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KNIGHTON,G. Licensing Branch 3

SUBJECT: Forwards responses to request for addl info re PRA for MHS, per 821122 request.

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Arizona Public Service Company
P.O. BOX 21666 • PHOENIX, ARIZONA 85036

January 31, 1983
ANPP- 22868 - WFQ/KEJ

Director of Nuclear Reactor Regulation
Attention: Mr. G. Knighton, Chief
Licensing Branch No. 3
Division of Licensing
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Subject: Palo Verde Nuclear Generating Station (PVNGS) Docket Nos. STN-50-528/529/530
File: 83-056-026; G.1.01.10

References:
1. Letter from G. W. Knighton, NRC to E. E. Van Brunt, Jr., APS, dated November 22, 1982
2. Letter from E. E. Van Brunt, Jr., APS to T. H. Novak, NRC, dated January 7, 1983

Dear Mr. Knighton:

Attached are responses to the questions forwarded per Reference (1) concerning the Probabalistic Risk Assessment (PRA) for the Palo Verde Ultimate Heat Sink. Should additional questions arise from these responses during NRC review, it may be beneficial for APS and NRC staff to meet and discuss them.

Please contact me if you require any additional information concerning this matter.

Very truly yours,

E. E. Van Brunt

E. E. Van Brunt, Jr.
APS Vice President,
Nuclear Projects
ANPP Project Director

EEVBJr/KEJ/sp
Attachment

cc: E. Licitra (w/a)
J. Wermiel "
L. Bernabei "
P. Hourihan "
K. Berlin "
A. C. Gehr "

B001
1/40

January 31, 1983
ANPP-22868 - WFQ/KEJ

STATE OF ARIZONA)
) ss.
COUNTY OF MARICOPA)

I, Edwin E. Van Brunt, Jr., represent that I am Vice President Nuclear Projects of Arizona Public Service Company, that the foregoing document has been signed by me on behalf of Arizona Public Service Company with full authority so to do, that I have read such document and know its contents, and that to the best of my knowledge and belief, the statements made therein are true.

Edwin E. Van Brunt

Edwin E. Van Brunt, Jr.

Sworn to before me this 31st. day of January, 1983.

David L. Graham

Notary Public

My Commission expires:

My Commission Expires May 19, 1986

PROBABILISTIC RISK ASSESSMENT (PRA) STUDY

PALO VERDE NUCLEAR GENERATING STATION

RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

1. Provide additional justification for exclusion of Class G missiles (auto) from the calculations presented in the PRA study. The justification should include:

(a) Site-specific estimates for the Palo Verde plant of the local surface density of Class G missiles. Such estimates are needed in view of the fact that the ratio between number of Class G missiles and total number of Class A through F missiles can vary from 0.67% to as much as 14.9% (see Table E-1 of PRA study and Table 6-2 of Tornado Missile Risk Analysis - Appendices by Twisdale, et al.).

(b) Estimates based on documented data of ratio between probability of injection of Class G missile and probability of injection of Class A through F missiles.

RESPONSE 1:

One of the assumptions listed in Section 1.4 of the PRA [1] study indicated that

> "...Class G missiles (auto) are excluded from consideration because the parking area and roads are far from the spray pond and a tornado of credible intensity cannot transport them such a distance nor to the elevation of the spray nozzles (12 ft)."

This assumption is more accurately stated as follows:

"...Class G missiles (auto) are excluded from explicit consideration..."

The seven plant survey reported by Twisdale in the EPRI study [2] (Table 6-2) shows a large variation in the number of cars at, and in the vicinity of, nuclear plant sites. The number ranges from a minimum of 50 to a maximum of 1527[a]. The number of cars quoted refers to the total within and surrounding the site boundary. The total number of cars projected to be at the PVNGS site and vicinity is given in Table 5.6-2 of the PVNGS ER-OL [3]. This number is expected to vary with time, but to reach a maximum of 93 cars in 1986. The majority of the cars on site will be located in parking lots outside the plant site security boundary (i.e. on enclosure of about 10^6 ft^2 around each of the power blocks). The nearest of these parking lots is 240 feet (closest corner-to-closest corner) from the spray ponds. Of the total 93 cars on site, a maximum of 10 is expected to be within the security boundary at any one time.

According to the EPRI study [2] the average distance of transportation of utility poles (standard missiles according to the report classification) for an F5 scale tornado is about 100 ft. The upper limit (95th

a. The number of cars appears to be strongly dependent upon the plant status (i.e. phase of construction or operation) and upon the number of communities around the plant site from which employees are drawn. Remote sites (i.e. those like Palo Verde with only a small number of communities within reasonable commute distances) have fewer cars on site because car pools have been shown to be very effective.

percentile) is about 230 ft (see Table 3-4 and Figure 3-10 of the EPRI study). (Note: in Arizona the maximum scale of observed tornadoes is F2.) Based upon consideration of missile velocities the average distance of automobile transport is about 40-60 ft. As discussed in the report, only local (less than 100 ft) potential missiles significantly affect the probability of hitting the target.

Mean values for probability of injection and tornado frequencies are given in Table 1 below. The probability of injection for cars is conservative because the model used in the computer code assumes the random orientation of potential missiles which gives more credit for favorable orientations.

By averaging over all Fujita scales using frequencies of Fujita scale occurrences, the probability of injection per tornado is shown in Table 2 is for standard missile and cars, for both site specific and generic Fujita scale frequencies.

TABLE 1

Fujita F Scale	Mean Injection Probability $\eta(F)$		Frequency of Fujita F Scale Tornado (year^{-1})	
	for "standard" missiles	for cars	Site-specific	Generic
0	0.0454	0.	0.3514	0.2013
1	0.1105	0.	0.6216	0.4336
2	0.1687	0.	0.0270	0.2592
3	0.2083	0.0141	0.	0.0818
4	0.3282	0.0550	0.	0.0194
5	0.4708	0.1053	0.	0.0038
6	0.5817	0.1624	0.	0.0009

TABLE 2

EXPECTED MEAN PROBABILITY OF INJECTION

	Site Specific	Generic
"Standard" Missiles	0.0846	0.1265
Cars	0.	0.0028

Using the above site specific data, the expected number of cars injected by a tornado is essentially zero. If the generic data is used, the probability of injection of a car is 45 times less than the probability of injection of the standard missile.

