NUREG-75/087

U.S. NUCLEAR REGULATORY COMMISSION
STANDARD REVIEW PLAN
OFFICE OF NUCLEAR REACTOR REGULATION

SECTION 3.5.1.3 TURBINE MISSILES

REVIEW RESPONSIBILITIES

Primary - Accident Analysis Branch (AAB)

Secondary - Auxiliary and Power Conversion Systems Branch (APCS)
Materials Engineering Branch (MTEB)
Structural Engineering Branch (SEB)
Electrical, Instrumentation and Control Systems Branch (EICSB)

I. AREAS OF REVIEW

The turbine missile analysis is reviewed with the objective of establishing whether safety-related plant structures, systems, and components have adequate protection against potential turbine missiles. The primary areas of review are the high trajectory turbine missile strike probabilities and the turbine-generator orientation and placement relative to the safety-related plant structures, systems, and components. Additional review areas include the following:

1. Turbine missile barrier design procedure adequacy (SEB).
2. Turbine disk failure analysis (MTEB).
3. Turbine disk fracture toughness properties and startup procedures which assure adequately high disk temperatures (MTEB).
4. Turbine overspeed protection system reliability (EICSB and APCSB).
5. Target redundancy and independence (APCSB).
6. Inservice inspection (MTEB and APCSB).

II. ACCEPTANCE CRITERIA

Plant design and layout must satisfy General Design Criterion 4 (Ref. 1), which states that structures, systems, and components important to safety should be protected against the effects of missiles that might result from equipment failures. Specifically, in the areas reviewed by the AAB, acceptability will be based on the following considerations:

1. Plant design and layout in relation to plant vital systems or structures exposed to potential low trajectory turbine missiles that may be ejected in the event of a destructive overspeed failure of any turbine-generator unit in the vicinity of the plant.

2. Protection against high trajectory turbine missiles including: the total plant area associated with a reactor unit's vital systems which are vulnerable to high trajectory turbine missiles, the overall high trajectory turbine missile strike and damage probability of leading to consequences greater than the 10 CFR Part 100 guidelines, the units within reach of potential high trajectory turbine missiles from more than one turbine-generator, redundant overspeed protection systems, and the exclusion of vulnerable vital systems from high trajectory turbine missile target areas on the basis of redundancy if the systems are sufficiently separated and isolated from each other so that a single missile could not damage both systems.

3. The turbine overspeed protection system should be designed to limit turbine speed to less than 130% of normal speed. There should be sufficient redundancy so that any single failure in the overspeed sensing and trip actuation portions of the system, as well as in the turbine steam valves, would not prevent the overspeed protection system from operating.

4. The overspeed protection system should be tested frequently to confirm that all overspeed detection and turbine trip actuation functions are operable. All turbine steam valves (i.e., stop valves, dump valves, etc.) which are used to reduce, divert, or otherwise limit the steam flow that is available for driving the turbine into an overspeed condition should be tested frequently. Where turbine design does not permit frequent stop valve testing an equivalent means of assuring comparable valve reliability should be provided.

5. Low pressure turbine disk materials, manufacturing processes and operating conditions should conform to the recommendations of Reference 3.

III. REVIEW PROCEDURES

The reviewer selects and emphasizes aspects of the areas covered by this review plan as may be appropriate for a particular case. The judgment on areas to be given attention and emphasis in the review is based on an inspection of the material presented to see whether it is similar to that recently reviewed on other plants and whether items of special safety significance are involved. The review procedure involves the following:

1. A review of turbine orientation and placement with respect to low trajectory turbine missiles.

2. A review of the plant vital systems with respect to high trajectory turbine missiles in terms of target plan areas, horizontal barriers, target turbine orientations, and distances. If necessary, a structural damage assessment will be made on the basis of information provided by the MTEB regarding turbine missile characteristics and from the

SEB regarding barrier penetration and spalling damage methodology using such techniques as described in Appendix A (Ref. 4).

The reviewer should be aware of the following parallel work which may affect the turbine missile evaluation:

1. The adequacy of structural turbine missile barrier design procedures are verified by the SEB.

2. The fracture toughness properties of the low pressure turbine wheels are reviewed by the MTEB.

3. The turbine overspeed protection system and its testing (including the turbine steam valves) are evaluated by the EICSB and the APCSB.

4. The identification of plant essential systems to be protected against turbine missiles is reviewed by the APCSB.

5. The description and analysis associated with the physical and kinematic properties of postulated turbine missiles are evaluated by the MTEB.

References 6 through 8 provide general background on the turbine missile problem.

IV. EVALUATION FINDINGS

The reviewer verifies that sufficient information has been provided and that the review and calculations support conclusions of the following type, one (or a combination) of which should be included in the staff's safety evaluation report:

1. The overall probability that turbine missiles could damage the plant and lead to consequences in excess of the 10 CFR Part 100 exposure guidelines is acceptably low, so that the plant essential systems are protected adequately against potential turbine missile damage.

2. The overall high trajectory turbine missile strike and damage probability for the plant is too high, and leads to potential consequences greater then the 10 CFR Part 100 guidelines. Additional protection against design overspeed high trajectory turbine missiles is required to reduce the essential system target area so that the overall turbine missile damage probability is acceptable.

