in meteorite weight is 2800 to 173 million tons. The data used to relate tsunami height to energy were obtained primarily from tsunamis that originated within ~100 miles from the points where runup was observed. Therefore, we consider only meteorites impacting within 100 miles of the site (and in the sea) in this analysis. It should be evident that meteorites with higher energies can impact further from the site and still produce a 20-ft runup. It is of interest to point out that the Alaska earthquake of Mar. 1964, which resulted in tsunami amplitudes along the U.S. Pacific coast (at distances of from about 1200 to 2400 miles) ranging from <1 ft to over 29 at Crescent City, California, registered about 8.5 on the Richter scale, indicating an energy release of about 3.5×10^{24} erg. A meteorite of 10^{12} tons, with the minimum velocity of 37 000 ft/sec, has a kinetic energy of 5.8×10^{29} erg, which is 166 000 times as great as the energy release of the Alaskan earthquake. This meteorite has a probability of 1×10^{-9} per year for an area the size of the U.S., which is equivalent to a semicircular area with a radius of 1570 miles. This alone should cast doubt upon the very low probability reported by Solomon et al.[2]

By using the data from Table I of Solomon et al.,[2] the probability is calculated and found to range from $\sim 2 \times 10^{-6}$ to 2×10^{-9} per coastal plant year (Table I) for 20-ft tsunamis resulting from meteorite impacts within 100 miles of the plant. It is evident from the above discussion that:

1. We still have a long way to go before we can even feel confident that we know the order of magnitude of the probability of coastal plant damage due to meteorite-induced tsunamis. Our understanding of seismically produced tsunamis is limited, yet people have seen and recorded those. We know of no documented case, however, of a tsunami produced from a meteorite impact.
2. The value given by Solomon et al.[2] for tsunami damage to coastal plants is probably orders of magnitude too low. The one extreme value of 2×10^{-6} per year is probably too high. A reasonable guess would put the value at about 10^{-7} to 10^{-8}. This value is only for tsunamis generated within 100 miles of the site, and does not consider tsunamis generated by larger meteorites impacting further away.

Implicit in the above discussion was the assumption that the plant is located near an "average" coast. However, tsunami runup can be very sensitive to the local bathymetry and shoreline configuration. Some locations (such as Crescent City, California) can focus an incoming tsunami wave resulting in much higher than average runups, while other locations will diverge tsunami energy resulting in lower than average runups. We can therefore conclude that meteorites within the energy range given in Table I can generate 20-ft tsunamis at distances greater than 100 miles if local bathymetry and shoreline geometry are conducive to long-wave amplification.

The U.S. Nuclear Regulatory Commission looks carefully at all proposed coastal plants, even those in aseismic areas, to provide assurance that a plant will either be built in a location relatively insensitive to tsunamis or be designed to withstand such events. It is for this reason that we believe that the probability of meteoritic tsunami damage to a coastal nuclear plant is well below the design level of 10^{-7} per plant year. It is our position, however, that the probability is not as insignificant as indicated by Solomon et al.,[2] and thus the problem cannot be considered as closed.

Myron H. Fliegel
Lewis G. Hulman

U.S. Nuclear Regulatory Commission
Division of Technical Review
Office of Nuclear Reactor Regulation
7920 Norfolk Avenue
Bethesda, Maryland 20015

March 3, 1975

REFERENCES

1. K. A. SOLOMON, R. C. ERDMANN, T. E. HICKS, and D. OKRENT, "Estimate of the Hazards to a Nuclear Reactor from the Random Impact of Meteorites," UCLA-ENG-7426, University of California at Los Angeles (Mar. 1974).

2. K. A. SOLOMON, R. C. ERDMANN, and D. OKRENT, "Estimate of the Hazards to a Nuclear Reactor from the Random Impact of Meteorites," *Nucl. Technol.*, **25**, 68 (1975).

3. KUMIZI IIDA, "Magnitude and Energy of Earthquakes Accompanied by Tsunami, and Tsunami Energy," *J. Earth Sci., Nagoyi Univ.*, **6** (1958).

4. KUMIZI IIDA, "Magnitude, Energy, and Generation of Tsunamis, and Catalogue of Earthquakes Associated with Tsunamis," *Proc. Tsunami Mtgs. Associated with the 10th Pacific Science Congress*, Monograph No. 24, IUGG (1963).

5. S. L. SOLOVIEV, "Recurrence of Tsunamis in the Pacific," *Proc. Intern. Symp. Tsunamis and Tsunami Research* (1969).

ADDITIONAL COMMENTS ON "ESTIMATE OF THE HAZARDS TO A NUCLEAR REACTOR FROM THE RANDOM IMPACT OF METEORITES"

In a recent paper[1] it was estimated that potential serious damage to a reactor in the U.S. due to a postulated meteorite impact has a likelihood of $\sim 7 \times 10^{-9}$ per reactor per year, assuming a target area of 10^5 ft^2. At the end of the paper, the estimate was reported, with reference to a UCLA report,[2] that the likelihood of coastal reactor destruction due to a meteorite-induced sea wave was $\sim 2 \times 10^{-10}$ per coastal reactor per year.