In summary, the following conditions support the belief that including class G missiles (cars) would not significantly change the conclusions of the analysis: 1) the 10 cars within the security boundary (10^6 ft^2) is a factor of 27 less than the total of 270 potential standard missiles[c] assumed within the same boundary and, 2) the generic probability of car injection is only 2.2% of the probability of standard missile injection. As an additional conservatism, the destructive effect of all class A through F missiles in the report was considered the same and equal to that of a standard missile.

c. 270 = Potential Missile density ($2.7 \times 10^{-4}/ft^2$) x area of security boundary (10^6 ft^2).

2. Explain why "a", rather than the average tornado path area, "$\bar{a}$", is used in Eq. 4.2.

RESPONSE 2:

The use of $\bar{a}$ in Equation 4.2 would yield the average tornado occurrence rate ($\bar{P}_o$). The PVNGS study did not use $\bar{P}_o$; rather, it handled uncertainty explicitly by considering a distribution of the tornado occurrence rate (refer to Table II). Additionally, the use of averaged value $\bar{P}_o$ could lead to erroneous results as shown in Appendix B.

3. Explain why the total probability is not considered in Eq. 4.6, i.e., why the right hand side is not multiplied by $P_o(a)$ and the resultant product is not subjected to summation with respect to a.

RESPONSE 3:

To calculate the expectation (or mean) for the probability of tornado strike, one would multiply equation 4.6 on page 7 of the PVNGS report by $P_o(a)$ and f(a), the probability density of a, thereafter summing (or integrating) over all a. This is the method suggested by the request for additional information. However, since the PVNGS report propagates uncertainties explicitly, such an averaging is unnecessary. Appendix B details the differences and values of both the uncertainty propagation method (the PVNGS method) and the expectation method.

4. Explain discrepancy between values of h_o in section 4.2.5 ($h_o = 2 \times 12$ ft) and on p. 10 ($h_o = 20$ ft).

RESPONSE 4:

The results of the PRA analysis were provided in Table I of the report. The values in Table I were calculated using a computer program that conservatively assumed $h_o = 2 \times 12 = 24$ feet. Table IV provides the results of an earlier hand calculation based on $h_o = 20$ and is provided to demonstrate the variation of $\eta(F)$ and $\Psi(Z, F)$ with F. A footnote should have been added to Table IV to clarify the source of the values. These Table IV values were not used in Table I and, also, are not available as output from the computer program used to generate Table I.

6. It is stated in the PRA study that the tornado missile problem has three times scales: $T_1 = \ell/w$, $T_2 = (\ell/g)^{\frac{1}{2}}$, $T_3 = R/w$, where ℓ = length of missile, w = maximum velocity of tornado, R = characteristic size of the tornado "footprint", and g = acceleration of gravity (p. B-4). An explanation is needed with regard to the characterization of T_2 in the study as a typical rotation time. Also, the validity of the inequality $T_2 < T_3$ (in Eq. B-11) is not clear and should be explained. (For example, if $R \cong 150$ ft and $w \cong 300$ ft/sec, $T_3 = 0.5$ sec, while for $\ell \cong 20$ ft, $T_2 \cong (20/32.2)^{\frac{1}{2}} = 0.8$ sec.)

RESPONSE 6:

There are three aspects to this question: 1) Is T_2 a typical rotation time, 2) Is T_2 less than T_3, and 3) To what extent does the PVNGS analysis depend upon the three time scales T_1, T_2 and T_3? The proof that T_2 is the typical rotational time can be derived from Newton's equation of rotational motion, as shown in Appendix C.

Regarding the second question, it is important to recognize that the values used in the calculation of T_2 and T_3 must be representative of the physical situation. For example, if the wind speed is W = 300 ft/sec (F4 tornado) the typical size of the tornado "footprint" (instant area covered by tornado wind field) is R = 1800 ft (see reference 6 of the report). In this case $T_3 = 1800/300 = 6$ sec and $T_2 < T_3$. Because of correlation between W and R arbitrary values for R and W cannot be put into the expression for T_3. Appendix D calculates typical values for T_2 and T_3.

Regarding the third question, the PVNGS analysis does not depend upon whether $T_2 < T_3$ or $T_2 > T_3$ since there are several randomizing factors. For example, the displacement of a tornado missile changes the vector $\vec{u}$ defined by equation B-3, and changes the directions and values of aerodynamic forces given by equations B-4, B-5 and B-6 of the report.

7. With the respect to the relation

$$\sum_{\gamma} P_o(F, \gamma)\ G(\bar{r}_o, t_o, \bar{r} - \bar{r}_o, t - t_o, \bar{\Omega}, F, \gamma) =$$

$$P_o(F, a)\ G(\bar{r}_o, t_o, \bar{r} - \bar{r}_o, t - t_o, \bar{\Omega}, F, a)$$

(Eq. B-29), where

$$\bar{G}(\bar{r}_o, t_o, \bar{r} - \bar{r}_o, t - t_o, \bar{\Omega}, F, a) =$$

$$\sum_{\gamma'} G(\bar{r}_o, t_o, \bar{r} - \bar{r}_o, t - t_o, \bar{\Omega}, F, \gamma')$$

(Eq. B-30), and

$$\bar{\gamma} = \gamma' \cup a, \ \gamma' \cap a = 0,$$

an explanation is required as to why equation B-29 is not written as follows:

$$\sum_{\gamma} P_o(F, \gamma) G = \sum_{a}\sum_{\gamma'} P_o(\gamma', F, a) G = \sum_{a}\sum_{\gamma'} P_o(\gamma' | F, a)\ P_o(F, a) G$$

$$= \sum_{a} P_o(F, a)\ \bar{G}$$

(note the summation with respect to a, which is absent in equation B-29), where $\bar{G}$ is given by

$$\bar{G}(\bar{r}_o, t_o, \bar{r} - \bar{r}_o, t - t_o, \bar{\Omega}, F, a) =$$

$$\sum_{\gamma'} P_o(\gamma' | F, a)\ G(\bar{r}_o, t_o, \bar{r} - \bar{r}_o, t - t_o, \bar{\Omega}, F, \gamma', a)$$

rather than by equation B-30. For example, if one of the parameters γ' is the direction of translation of the tornado, θ, $P_o(\theta|F, a)$ is a function of θ, rather than being constant for all values of θ (at least to the extent that tornadoes are directed predominantly toward the Northeast). An explanation concerning equations B-29 and B-30 in light of the above comments is required. Note that the relation

$$\sum_{\gamma} P_o(F, \gamma)\ G = \sum_{a} P_o(F, a)\ \bar{G}$$

entails the presence of the summation sign $\sum_a$ in front of the right hand side of equation B-31.