3. The indicated turbine orientation and placement exposes the (<u>plant systems</u>) to potential low trajectory or direct strike turbine missiles. Reorientation of the turbine unit(s) or repositioning of the (<u>plant systems</u>) are required to reduce the probability of destructive overspeed turbine missile damage to an acceptable level.

V. REFERENCES

1. 10 CFR Part 50, Appendix A, "General Design Criteria for Nuclear Power Plants."

2. 10 CFR Part 100, "Reactor Site Criteria."

3. Standard Review Plan 10.2.3, "Turbine Disk Integrity."

4. Appendix A, "High Trajectory Turbine Missile Analyses," appended.

5. S. H. Bush, "Probability of Damage to Nuclear Components," Nuclear Safety, Vol. 14, No. 3, May-June 1973.

6. ANSI N177, "Plant Design Against Missiles," draft standard of ANS 20.1 Working Group (1973).

7. H. G. Mangelsdorf, letter from the Advisory Committee on Reactor Safeguards on turbine missiles, April 18, 1973.

APPENDIX A

STANDARD REVIEW PLAN 3.5.1.3

HIGH TRAJECTORY TURBINE MISSILE ANALYSES

I. STRIKE PROBABILITY ANALYSIS FOR HIGH TRAJECTORY TURBINE MISSILES

If various turbine internals (such as stator blade rings) did not offer any resistance to turbine missiles, the missile trajectories would tend to stay within the plane of the original wheel. In practice, failed wheel fragments can interact with various parts of the turbine, and thus can be deflected away from the plane of the wheel. The limit of angular deviation, Δ, from the wheel plane usually is less for inner wheels than for the end wheels. In this analysis, it is assumed that all turbine missiles are limited to inner wheel deflections. This is a conservative assumption when analyzing high trajectory strike probabilities because a greater departure from the wheel plane would spread the missiles over a larger target area, thus lowering the strike probability density. It should be noted that there are significantly more inner wheels than end wheels.

Denoting the solid angle described by the deflection angles Δ as Ω^*, we can formulate the directional probability density as follows. Assuming a uniform distribution of initial missile directions within the solid angle Ω^*, the directional probability density per unit solid angle, ρ_Ω, can be written as

$$\rho_\Omega \, d\Omega \equiv \frac{d\Omega}{\Omega^*} \tag{1}$$

The incremental solid angle $d\Omega$ can be expressed in terms of the missile elevation angle ϕ as (see Figure 1)

$$d\Omega = \frac{(R d\phi)(R \cos\phi \, d\theta)}{R^2} = \cos\phi \, d\phi \, d\theta \tag{2}$$

where R is an arbitrary radius of a sphere. The total solid angle is given by

$$\Omega^* = \frac{\frac{1}{2} \displaystyle\int_{\phi = \frac{\pi}{2} - \Delta}^{\phi = \frac{\pi}{2} + \Delta} (R d\phi)(2\pi R \sin\phi)}{R^2} = 2\pi \sin\Delta \tag{3}$$

where the 1/2 in front of the integral denotes that the locus of all eligible missiles is confined to a surface above the horizontal plane.

