a missile through the basin water,

$$m\ddot{x} = mg - \left(\frac{C_d A \dot{x}^2}{2}\right) - \rho v g ,$$

or

$$\ddot{x} = g - \left(\frac{C_d A \dot{x}^2}{2m}\right) - \frac{\rho v g}{m} = \left(1 - \frac{\rho v}{m}\right) - \left(\frac{C_d A}{2m}\right)\dot{x}^2 ,$$

and

$$\ddot{x} = \frac{d\dot{x}}{dt} = \left(\frac{d\dot{x}}{dx}\right)\left(\frac{dx}{dt}\right) = \frac{\dot{x}d\dot{x}}{dx}$$

Letting $\theta = C_d A/m$ and $\phi = g\,(1 - \rho v/m)$ and noting that $\dot{x} = V_0$ at x = 0,

$$\dot{x}^2 = \frac{2\phi}{\theta} + \left(V_0^2 - \frac{2\phi}{\theta}\right)e^{-\theta x}$$

In the case of the telephone pole, a step-by-step solution was developed to evaluate its velocity at different depths of penetration, assuming constant end-on orientation. On this basis, velocity after penetrating to a depth of 8 ft. is 138 ft./sec.; after 14 ft., 111 ft./sec.; and after 21 ft., 88 ft./sec.. Total penetration required to stop the pole exceeded the depth of the basin. On striking the bottom liner, missile kinetic energy would be approximately 5×10^4 ft.-lb.

For the automobile, no buoyancy was assumed until after it had penetrated 2 ft. into the basin water and its submerged volume then was assumed to remain constant to account for leaks. On this basis, total penetration for deceleration to terminal velocity (< 6 ft./sec.) was 7.3 ft.

A.15.6.2 Effects of Missile Impact on Basin Structure

The potential penetration of the basin liners and wall by the postulated missiles was evaluated[5]. The penetration of a steel plate is described by the equation:

$$\frac{E}{D} = U\left(0.344t^2 + 0.00806wt\right)$$

where:

E = critical kinetic energy required for penetration;

D = diameter of missile (in.);

U = ultimate tensile strength of steel;

t = thickness of steel plate (in.); and

w = distance between supports of the plate (in.).

The penetration and perforation of concrete, masonry and sand is similarly described by the equation:

$$D' = KAV'R$$

where

D' = depth of penetration (ft);

K = penetration coefficient for reinforced concrete = 4.76 ft./lb.;

A = sectional mass of missile (lb./ft.^{3});

R = thickness ratio of the penetration of a slab of thickness T to the penetration of a slab of infinite thickness;

V' = velocity factor for impact penetration = $\log_{10}\left[1 + \frac{V^2}{215{,}000}\right]$

where:

V = missile velocity.

Material properties and structural dimensions used in the analysis were:

t = 0.125 in. for basin liners up to 16 ft. elevation

= 0.0625 in. for basin liners above 10 ft. elevation

= 2 in. for deep pit floor

U = 75,000 psi (70,000 for deep pit)

D (telephone pole) = 13.5 in. diameter

D (small automobile) = 61.2 in. diameter

W = 3 ft.

Analyses were performed, for each postulated missile, for potential penetration of each type of material (i.e., assuming no concrete backing for the steel plate and for concrete penetration assuming no liner). Both the walls and floor of the basin were analyzed for potential penetration.

A.15.6.2.2 Analysis

Wood planks, sections of steel pipe, a telephone pole and a small automobile have been analyzed as potential missiles. Of these missiles, the telephone pole and the automobile represent equivalent or greater potential damage than the others. The analysis of the automobile missile indicates that it does not have sufficient energy to penetrate the 1/16 in. thick wall liner even at its maximum horizontal velocity of 440 ft./sec. due to the large impact cross-sectional area of the automobile. At the maximum horizontal velocity, the kinetic energy of the automobile (5.4×10^6 ft.-lb.), ignoring the fact that the liner is backed by reinforced concrete. The automobile would be traveling in a trajectory and thus would not strike the wall perpendicularly. There is no possibility of penetrating the 3/16 in. thick floor liner as the automobile would be traveling at its settling velocity (< 6 fps) and the kinetic energy is only about 1,000 ft.-lb.

The analysis of the impact of the telephone pole missile indicates that puncture of the basin liner is extremely improbable. For example, the energy required to penetrate the floor liner in the basin, ignoring the backup strength of the concrete, is in excess of 1.6×10^6 ft.-lb. for an impact perpendicular to the liner. At that depth, the kinetic energy of the telephone pole is less than 5×10^4 ft.-lb., and, thus, there will be no penetration of the floor liner in the basins. A recent report[6] indicates that telephone poles (utility poles) are ineffective in producing significant local and structural damage even under the most improbable missile impact conditions.

The telephone pole cannot strike the walls at any angle that is nearly perpendicular at a depth sufficient to cause significant leakage even if the liner should be penetrated. Penetration of the liner near the top of the pool would not be of concern and penetration of a vertical wall deep in the pool would require more energy than bottom penetration (1.6×10^6 ft.-lb.) due to the angle of impact. For example, after travel through 21 ft. of water, the impact kinetic energy would be only about 4.29×10^5 ft.-lb. Even for a perpendicular impact, penetration can occur only if the concrete backing is ignored. The compressive strength of the concrete might be exceeded in

local areas, but due to the low void fraction of structural concrete and its confinement, there would be no significant crushing. Therefore, the telephone pole will not penetrate the wall liners based on the strength and ductility of the liner, on the possible angle of impact, and on the relative crushing strengths of the pole and the concrete.

It is concluded that penetrations of the basin liners caused by the telephone pole missile are very unlikely and that the leaks resulting from such penetrations, if any, are well within the repair capability of GE-MO.

A.15.7 REFERENCES

1. Other postulated missiles (pipe, wood planks, steel rod, etc.) have less damage potential than those missiles considered.

2. D. R. Miller and W. A. Williams, Tornado Protection for the Spent Fuel Storage Pool, General Electric Company, November 1968 (APED-5696).

3. F. C. Bates and A. E. Swanson, Tornado Design Considerations for Nuclear Power Plants, Black & Veatch, Engineers

4. P. L. Doan, Tornadoes and Tornado Effect Considerations for Nuclear Power Plant Structures including the Spent Fuel, United Engineers and Constructors.

5. C. V. Moore, Design of Barricades for Hazardous Pressure Systems, Nuclear Engineering and Design (1967).

6. Sandia Laboratories, Full-Scale Tornado-Missile Impact Tests, July 1977 Electric Power Research Institute Report No. EPRI NP-440.