RESPONSE 7:

Summation with respect to a was not included because the PVNGS study does not calculate expectation; rather, it propagates uncertainties. Refer to Appendix I.

8. In the expression

$$P_o(F, a) = P_o(a) \cdot \phi(F|a), \tag{B-32}$$

$P_o(a)$ is defined in the PRA study as probability of any tornado striking per year given by Thom in Ref. 6 of p. B-14. An explanation is required as to why $P_o(a)$ was not defined as the probability of a tornado <u>with area a</u> striking per year, and why equation B-33 does not include the summation sign with respect to a, i.e.,

$$P(\bar{r}, \bar{\Omega}) = \sum_a P_o(a) \cdot h(\bar{r}, \bar{\Omega}|a)$$

The explanation should take into account the fact that the summation does not involve $P_o(a)$ alone, but its product with the function $h(\bar{r}, \bar{\Omega}|a)$.

RESPONSE 8:

The quantity $P_o(a)$ is the conditional probability of tornado occurrence with path area a striking the plant site. It implicitly is restricted to a tornado with area a. The PVNGS study then considered a distribution of tornadoes by path area (refer to Table II). Thus, the final results include a dependence upon the tornadoes included in the distribution.

Summation with respect to a was not included because the PVNGS study does not calculate expectation; rather, it propagates uncertainties. Refer to Appendix I.

9. The angle θ is defined on p. C-1 as the angle between the drag force, F_D, and the vertical axis, Oz. The drag force, F_D, is in turn directed along the velocity $\bar{u} = \bar{w} - \bar{v}$, where $\bar{v}$ = missile velocity (Fig. B-1 and Eq. B-3, Appendix B). Since, at the time of injection, $\bar{u} = \bar{w}$, the drag force vector is colinear with the vector $\bar{w}$. Hence, the angle between the velocity $\bar{w}$ and the vertical axis equals θ. An explanation is required as to why the study assumes that the angle between the tornado velocity, w, and the vertical is uniformly distributed between 0 and π (Eq. C-29).

RESPONSE 9:

In nature the angle θ would be at or near $\pi/2$ since the wind vector is most likely horizontal. However, by choosing a uniform distribution of θ, the PVNGS study increases the frequency of θ to be near an angle of zero, specifically an angle of about 35° ($\theta = \pi/2 - \alpha \cong 90° - 55° = 35°$). Angles near 35° relative to the wind vector correspond to a favorable orientation for injection. Such orientation maximizes the probability of injection (see page B-3 of the report). Thus, the PVNGS study has conservatively overestimated the injection probability by considering θ to be uniformly distributed between 0 and π.

10. Let

$$D_1(\cdot) = \sum_{\gamma} \int_{\vec{v}_o} \int_{\vec{v}\cdot\vec{\Omega}<0} \rho(\vec{v}_o)\,|\vec{v} \cdot \vec{\Omega}|\,(\cdot)\,d\vec{v}_o^{\,3}\; d\vec{v}^{\,3}$$

By definition, $D_1(G) = \bar{G}$. Let now

$$D_2(\cdot) = \frac{1}{n_p} \int_{V_o} \int_{t_o} \int_{t} \rho(\vec{r}_o,\, t_o)(\cdot)\,dV_o\,dt_o\,dt$$

Then

$$D_2[a_i(\vec{r},\, t,\, F,\, a,\, \vec{\Omega}] = D_2\{D_1[a_i(\vec{r},\, \vec{v},\, t,\, F,\, \gamma)G]\}$$

Owing to the presence of the argument t both in $a_i(\vec{r}, \vec{v}, t, F, \gamma)$ and in G, in general

$$D_2\{D_1[a_i G]\} \neq D_2[D_1(a_i)] \cdot D_2\,[D_1(G)] \qquad \text{(relation "A")}$$

by virtue of Eq. D-17,

$$\psi = D_2\,[D_1(G)]$$

The derivation of Eq. D-33 requires substituting the equal sign for the unequal sign in Relation "A" above. An explanation is needed as to why such a substitution is permissible.

RESPONSE 10:

Equation D-33 was not derived in that manner.

The following clarifies the report derivation:

Define:

$$D_1(G) = \bar{G} \tag{10-1}$$

$$D_2[D_1(G)] = D_2(\bar{G}) = \psi \tag{10-2}$$

Step 1. Applying the operator $D_1(\cdot)$ to a_iG:

$$\therefore \quad D_1(a_iG) = \bar{a}_i \bar{G} \tag{10-3}$$

This equation is the definition for $\bar{a}_i$ (see D-28 of report for example):

$$\bar{a}_i \equiv \frac{D_1(a_iG)}{\bar{G}} \tag{10-4}$$

[Note: a_i is not equal to $D_1(a_i)$ as the question implies]

Step 2. Using the axial symmetry and uniformity for variables $\vec{r}_o$, $\vec{v}_o$ and t_o, it was shown that

$$\bar{a}_i \equiv a_i(\vec{r}, t; F, a, \vec{\Omega})$$

actually depends on variable z only (see Eq. D-32 of the report). The details of this step are explained in Response 11.

Step 3. Applying the operator $D_2(\cdot)$ to the expression (10-3):

$$D_2[D_1(a_i G)] = D_2 [\bar{a}_i \bar{G}] = \bar{a}_i \cdot D_2(\bar{G}) = \bar{a}_i \psi$$

As mentioned in Step 2, coefficient $\bar{a}_i$ depends only on z and the integration in the operator D_2 is taken over variables x_o, y_o, z_o, t_o, t. Therefore, coefficient $\bar{a}_i$ can be taken out of operator D_2.

11. A detailed explanation is required of the steps leading from Eq. D-31 to Eq. D-32.

RESPONSE 11:

For the detailed explanation of the steps leading from Eq. D-31 to Eq. D-32, start from the expressions D-22, D-23, D-24, D-25, and D-26 for coefficients a_i, c_i, c_{ik}, d_{ik} and f_{ik}.

The Green's function was averaged over all parameters γ (excluding F and a) before the derivation of equation for Green's function for the sake of simplicity. In this case the equations D-19, D-21 and all equations from D-22 to D-26 reduced to

$$\bar{G}(\vec{r}_o, \vec{v}_o, t_o; \vec{r} - \vec{r}_o, \vec{v} - \vec{v}_o, t - t_o; F, a) \tag{11-1}$$

According to the equation of missile motion (B-7), the gravity force mg and the distribution functions for the random force $\vec{R}$ do not depend on $\vec{r}_o$, $\vec{v}_o$ and t_o. Therefore, the Green's function is satisfied as to the condition of uniformity for variables $\vec{r}_o$, $\vec{v}_o$ and t_o and should not depend on them.