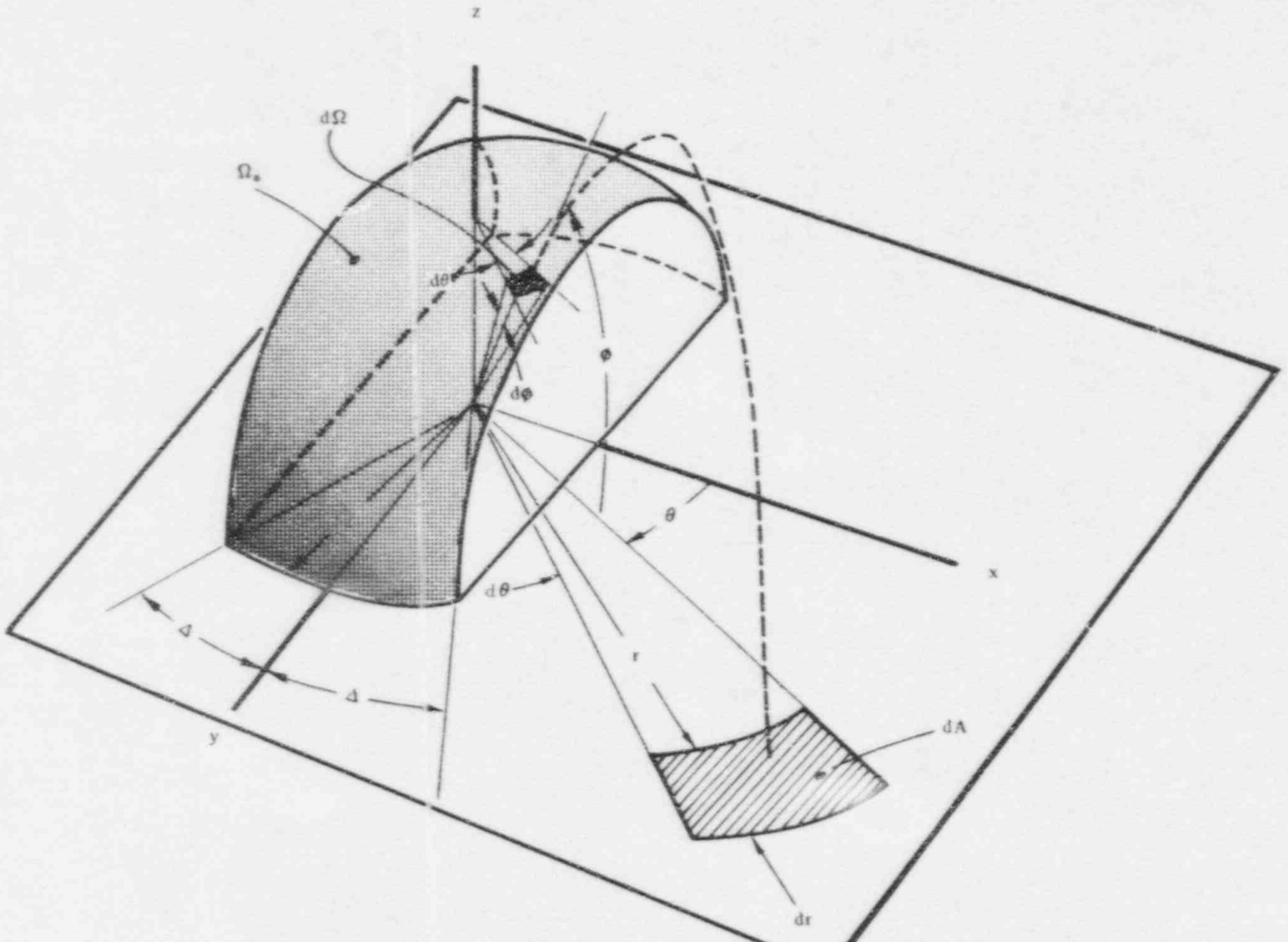

FIGURE 1. MISSILE TRAJECTORY GEOMETRY

In order to define a directional probability density per unit elevation angle, we may note the following. The probability of finding a missile direction within the incremental solid angle $d\Omega$ should be the same as the probability of finding a missile direction within the angular increments $d\theta$ and $d\phi$ which bound $d\Omega$. That is,

$$\rho_\Omega \, d\Omega = \rho_\phi(\theta,\phi) \, d\phi \tag{4}$$

Applying Equations (2) and (3) to (4), we obtain

$$\rho_\phi(\theta,\phi) \, d\phi = \frac{\cos\phi}{2\pi \sin\Delta} \, d\theta d\phi \tag{5}$$

Assuming a uniform distribution of initial missile speeds in the range V_1 to V_2, the speed probability density per unit speed, $\rho_V(V)$, is defined by

$$\rho_V(V) \equiv \frac{dV}{V_2 - V_1} \tag{6}$$

where

$$V_1 \leqslant V \leqslant V_2$$

The compound probability that a missile will have an initial speed within V and V + dV, and an initial direction within ϕ and $\phi + d\phi$, , θ and $\theta + d\theta$, is given by

$$\rho_V(V) \, \rho_\phi(\theta,\phi) \, dV d\phi = \frac{d\theta}{V_2 - V_1} \quad \frac{\cos\phi}{2\pi \sin\Delta} \, dV d\phi \tag{7}$$

with the ballistic constraint that the corresponding missile strike range is given by

$$r = \frac{V^2}{g} \sin 2\phi \tag{8}$$

Using the variable transformation

$$\chi = V \sin 2\phi \tag{9}$$

we have from Equation (8) that

$$\phi = \frac{1}{2} \sin^{-1}\left(\frac{\chi^2}{rg}\right) \tag{10}$$

and

$$V = \frac{rg}{\chi} \tag{11}$$

for which the Jacobian is given by

$$|J| = \frac{1}{2r\sqrt{1 - \left(\frac{\chi^2}{rg}\right)^2}} \tag{12}$$

Using the Jacobian, the strike probability density per unit horizontal strike area, ρ_A can be written as

$$\rho_A \, dA = \iint\limits_{\substack{\phi \; V \\ \phi, V \,\epsilon\, dA}} \rho_V(V)\, \rho_\phi(\phi)\, dV d\phi = \int\limits_{\chi} \rho_V(V(r,\chi))\, \rho_\phi(\phi(r,\chi))\, |J|\, dr d\chi \tag{13}$$

where the incremental strike area dA is given by

$$dA = r d\theta dr \tag{14}$$

Applying Equations (7), (10), (11), (12), and (14) to (13) we have

$$\rho_A \, dA = \int\limits_{\chi} \left(\frac{1}{V_2 - V_1}\right) \left(\frac{\cos\phi}{2\pi \sin\Delta}\; d\theta\right) \left(\frac{1}{2r\sqrt{1 - \left(\frac{\chi^2}{rg}\right)^2}}\right) \left(\frac{r}{r}\right) dr d\chi \tag{15}$$

which yields

$$\rho_A = \left(\frac{1}{V_2 - V_1}\right) \left(\frac{1}{2\pi \sin\Delta}\right) \left(\frac{1}{2r^2}\right) \int_{\chi_{min}}^{\chi_{max}} \cos\left[\frac{1}{2} \sin^{-1} \frac{\chi^2}{rg}\right] \frac{d\chi}{\sqrt{1 - \left(\frac{\chi^2}{rg}\right)^2}} \tag{16}$$