The comments to this paper given by Fliegel and Hulman[3] take issue with the wave destruction likelihood cited above. They suggest that the probability of meteorite-induced wave damage is certainly $<10^{-7}$ per plant year for a coastal plant, but not as low as the 2×10^{-10} number cited earlier. In attempting to respond to the interesting points raised by Fliegel and Hulman, we first outline the method used in Ref. 2 and then give some further considerations of the wave-induced damage mechanism.

In Ref. 2, the reactor was assumed to be located one-tenth mile from shore and 30 ft above sea level on a straight coast line, and to be protected by a 20-ft sea wall. For these conditions, and treating meteorite impact into the sea as an explosion, Van Dorn's formula[4] (relating wave height, distance from explosion, and TNT equivalent of the explosion) was applied. It was assumed that runup would be small and that a wave height of ~50 ft at the coastline was needed to top the sea wall and damage the reactor. The forcing function for the meteorite case is basically a point rather than a planar source, and it was not anticipated that a seismically induced tsunami would be representative.

The technique applied was as follows:

1. For each distance, $d(R)$, [where for practical purposes $d(R)$ = 1, 50, 100, 150, . . . 1000 miles] estimate the amount of energy $Y(R)$ that is needed to produce a tidal wave of 50 ft at the coast [a distance of $d(R)$ away].

2. Assume the meteorite impact to be inefficient (1% conversion); hence multiply $Y(R)$ by a factor of 100 to get $E(R)$, the energy of the meteorite required to produce $Y(R)$ in the water. Thus $E(R) = 100\ Y(R)$.

3. Determine the required meteorite mass to produce $Y(R)$ (at each distance) from $E(R) = \frac{1}{2} M(R)V^2$. Select V in the range of 37 000 ft/sec.

4. From Blake's paper[5] determine the probability of having a meteorite of mass $M(R)$ as a function of distance.

TABLE I

Kinetic Energy and Likelihood of Impact of the Meteorite

Meteorite Weight (tons)	Kinetic Energy (g cal)	Likelihood of Impact Anywhere on Earth (per year)
10^{12}	2.76×10^{22}	6.0×10^{-8}
10^{11}	2.76×10^{21}	2.6×10^{-7}
10^{10}	2.76×10^{20}	1.3×10^{-6}
10^{9}	2.76×10^{19}	7.0×10^{-6}
10^{8}	2.76×10^{18}	3.0×10^{-5}
10^{7}	2.76×10^{17}	1.6×10^{-4}
10^{6}	2.76×10^{16}	8.0×10^{-4}

We have extended the original estimate to include effects of a potentially larger efficiency of conversion, as well as damage from lesser wave heights to provide some basis for comparison.

For a 1% energy conversion and a required wave height of 50 ft at the reactor location on the coast, the probability of significant damage to a coastal reactor by a meteorite-induced wave is estimated to be 2×10^{-10} per yr. For a 1% energy conversion and a required wave height of 20 ft at the coast, this probability is increased to $\sim 2 \times 10^{-9}$ per yr. For a 100% energy conversion and a required wave height of 50 ft, this probability is $\sim 7 \times 10^{-9}$ per yr. Finally, the probability of damaging a coastal reactor by a meteorite-induced wave for a 100% conversion and a required 20-ft wave height of the coast is $\sim 5 \times 10^{-7}$ per yr.

Similar results (within ~20%) were obtained using another formula; details of the second calculation are given below.

The kinetic energy of the meteorite (immediately prior to impact) is given in Table I, assuming an incident velocity of 3.7×10^4 ft/sec. Also given is the likelihood of impact anywhere on earth.

Given a meteorite impact, the likelihood of being within a given distance from ground zero is shown below.

Distance from Ground Zero (miles)	Likelihood of Being Within a Half Circle
100	7.9×10^{-5}
500	2.0×10^{-3}
1000	7.9×10^{-3}
2000	3.2×10^{-2}

When a meteorite crashes into the ocean it transfers a great deal of energy to the water, either in the form of surface waves or as heat. According to Hwang,[6] an estimate of 1% efficiency for conversion of kinetic energy to wave energy is not unreasonable, and the efficiency should be larger for very large meteorites, perhaps 10%. Herein, we use 100% efficiency to provide some form of upper bound in this regard.