However, due to boundary conditions limiting the missile motion in the vertical direction (see Appendix E) Green's function depends on z_o explicitly:

$$\bar{G}(z_o, \vec{r} - \vec{r}_o, \vec{v} - \vec{v}_o, t - t_o; F, a) \tag{11-2}$$

Thus, the expressions for coefficients of interest a_i and c_{ik} take form:

$$a_i(z; F, a) = \lim_{t' \to t} \left\{ \frac{1}{t' - t} \int_{(V')} \int_{(J')} (x_i' - x_i) \bar{G}(z; \vec{r}' - \vec{r}, \vec{v}' - \vec{v}, t' - t; F, a)\, dV'\, d^3\vec{v}' \right\} \tag{11-3}$$

$$c_{ik}(z; F, a) = \lim_{t' \to t} \left\{ \frac{1}{t' - t} \int_{(V')} \int_{(J')} (x_i' - x_i)(x_k' - x_k) \bar{G}(z; \vec{r}' - \vec{r}, \vec{v}' - \vec{v}, t' - t; F, a)\, dV'\, d^3\vec{v}' \right\} \tag{11-4}$$

All other coefficients disappear after integration of the equation (D-21) over the variable $\vec{v}$.

Because the integrands of the expression (11-3) and (11-4) depend on differences $\vec{v}' - \vec{v}$, $x' - x$, $y' - y$ only the coefficients a_i and c_{ik} do not depend on $\vec{v}$, x and y. Due to $\lim(t' - t) = 0$ these coefficients do not depend on $t' - t$.

Now we take into account the axial symmetry of Green's function:

$$\bar{G}(z; \vec{r}' - \vec{r}, \vec{v}' - \vec{v}, t' - t; F, a) \equiv \bar{G}(z; \sqrt{(x' - x)^2 + y' - y)^2}, z' - z, \vec{v}' - \vec{v}, t' - t; F, a) \tag{11-5}$$

The expression (11-5) is an even function of variables $x' - x$ and $y' - y$. The expressions a_1, a_2, c_{12}, c_{13}, c_{23} are integrals between symmetrical limits for odd functions of arguments $x' - x$ and $y' - y$ and, therefore, are equal to zero.

Because ψ, c_{11} and c_{22} do not depend on x and y, derivatives over these variables are equal zero. Therefore, the final equation for ψ takes the form of equation D-33.

As our derivation shows parameters a(z; F, a) and D(z; F, a) in the equation D-33 formally could depend on path area a. Actually the path area of tornadoes does not affect the Green's function directly. The thing which really affects the Green's function is the width of a tornado.

Really, parameters α_0, α_1, and α_2 in the equations D-41 and D-47 are calculated for wide tornadoes because we implicitly assumed that a tornado missile travels within tornado wind field.

In the case of a narrow tornado, the missile can leave the wind field before landing and the missile trajectory will be cut by length and height. Because of correlation between tornado width and path area it will cause some dependency of Green's function from path area a. We can eliminate this dependency from a if we conservatively assume that the expression for $\psi(z, F)$ which is valid for wide tornadoes is applicable for all tornadoes.

Therefore, the Equation D-33 with parameters a(z, F) and D(z, F) which are not dependent on path area a is conservative because the function $\psi(z, F)$ overestimates the number of missiles elevated on height z for narrow tornadoes.

APPENDIX I

RANDOM VARIABLE TREATMENT

There are several useful approaches to deal with random variables. One uses the expectation of random value. Another calculates expectation relative to a group of random parameters. A third, used in the PVNGS study, considers the confidence interval for a random variable. This appendix examines each approach and its suitability for use in the tornado PRA.

In using the first approach, the probabilities under consideration for the expectation of random value are:

$P_o(a) = \nu \frac{a}{s}$ = Probability per year that a tornado with path area a strikes the plant site.

$f(a)$ = Probability density that a tornado has the path area a.

$\phi(F/a)$ = Conditional probability that a tornado has Fujita scale F given path area a.

$\eta(F)$ = Probability of tornado missile injection given Fujita scale F.

$\psi(Z, F)$ = Probability that an injected missile for Fujita scale F will hit the unit area of a target at elevation Z.

If we introduce the density of potential missiles n_p (the number of potential missiles per unit area) and the area of a target A, the expectation P that the target will be hit by a tornado missile is:

$$P = n_p A \sum_{F=0}^{6} \int_0^{\infty} P_o(a)\ f(a)\ \phi(F/a)\ \eta(F)\ \psi(Z,\ F)\ da \qquad \text{(I-1)}$$

The expression:

$$f(a,F) \equiv f(a)\ \phi(F/a) \qquad \text{(I-2)}$$

is the joint distribution of path area a and Fujita scale F. The expression:

$$P(a,F) \equiv P_o(a)\ n_p\ A\eta(F)\ \psi(Z,\ F) \qquad \text{(I-3)}$$

is the probability per year of hitting the target given path area a and Fujita scale F of the striking tornado.

The limitations of expressions (I-1) and (I-2)) can be shown using a one dimensional example. Let X be a random value distributed by density function f(x). Let R be another random variable dependent upon X according to:

$$R = r(x) \qquad \text{(I-4)}$$

Thus, the random value X will generate another random variable R. Let G(R) represent the distribution of R. This distribution can be expressed analytically as:

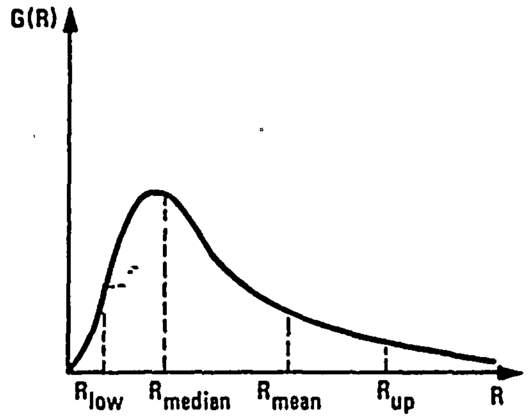
$$G(R) = f[q(R)]\,|q'(R)| \qquad \text{(I-5)}$$

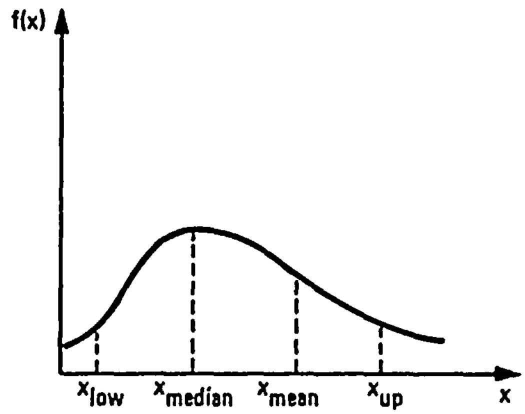
where

$$X = q(R) \tag{I-6}$$

is the inverse function of expression (I-4). The distribution can also be obtained using Monte Carlo simulation techniques.