The values χ_{min} and χ_{max} represent the limits on χ such that the target area dA at r is struck. These limits are subject to change as the azimuth angle θ and distance r to the target change due to the constraints imposed by the speed range V_1, V_2 and the deflection angles Δ . The variation of χ_{max} and χ_{min} can be illustrated as follows (Figure 2). Consider a qualitative graph of V versus ϕ as constrained by Equation (8) for some value of r and θ . The graph segment AB represents the locus of all combinations of $V_1 \leq V \leq V_2$ and $\frac{\pi}{4} \leq \phi \leq \frac{\pi}{2}$ which permit a missile to reach the target at r, θ as indicated in Figure 2. The variable χ can be expressed as

$$\chi = \sqrt{rg \sin 2\phi} \tag{17}$$

Its graph versus ϕ is indicated by the dashed curve in Figure 2. The graph segment CD of χ versus ϕ represents the range of corresponding values of χ , such that in going from V_1, ϕ_1 to V_2, ϕ_2, the variable χ ranges from χ_{max} to χ_{min} . In this illustration, the limits on χ are dictated by the dynamic constraint given in Equation (8). The limits can be expressed by

$$\chi_{min} = \frac{rg}{V_2}\,, \quad \chi_{max} = \frac{rg}{V_1} \tag{18}$$

As mentioned earlier, the deflection angles Δ represent an additional constraint which is illustrated in Figure 3 by the vertical line EF for a given azimuthal direction θ . In this case, missiles with speeds between V_1 and V_i cannot reach a target at r, θ since the necessary elevation angles below ϕ_i are not permitted by the constraint

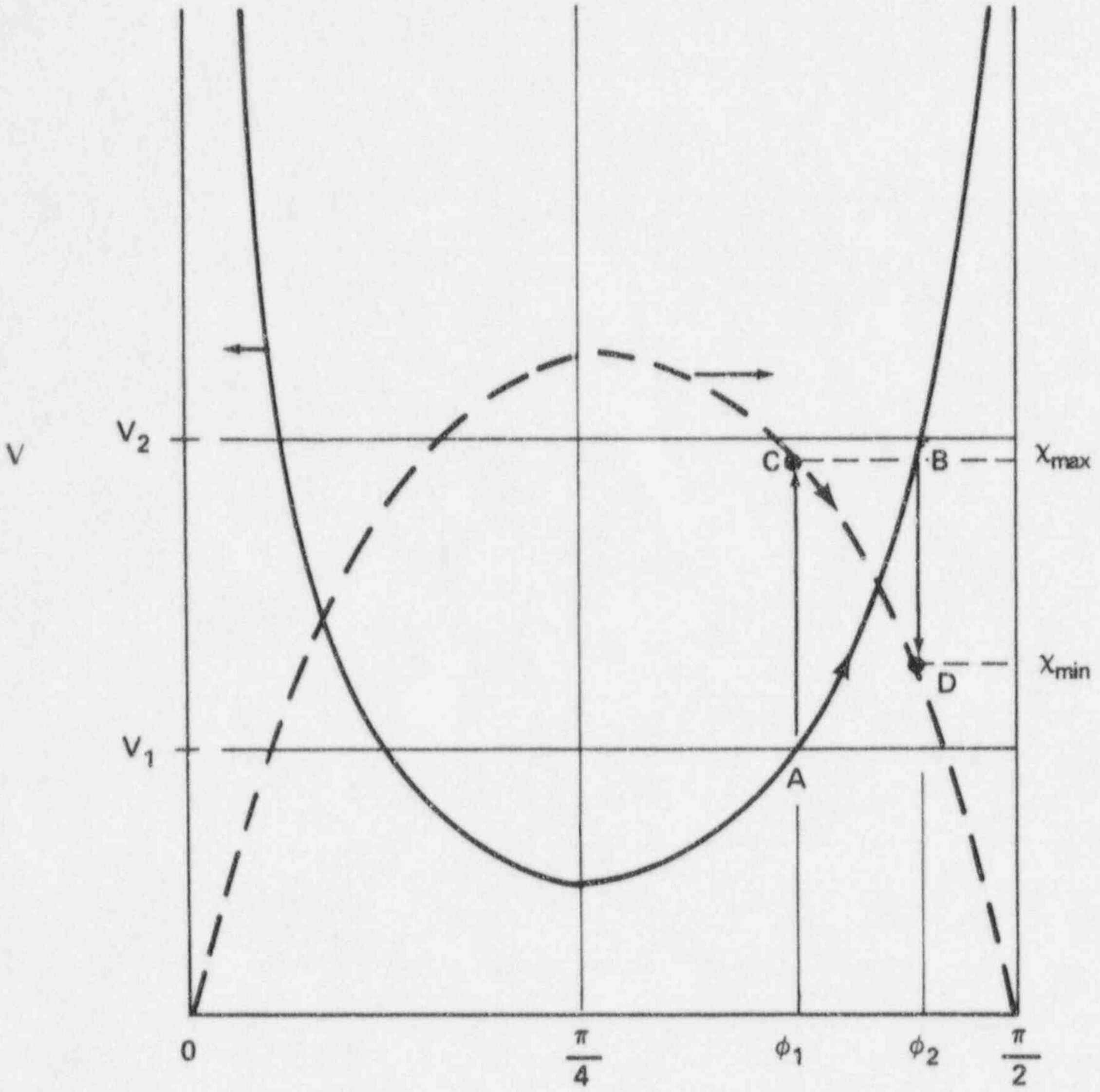

Figure 2. Dynamic Constraints on ϕ.