The waves generated are large and they attenuate with distance in deep water. We expect their deep ocean behavior to follow the formulas developed from nuclear

TABLE II

Wave-Height Data for Various Meteorite Weights

Meteorite Weight (tons)	Wave Height at Various Distances from Ground Zero (ft)			
	100 miles	500 miles	1000 miles	2000 miles
10^{12}	7.71×10^3	1.54×10^3	7.71×10^2	3.85×10^2
10^{11}	2.44×10^3	4.9×10^2	2.44×10^2	1.22×10^2
10^{10}	7.71×10^2	1.54×10^2	7.71×10^1	3.85×10^1
10^{9}	2.44×10^2	4.9×10^1	2.44×10^1	1.22×10^1
10^{8}	7.71×10^1	1.54×10^1	7.71	3.85
10^{7}	2.44×10^1	4.9	2.44	1.22
10^{6}	7.71	1.54	0.77	0.38

TABLE III

Likelihood per Year of Impact in Ocean of Meteorite of Given Weight Within Given Distance from Reactor

Meteorite Weight (tons)	Likelihood/yr Within Radius (miles)			
	100	500	1000	2000
10^{12}	4.7×10^{-12}	1.2×10^{-10}	4.7×10^{-10}	1.9×10^{-9}
10^{11}	2.2×10^{-11}	5.5×10^{-10}	2.2×10^{-9}	8.0×10^{-9}
10^{10}	1.0×10^{-10}	2.8×10^{-9}	1.1×10^{-8}	4.4×10^{-8}
10^{9}	5.5×10^{-10}	1.4×10^{-8}	5.5×10^{-8}	2.2×10^{-7}
10^{8}	2.3×10^{-9}	6.0×10^{-8}	2.4×10^{-7}	9.5×10^{-7}
10^{7}	2.3×10^{-8}	3.2×10^{-7}	1.3×10^{-6}	5.0×10^{-6}
10^{6}	6.5×10^{-8}	1.6×10^{-6}	6.5×10^{-6}	2.5×10^{-5}

ocean surface explosions. There may, however, be some increase in wave height as land is approached. However, since this phenomenon will be uniquely site-related, we have not taken it into account explicitly. (We do not expect the Crescent City data to be applicable at a carefully chosen reactor site.)

From Ref. 7, for example, one can write a formula similar to Van Dorn's, i.e.,

$$H = 2.45 \times 10^4 \sqrt{W}/R \qquad (1)$$

as the relation between wave height, H, in feet above sea level, kiloton explosive equivalent, $\sqrt{W}$, of the meteorite and distance from ground zero, R, in feet. Note that

$$1\ kT\ \text{(equiv)} = 4.18 \times 10^{19}\ \text{erg} \ .$$

Table II provides wave-height data for the various meteorite weights.

Table III combines the data on meteorite strike probability with the likelihood of being at or less than some distance from point of impact as a function of meteorite weight.

In summary, the original estimate appears to be reasonable, assuming a 50-ft wave requirement and 1% efficiency of conversion of kinetic energy to wave formation. Probabilities larger by 2 or 3 orders of magnitude can be calculated assuming up to 100% efficiency and only a 20-ft wave requirement at the reactor site. Hence, Fliegel and Hulman raise an interesting point.

Kenneth Alvin Solomon

NUS Corporation
14011 Ventura Boulevard
Sherman Oaks, California 91423

Robert C. Erdmann

Science Applications, Inc.
2680 Hanover Street
Palo Alto, California 94303

Gerald S. Lellouche

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

David Okrent

University of California
Department of Energy and Kinetics
Los Angeles, California 90024

June 9, 1975

REFERENCES

1. K. A. SOLOMON, R. C. ERDMANN, and D. OKRENT, "Estimate of Hazards to a Nuclear Reactor from the Random Impact of Meteorites," *Nucl. Technol.*, **25**, 68 (1975).

2. K. A. SOLOMON, R. C. ERDMANN, T. E. HICKS, and D. OKRENT, "Estimate of the Hazards to a Nuclear Reactor from the Random Impact of Meteorites," UCLA-ENG-7426, University of California at Los Angeles (Mar. 1974).

3. M. H. FLIEGEL and L. G. HULMAN, "Comments on 'Estimates of Hazards to a Nuclear Reactor from the Impact of Meteorites,'" *Nucl. Technol.*, **27**, 527 (1975).

4. W. G. VAN DORN, "Handbook of Explosion Generated Water Waves," Vol. 1, Report #447-464, Tetra-Tech, Inc. (1970).

5. V. E. BLAKE, "A Prediction of Hazards from the Random Impact of Meteorites in the Earth's Surface," *Aerospace Nuclear Safety*, SC-RR-68-838 (Dec. 1968).

6. LI SAN HWANG, Tetra-Tech, Inc., Pasadena, California, Personal Communication.

7. S. GLASSTONE, *The Effect of Nuclear Weapons*, U.S. Department of Defense and the U.S. Atomic Energy Commission (1969).

COMMENTS ON REVIEW OF *PUBLIC ISSUES OF NUCLEAR POWER*

I appreciate this opportunity to provide my comments to the review[1] by James Smathers which, in my opinion, is insensitive to the structure, contents, and purposes of the publication. In writing these comments, I am aware that my involvements with the planning and development of the proceedings became a labor of love and dedication