The distributions of both random variables are shown in the following figures.





The mean or expectation of random variable R can be estimated according to:

$$R_{mean} = \int_{-\infty}^{+\infty} RG(R)\ dR = \int_{-\infty}^{+\infty} r(x)\ f(x)\ dx \tag{I-7}$$

It should be clear that the expectation approach does not identify the spread of the random variable R about the mean.

As a second approach, the expectation relative to one group of random parameters can be calculated. From thence, confidence intervals can be developed for the rest of the variables. The result is a distribution of conditional

expectations. Equation (4.6) of the PVNGS report is an example of a typical conditional expectation. As used therein, it is the expectation for Fujita scales and distribution of all other parameters.

However, the PVNGS study used the more rigorous third approach, namely, propagation of uncertainty. The approach considers the confidence interval for the random variable R. For every level of confidence γ we can estimate the upper and lower limits. The random variable is bounded by the interval $R_{low} - R_{up}$ with the probability γ. The PVNGS study used a 90% confidence interval.

Instead of a single independent random variable x, the PVNGS study considered two variables, a and F. The analog of dependent random variable R is P(a,F). The analog of the function shown in expression (I-4) is expression (I-3). The analog of the distribution f(x) is the joint distribution of expression (I-2). The joint distribution f(a, F) is considered in the PVNGS report in Section 3 of Appendix A. It is also presented as Table V of the report. Moreover, values such as ν, η_p, $\eta(F)$, etc., are random variables also, albeit for different reasons. Their distribution functions are presented in Tables II, III, and IV of the PVNGS report. Through computer analysis, the PVNGS study randomly generated all variables of expression (I-3). It then developed the distribution for $P(a,F,\nu,n_p,\eta(F), \ldots)$. Based upon this distribution, the PVNGS study obtained the confidence interval for the probability P.

Due to this rigorous analysis of uncertainty, the only expression needed for simulation is expression (I-3). Thus, integration over a (or other parameters) is not required.

Question 3 of the request for additional information implies that expression (I-1) is the total probability. However, the total probability is the cumulative probability for some interval (or domain under multidimensional analysis). In other words, it is the integral over the density function. For example, the expressions:

$$F(x) = \int_0^x f(x')\, dx' \qquad \text{(I-8)}$$

$$f(a) = \sum_{F=0}^{6} f(a, F) \qquad \text{(I-9)}$$

$$\psi(F) = \int_0^\infty f(a, F)\, da \qquad \text{(I-10)}$$

are examples of total probabilities because the individual probabilities of different values of the random parameters are summed.

The PVNGS study did not lose information or reject any contributions to different values of parameters (such as path area a) since all information is contained in the distribution of probability P. The medians and upper limits are presented in Table I of the report.

The request for additional information also proposed to use $P_o(\bar{a}) = \nu\,\bar{a}/s$ rather than $P_o(a) = \nu\,a/s$ (see question 2). The use of the averaged expression, as proposed, requires an assessment of its applicability. Consider the following example. Let the wall of some building be designed to withstand tornado winds up to some value w_o. A simplified expression for the probability of wall destruction D(w) is:

$$D(w) = \begin{cases} 0, & w \leq w_o \\ 1, & w > w_o \end{cases} \tag{I-11}$$

Using the averaged approach, the probability of wall damage P_D is the product of the probability of tornado strike per year, $P_o(\bar{a})$, and the probability of the exceeding wind speed w_o given tornado strike $F(w > w_o)$:

$$P_D = P_o(\bar{a})\ F(w > w_o) \tag{I-12}$$

where

$$P_o(\bar{a}) = \nu \frac{\bar{a}}{s}$$

and

$$F(w > w_o) = \int_0^\infty f(w)\ D(w)\ dw = \int_{w_o}^\infty f(w)\ dw$$

where f(w) is the density function for tornado wind speed.

Using a lognormal distribution for the function f(w) with parameters μ_w and σ_w we obtain:

$$P_D = P_o(\bar{a}) \left[\frac{1}{2} - \Phi\left(\frac{\ln w_o - \mu_w}{\sigma_w}\right)\right] \tag{I-13}$$

where

$$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_0^x e^{-Z^2/2}\, dZ \tag{I-14}$$

A rigorous analysis requires the consideration of the joint distribution f(a, w) because of the correlation between a and w:

$$P_D = \int_0^\infty \int_0^\infty P_o(a)\, D(w)\, f(a, w)\, da dw \equiv \int_0^\infty \int_{w_o}^\infty P_o(a)\, f(a, w)\, da dw \tag{I-15}$$

Using the lognormal distributions with parameters μ_a and σ_a for argument a and the correlation coefficient ρ we obtain a more correct formula:

$$P_D = P_o(\bar{a}) \left[\frac{1}{2} - \Phi\left(\frac{\ln w_o - \mu_w - \rho\sigma_a \sigma_w}{\sigma_w}\right)\right] \tag{I-16}$$

This expression yields a significantly higher value for P_D than expression (I-13). For a wall designed to withstand Fujita Scale F4, expression (I-13) may underestimate the probability of damage by more than two orders of magnitude.

Thus, the averaged approach can only be used where the risk does not depend upon wind speed or the Fujita Scale. In the PVNGS study, the probabilities of injection, $\eta(F)$, and missile elevation, $\psi(F)$, depend upon Fujita Scale. Thus, $P_o(a)$ was used instead of $P_o(\bar{a})$.