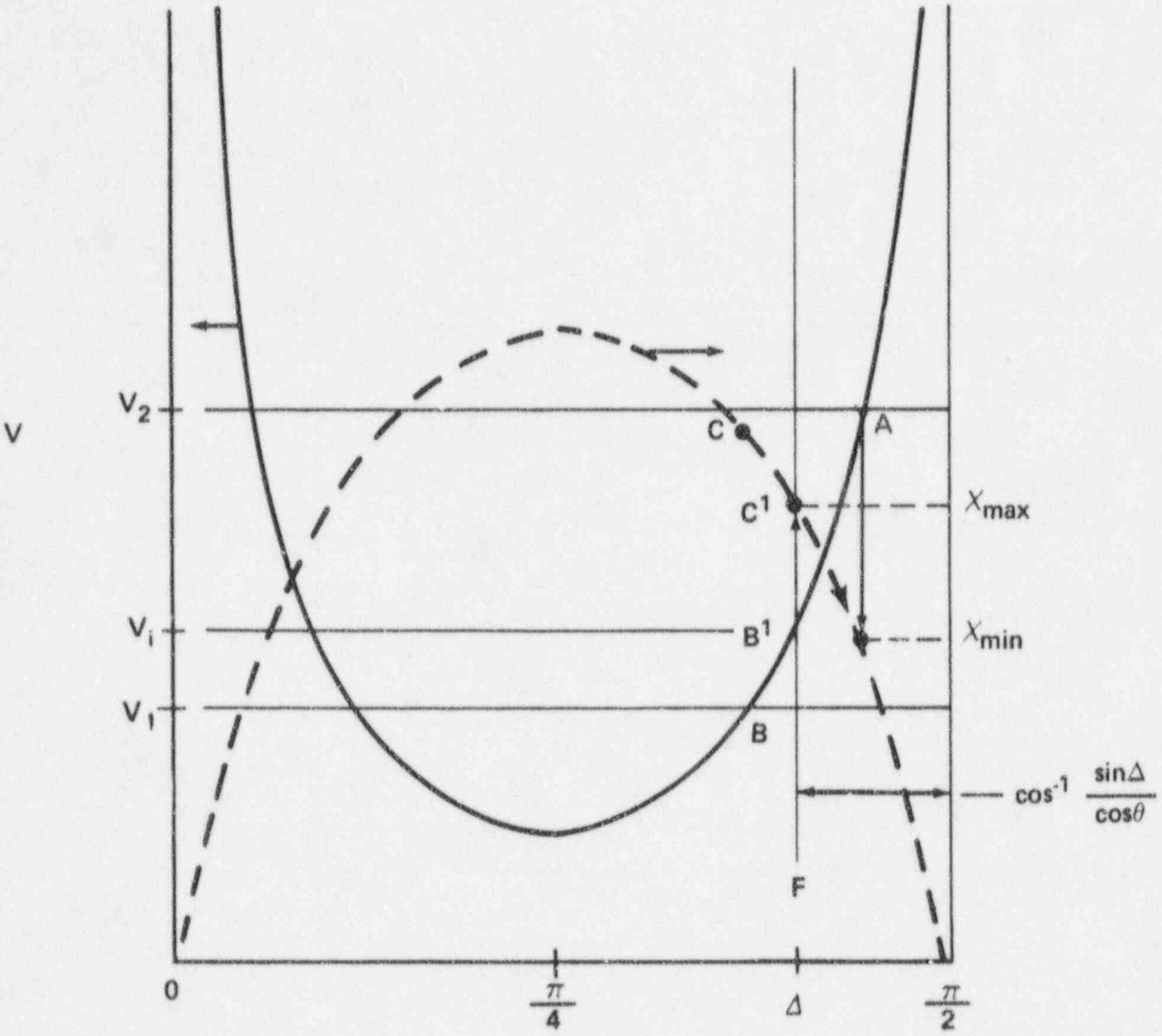

Figure 3. Deflection Angle Δ Constraint on ϕ.

$$\phi \geqslant \cos^{-1} \frac{\sin\Delta}{\cos\theta} \tag{19}$$

In this case, the limits on χ are of the form

$$\chi_{min} = \frac{rg}{V_2}, \quad \chi_{max} = \sqrt{rg \sin 2\left[\frac{\pi}{2} - \cos^{-1}\left(\frac{\sin\Delta}{\cos\theta}\right)\right]} \tag{20}$$