To avoid confusions in Appendix B of the report, some change in notation is proposed. The last two lines of the page B-8 through equation (B-31) should read:

"Excluding parameter "a" from parameter set γ and taking sum over a new set γ' we obtain:

$$\sum_{\gamma'} P_o(F,\ \gamma)\ G(\vec{r}_o,\ t_o;\ \vec{r} - \vec{r}_o,\ t - t_o;\ \vec{\Omega};\ F,\ \gamma) =$$

$$\sum_{\gamma'} P_o(F,\ a)\ G(\vec{r}_o,\ t_o;\ \vec{r} - \vec{r}_o,\ t - t_o;\ \vec{\Omega};\ \vec{F},\ a,\ \gamma') = \qquad \text{(B-29)}$$

$$P_o(F,\ a)\ \bar{G}(\vec{r}_o,\ t_o;\ \vec{r} - \vec{r}_o,\ t - t_o;\ \vec{\Omega};\ F,\ a)$$

where $\bar{G}$ is an averaged Green's function determined by the formula:

$$\bar{G}\ (\vec{r}_o,\ t_o;\ \vec{r} - \vec{r}_o,\ t - t_o;\ \vec{\Omega};\ F,\ a) =$$

$$\sum_{\gamma'} G\ (\vec{r}_o,\ t_o;\ \vec{r} - \vec{r}_o,\ t - t_o;\ \vec{\Omega},\ F,\ \gamma') \qquad \text{(B-30)}$$

The averaged Green's function posseses a higher degree of symmetry that simplifies the calculations.

The conditional expectation $P(\vec{r}, \vec{\Omega}, a)$ can be determined by formula:

$$P(\vec{r}, \vec{r}, a) = \sum_F P_o(F, a)\ \eta(F) \times$$

$$\int_{V_o} \int_{t_1}^{t_2} \int_{t_1}^{t_2} P_p(\vec{r}_o, t_o)\ \bar{G}(\vec{r}_o, t_o; \vec{r} - \vec{r}_o, t - t_o; \vec{\Omega}; F, a)\ dV_o dt_o dt \quad \text{(B-31)}$$

The beginning of the section B.3 should be read as follows:

"The joint distribution f(a, F) of path area a and Fujita scale F given tornado strike is:

$$f(a, F) = f(a)\ \Phi(F/a) \quad \text{(B-32)}$$

where f(a) is the distribution of path area given by Thom and $\Phi(F/a)$ is the relative frequency of occurrence of F-scale tornado given path area a.

The probability per year $P_o(F,a)$ that tornado with path area a and Fujita scale F strikes a point target is:

$$P_o(F, a) = P_o(a)\ f(a)\ \Phi(F|a) \quad \text{(B-32A)}$$

The expression (B-31) can be rewritten as:

$$P(\vec{r}, \vec{\Omega}, a) = P_o(a) \cdot h(\vec{r}, \vec{\Omega}|a) \quad \text{(B-33)}$$

APPENDIX II

DERIVATION OF T_2

According to the equation of moment:

$$J \cdot \beta = M \tag{II-1}$$

where:

J = Moment of inertia

β = Angular acceleration

M = Moment of force

It is clear that:

$$J \sim m \times \ell^2 \tag{II-2}$$

$$\beta \sim \frac{1}{T_2^2} \tag{II-3}$$

and for most cases:

$$M \sim mg\ell \tag{II-4}$$

The Eq. (II-4) does not mean that we take into account only gravitational force. It is only the order of magnitude evaluation of resultant moment of forces including gravity, restraint and aerodynamic forces.

During the missile flight the center-of-mass and the center-of-pressure for symmetrical bodies, such as a cylinder, coincide. Therefore, the moment of force M equals zero, and the state of rotation cannot be changed. The rotation of missile could be created at the moment of injection, however. Consider two most frequent scenarios leading to the missile rotation.

Scenario 1. The horizontal injection of a missile

Consider a potential missile initially located at some elevation. At some moment the aerodynamic force can overcome the restraint and move the potential missile to the brink of a storage area. The moment created by aerodynamic force and restraint will orient the missile in downwind direction. The very moment of horizontal injection is shown in Figure II-1.

For this case:

$$J = \frac{1}{12} m\ell^2 \tag{II-5}$$

$$M = \frac{1}{2} mg\ell \tag{II-6}$$

$$\beta = \frac{2\pi}{T_2^2} \tag{II-7}$$

and finally

$$T_2 = \sqrt{\frac{2\pi}{6} \cdot \frac{\ell}{g}} \approx \sqrt{\frac{\ell}{g}}$$

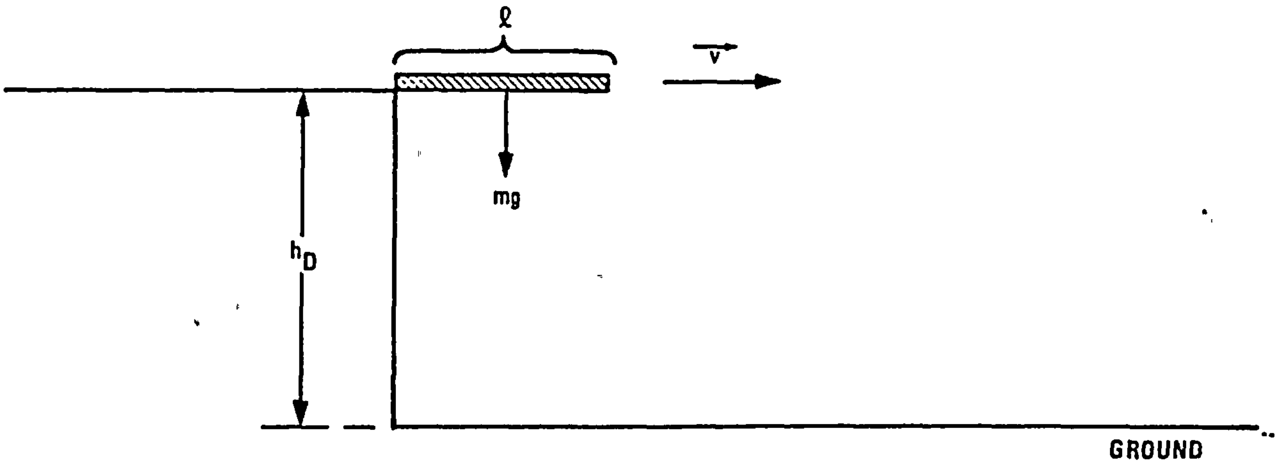


Figure II-1

Scenario 2. The vertical injection of a missile.

The very moment of vertical injection is shown in Figure II-2.

At the moment of injection (see equations C-33 and C-53):

$$F_L = mg \tag{II-8}$$

because the lift force F_L has to overcome gravity.

According to equations C-9 and C-10:

$$\frac{F_L}{F_D} = \cot(\alpha) \tag{II-9}$$

and

$$F_D = mg\tan(\alpha) \tag{II-10}$$

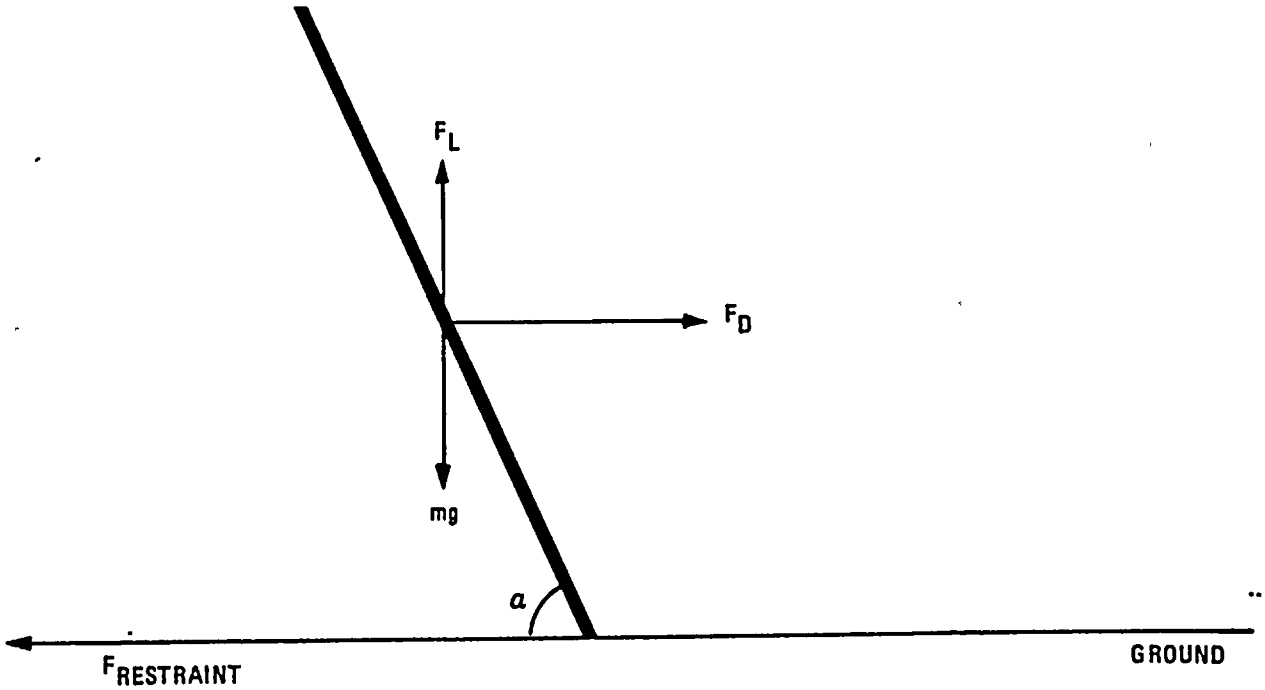


Figure II-2

The expression for the moment M is:

$$M = \frac{1}{2} mg\ell \cdot \alpha \cdot \sin\alpha \tag{II-11}$$

The expressions for J and β are the same as for Scenario 1. Putting (II-5), (II-7) and (II-11) into (II-1) we get:

$$T_2 = \sqrt{\frac{2\pi}{6} \quad \frac{\cos\alpha}{\sin^2\alpha} \quad \frac{\ell}{g}} \tag{II-12}$$

Usually, the condition of vertical injection (II-8) takes place when the angle of attack α is close to 55° (maximum value for F_2). For this case:

$$T_2 = 0.95 \sqrt{\frac{\ell}{g}} \approx \sqrt{\frac{\ell}{g}} \tag{II-13}$$

Therefore, for most important cases the typical rotational time has the order of magnitude $\sqrt{\ell/g}$.

APPENDIX III

CALCULATION OF TYPICAL VALUES FOR T_2 AND T_3

As defined in the PRA study:

$$T_2 = \sqrt{\frac{\ell}{g}} \qquad \text{(III-1)}$$

$$T_3 = \frac{R}{W} \qquad \text{(III-2)}$$

where:

ℓ = length of tornado missile (ft)

g = gravitational constant (g = 32.19 ft/sec^2)

R = characteristic size of tornado "footprint" (ft) (equal to tornado path width)

W = average velocity of tornado wind field (ft/sec)

Let $f(\ell)$ be a density function for missile length distribution and f(R,W) be a joint distribution of tornado width and average wind speed. Then the average, or typical, values for T_2 and T_3 are:

$$\bar{T}_2 = \int_0^\infty \sqrt{\frac{\ell}{g}}\, f(\ell)d\ell \qquad \text{(III-3)}$$

$$\bar{T}_3 = \int_0^\infty \int_0^\infty \frac{R}{W}\, f(R,W)\ dRdW \qquad \text{(III-4)}$$

Length distribution according to survey data shown in EPRI study is given in Table III-1.

TABLE III-1

LENGTH DISTRIBUTION

Length of Missile (ft)	Number of Potential Missiles	Frequency	$\sqrt{\frac{\ell}{g}}$
2	1306	0.0498	0.2493
4	5804	0.2212	0.3525
6	1876	0.0715	0.4317
8	2584	0.0985	0.4985
10	4577	0.1744	0.5574
12	3801	0.1449	0.6106
14	217	0.083	0.6595
16	1371	0.0522	0.7050
18	0	0.0000	0.7478
20	4702	0.1792	0.7882

The average $\bar{T}_2$ is:

$$\bar{T}_2 = 0.5396 \text{ sec.}$$

[Even for a hypothetical conservative spectrum of lengths assumed in the study (80% ℓ = 20 ft and 20% ℓ = 35 ft), the average time $\bar{T}_2$ is:

$$\bar{T}_2 = 0.8391 \text{ sec.}$$]

The distribution $f(R,\dot{W})$ based on nationwide data for 30 years of data is presented in Table III-2.