Considering the typical values of V_1, V_2, r, and Δ for turbine units on nuclear power plant sites, it can be shown that the integrand of Equation (16) is a slowly varying function near unity. Thus, an approximate solution of Equation (16) is

$$\rho_A \cong \frac{\chi_{max} - \chi_{min}}{(V_2 - V_1)\, 4\pi r^2 \sin\Delta} \tag{21}$$

Applying the limits in (18) and (20), we have

$$\rho_A \cong \frac{g}{V_1 V_2\, 4\pi r \sin\Delta} \qquad \text{for } \cos^{-1} \frac{\sin\Delta}{\cos\theta} > \frac{\pi}{2} - \frac{1}{2} \sin^{-1} \frac{rg}{V_1^2} \tag{22}$$

$$\rho_A \cong \frac{\sqrt{rg \sin 2\left[\frac{\pi}{2} - \cos^{-1}\left(\frac{\sin\Delta}{\cos\theta}\right)\right]} - \frac{rg}{V_2}}{(V_2 - V_1)\, 4\pi r^2 \sin\Delta} \qquad \text{for } \cos^{-1} \frac{\sin\Delta}{\cos\theta} \leqslant \frac{\pi}{2} - \frac{1}{2} \sin^{-1} \frac{rg}{V_1^2} \tag{23}$$

Figure 4 shows a plot of Equations (22) and (23) versus target distance for a speed range between 200 and 600 feet per second and several values of θ, where $\Delta = 5°$.

II. ESTIMATES OF THE PROBABILITY OF PENETRATION OF STRUCTURES BY TURBINE MISSILES

Estimates of the minimum reinforced concrete thickness required for preventing turbine missile penetration can be obtained using the Petry equation described in Reference 1. This equation is limited to estimating penetration depths in concrete. It does not take into account the possibility of concrete spalling. Suitable safety factors should be applied to the equation to account for spalling unless design features preclude spalling. Figure 5 illustrates the thickness T required to prevent penetration at various speeds, V, for various missile sizes and shapes (as characterized by the parameter A_p), where:

T = Minimum concrete thickness,

V = Missile strike speed,

A_p = Sectional Pressure = $\dfrac{\text{Missile Weight}}{\text{Cross Sectional Missile Area}}$

The curves in Figure 5 correspond to 5500 psi concrete.

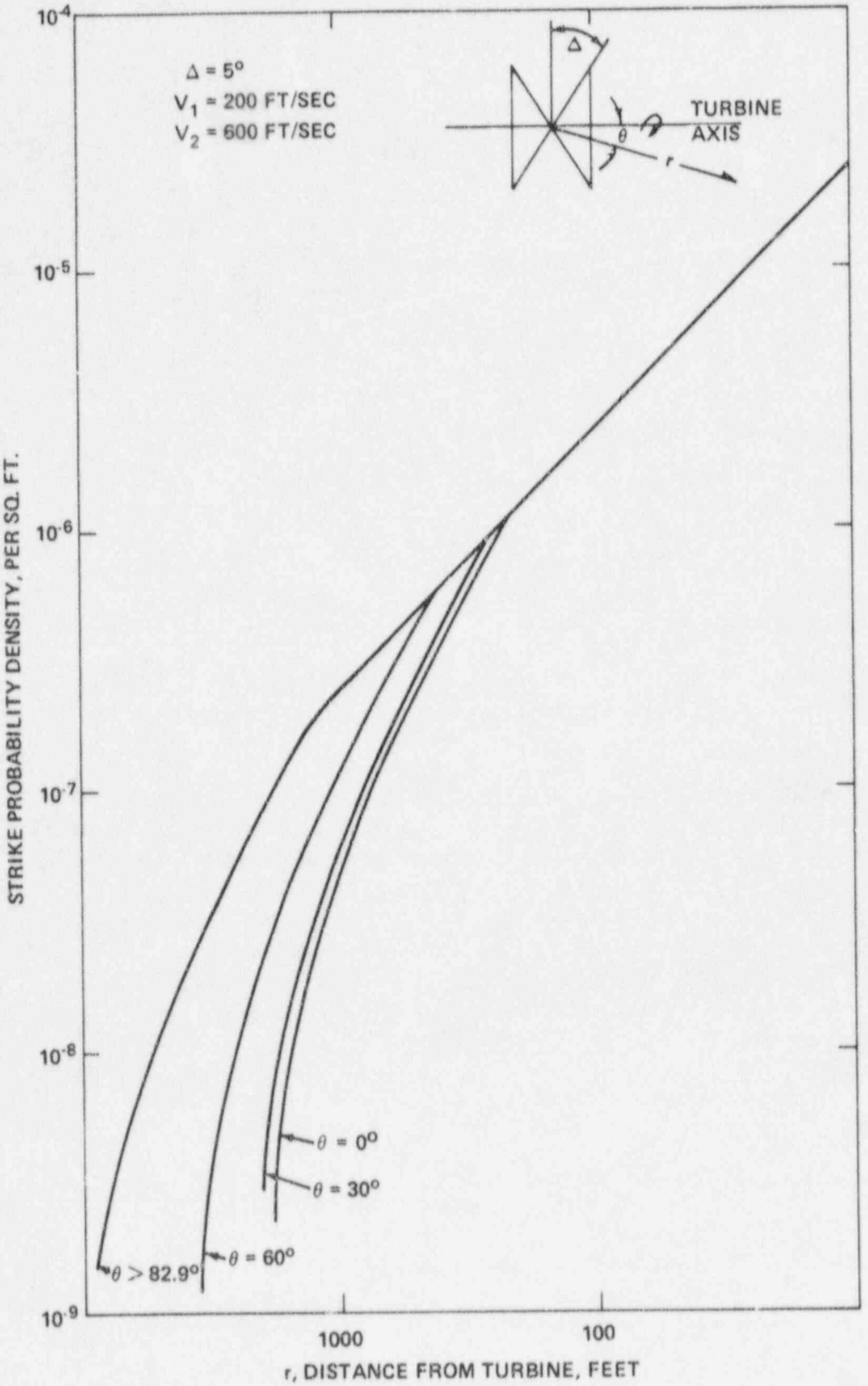

Figure 4. Strike Probability Density Verus Distance from Turbine

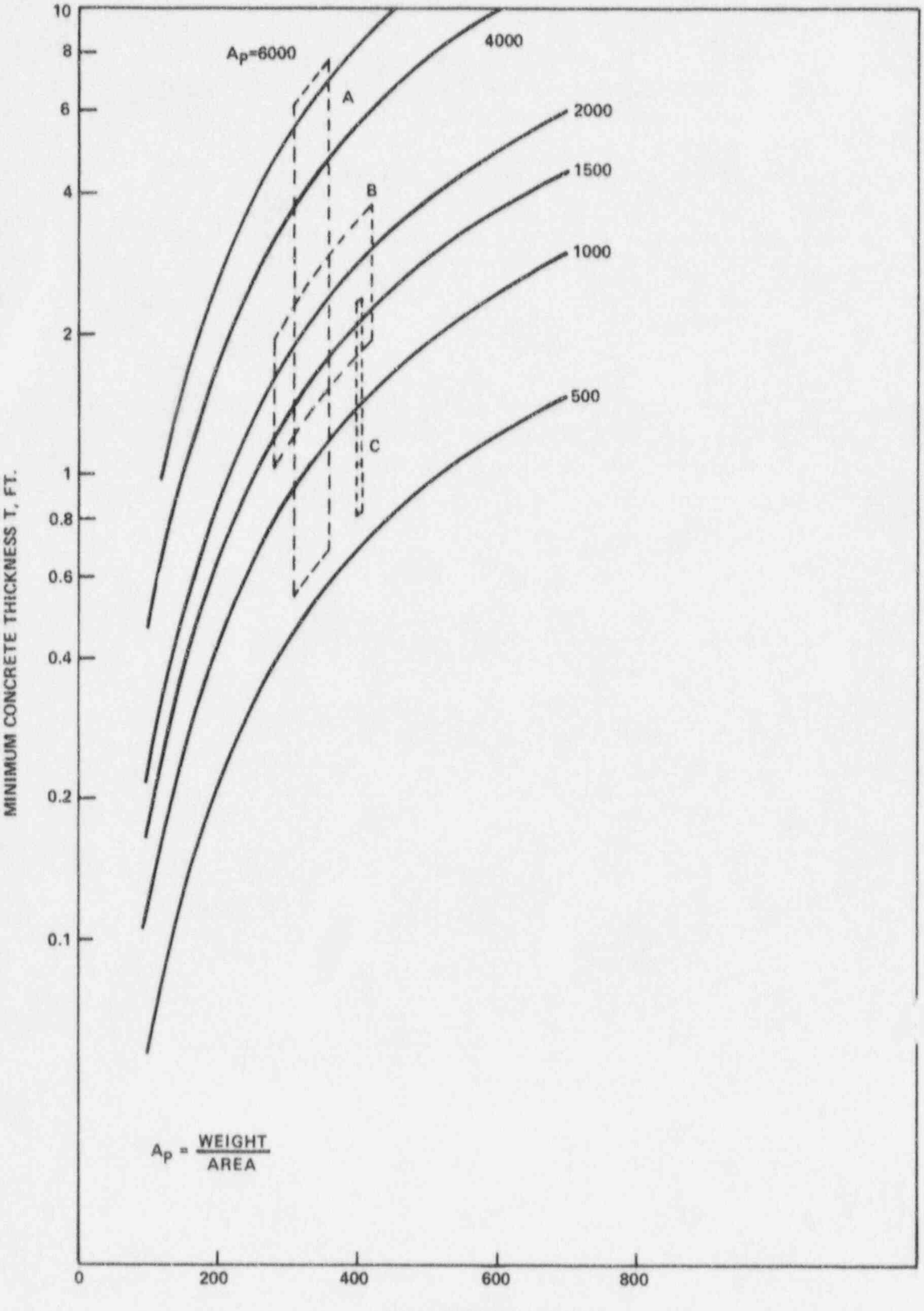

Figure 5. Minimum Concrete Thickness Versus Missile Speed for Various Missiles

The closed boundary areas indicated in Figure 5 represent the variation in missile speeds and missile orientations corresponding to several different examples of turbine missiles (Areas A, B, and C). It can be seen that for a given missile speed, the variation in sectional pressure A_p can be considerable, so that a considerable concrete thickness can be required to eliminate any possibility of penetration.