TABLE III-2

JOINT PROBABILITY DISTRIBUTION
(WIDTH-FUJITA SCALE)

	.0	1.0	2.0	3.0	4.0	5.0	6.0	WIDTH
1.25	.0375	.0262	.0050	.0006	.0000	.0000	.0000	.0693
1.75	.0765	.0955	.0311	.0040	.0004	.0000	.0000	.2074
2.25	.0567	.1883	.1459	.0354	.0073	.0009	.0000	.4344
2.75	.0095	.0478	.0635	.0335	.0145	.0006	.0000	.1694
3.25	.0042	.0210	.0368	.0272	.0147	.0039	.0000	.1079
3.75	.0003	.0011	.0034	.0038	.0025	.0004	.0000	.0116
4.25	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
4.75	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
FUJITA SCALE								
	.1847	.3799	.2857	.1046	.0393	.0058	.0000	

In Table III-2 the first column is log R where R is measured in feet and the first row is Fujita scale. Last column is a marginal distribution for R and last row is a marginal distribution for F. The joint frequency f(R, W) can be found on the intersection of row for given log R and column for given wind speed depending on Fujita scale F. Taking a middle value from this range we can calculate $T_3 = R/W$ for every frequency shown in Table III-2.

The average value for $\bar{T}_3 = 2.4537$ sec.

Therefore,

$$\bar{T}_2 < \bar{T}_3$$

If we take into account that an average wind speed W should be put into equation (III-2) rather than a maximum value, we can conclude that the real value for $\bar{T}_3$ is even greater.

APPENDIX IV

Consider the Feynman's interpretation of Green's function $G(\vec{r}_o, \vec{v}_o, t_o; \vec{r} - \vec{r}_o, \vec{v} - \vec{v}_o, t - t_o)$.[4, 5]

Let a missile be injected at moment t_o at point $\vec{r}_o$ with velocity $\vec{v}_o$ and hit a target at moment t at point $\vec{\ell}$ with velocity $\vec{v}$. Now consider the set of virtual trajectories which is consistent with equation of motion (equation B-7 of report) and satisfies the above initial and final conditions.

The probability of realization of some trajectory from the set Γ is denoted as:

$$P(\vec{r} - \vec{r}_o, \vec{v} - \vec{v}_o, t - t_o; \Gamma) \tag{IV-1}$$

According to Feynman, the Green's function $G(\vec{r}_o, \vec{v}_o, t_o; \vec{r} - \vec{r}_o, \vec{v} - \vec{v}_o, t - t_o)$ can be calculated by formula:

$$G(\vec{r}_o, \vec{v}_o, t_o; \vec{r} - \vec{r}_o, \vec{v} - \vec{v}_o, t - t_o) = \sum_{\Gamma} P(\vec{r} - \vec{r}_o, \vec{v} - \vec{v}_o, t - t_o; \Gamma) \tag{IV-2}$$

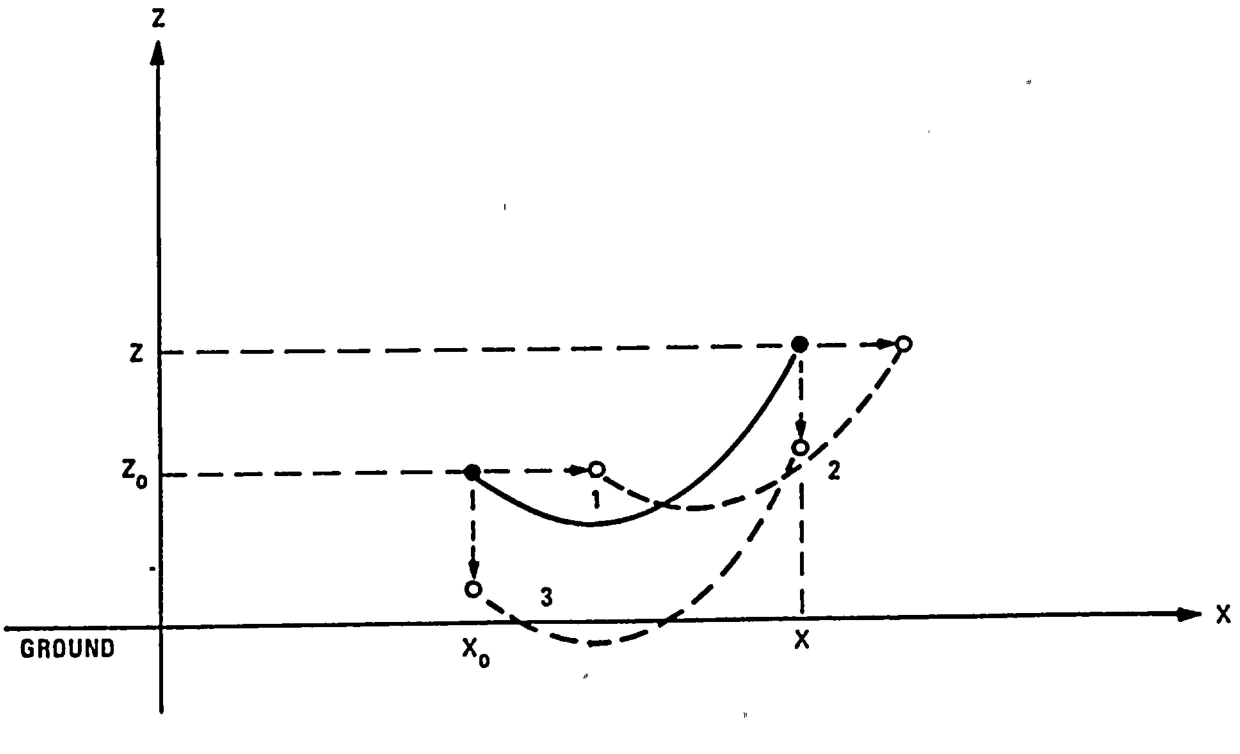
The uniformity of Green's function or dependence of Green's function only from differences $\vec{r} - \vec{r}_o$, $\vec{v} - \vec{v}_o$, and $t - t_o$ means that a parallel translation of the missile source and the target in the space of variables $\vec{r}$, $\vec{v}$, and t does not change the set of trajectories Γ and their probabilities of realization $P(\vec{r} - \vec{r}_o, \vec{v} - \vec{v}_o, t - t_o; \Gamma)$.

In our case it is true for all translations except of translation in the vertical direction (see Figure IV-1). For example, the virtual trajectory 1 connecting points (x_o, z_o) and (x, z) will correspond to the virtual trajectory 2 after parallel translation in the x-direction.

In the case of parallel translation in the z-direction, the corresponding trajectory 3 could intersect the ground and will not contribute into sum (IV-2) any more.

Therefore, the available set of trajectories $\Gamma(z_o)$ is a function of the missile source elevation z_o.

In the case when all potential missiles have the same elevation z_o = count (for example, ground distribution of potential missiles with $z_o = 0$) the parameters a and D in the equation D-33 do not depend on z (but their value depends on z_o).



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