Considering the randomness of missile orientation, it is possible to introduce the concept of penetration probability, P_3, by assuming that the variation in A_p, and thus in T, is uniformly distributed between the minimum and maximum values for a particular turbine. We may write with respect to each type of turbine that

$$P_3 = \frac{T\ max - T}{T\ max - T\ min} \tag{1}$$

where T_{min} and T_{max} correspond to concrete thicknesses defined by the extreme values of the closed boundaries in Figure 5. Application of Equation (24) to each of the three turbine examples in Figure 5 yields penetration probability curves such as those shown in Figure 6. (Note that this represents an example where measures have been taken to preclude spalling.

III. REFERENCES

1. Bush, S. H., "Probability of Damage to Nuclear Components Due To Turbine Failure," Nuclear Safety, Vol. 14, No. 3, May-June 1973.

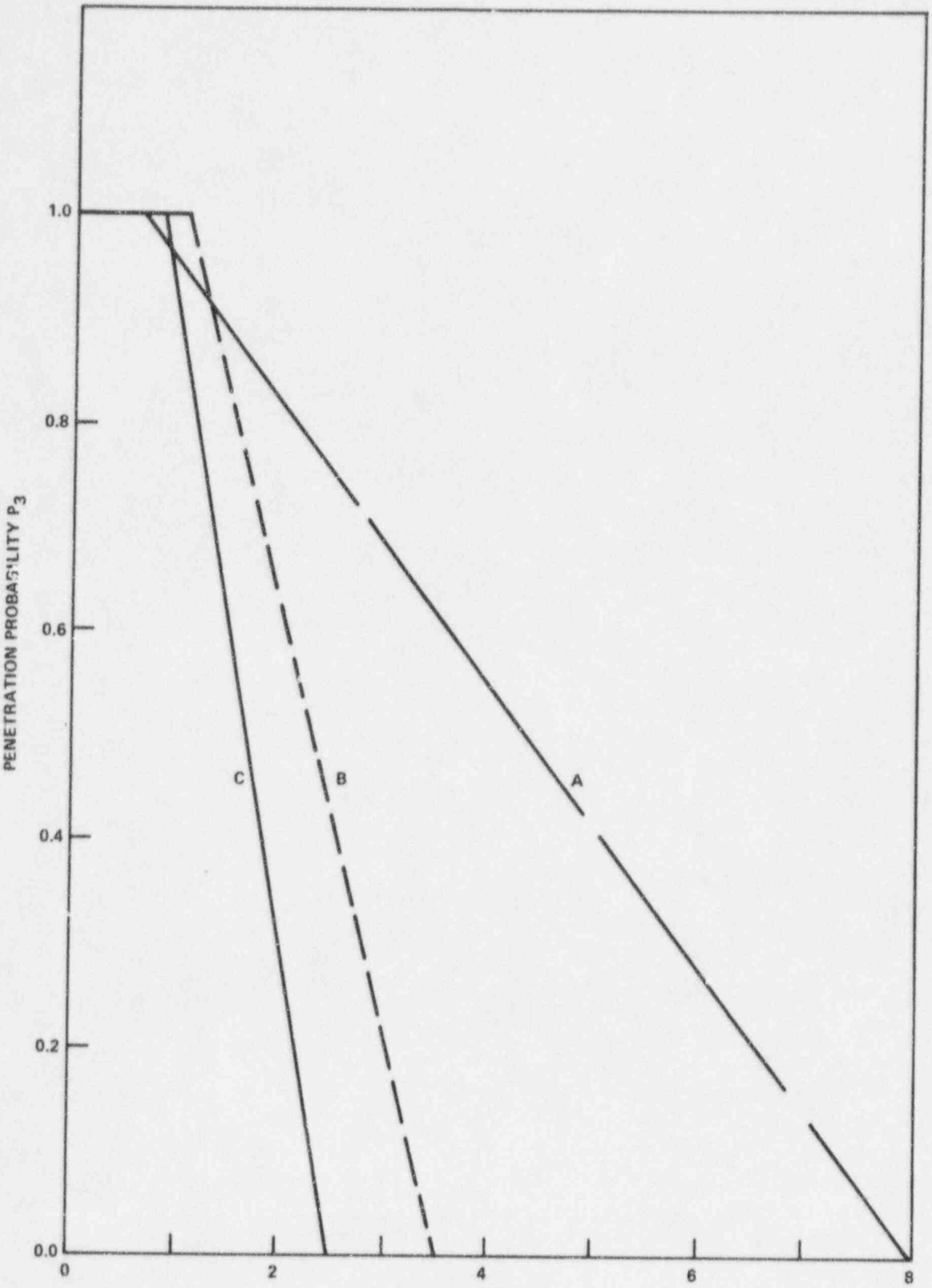

Figure 6. Penetration Probability P_3 Versus 5500 PSI Concrete Thickness Based on a Uniform Distribution in Missile Orientation

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