Waste Isolation Pilot Plant

Compliance Certification Application

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Long-Term Meteorite Hazards to Buried Nuclear Waste Report 2. In Assessment of Effectiveness of Geologic Isolation Systems: A Summary of FY-1978 Consultant Input for Scenario Methodology Development, B.L. Scott, G.L. Benson, R.A. Craig, and M.A. Harwell, eds., PNL-2851. Pacific Northwest Laboratory , Richland, WA.

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Assessment of Effectiveness of Geologic Isolation Systems

A SUMMARY OF FY-1978 CONSULTANT INPUT FOR SCENARIO METHODOLOGY DEVELOPMENT

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CHAPTER VI

LONG-TERM METEORITE HAZARDS TO BURIED NUCLEAR WASTE

Report 2

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SUMMARY

The main purpose of this study is to put into analytic form information on the frequency of meteorite impact events large enough to affect buried nuclear wastes. Part 1 presents new data on the relation between crater size and total impact energy, with equation (1) expressing the relation. Part 2 derives equation (6), which gives the rate of accumulation of area covered by craters larger than diameter D. A graphical relation between D and the depth of disturbance (Figure VI-2) is given. This section concludes that the probability of a single site 600 m deep being disturbed in a million years is of the order 2.5 x 10^{-6}. Part 4 points out that meteorite impacts are also sources of seismic disturbance and should be factored into the seismic model for the hazard study. Equation (8) gives a methodology for including meteorite impacts in the seismic model. Part 5 and equation (9) give a methodology for dealing with repositories with extended surface area. Part 6 gives examples of applications.

RELATION BETWEEN CRATER SIZE AND TOTAL ENERGY

Figure VI-1 shows the relationship between crater size and energy of an incoming meteorite. New information on this subject has come from several sources. In September 1976, a major symposium on "Planetary Cratering Mechanics" was held in Flagstaff, and the results were published in 1978 (Roddy et al., 1978). Several papers, especially Croft (1978) and Vortman (1978) discuss the energy needed to produce a terrestrial crater of certain size. A review of the material indicates that there is a significant spread in estimated total kinetic energy required to produce an impact crater of certain size, partly because most empirical data on large craters come from explosions of different types rather than impacts.

The solid line in Figure VI-1 shows the curves derived in previous work, based on Baldwin (1963), and the x's in Figure VI-1 show the recent estimates of total energy expended to make craters of several sizes, based on Croft (1978). The average of Croft's and Baldwin's figures tend to be a factor of about 2 or 3 less than the results of Baldwin.

A purpose of this report is to put relevant meteorite data into a simple analytical form for use in a computer model for release scenario analysis. An adequate fit to the new data (as well as the old data) in Figure VI-1 is given by:

$$\log D = 0.288 \log KE - 6.637 \qquad (1)$$

where

D = crater diameter (km)

KE = total kinetic energy of meteorite at impact (ergs)

Check: Using the diameter of Meteor Crater, Arizona, 1.04 km, the equation yields log KE = 23.1. This figure is in the range of energy currently estimated for that event, as summarized by Croft (1978).

DERIVATION OF ANALYTIC TREATMENT OF CRATERING HAZARD

Both terrestrial and lunar craters have been used to derive crater production rates. The lunar craters are easier to use because they offer more complete statistics, being well-preserved in the 3.5×10^9 year old lava flows of the moon. Studies indicate that the lunar and terrestrial rates are within a factor 2 of each other, an uncertainty comparable to or less than the uncertainty in the terrestrial rate. In previous work, therefore, a rough mean rate for the last 3.5×10^9 years was used, derived by dividing crater density on average lunar lava flows (craters/km^2) by the average age of the flows (in years) to get craters formed/km^2/yr.

This fit is accurate within an estimated 40% or better for craters larger than D = 2 km. Below this size, it is probably accurate for primary meteorite impact craters (those formed by meteorite impact) but neglects the secondary impact craters (formed by debris thrown out of primaries) that begin to be more numerous at sizes below about 2 km on the moon. For this study the curve for primaries will be used, because (1) secondaries on earth may be less numerous because of atmospheric drag effects, and (2) secondaries are of less significance at diameters above 500 m (which are of concern in this study) than at smaller sizes.

In the hazard evaluation program, a parameter that seems more useful than the total number of craters formed per km^2/yr is the total area A covered by craters per km^2/yr, because the total area covered by craters determines the fractional amount of ground excavated to below a given depth. A factor that is important in determing the total area covered by craters is crater diameter. The total area covered by craters per km^2/yr can be evaluated as follows. The incremental diameter frequency function is (by differentiating Equation 3):

$$dN = -1.80\ C\ D^{-2.8}\ dD$$

Therefore the area in each increment is:

$$dA = \pi\,(D/2)^2\ dN = \frac{\pi}{4}\,D^2\ dN$$

$$= \frac{1.80\pi C}{4}\,D^{-0.8}\ dD$$

TABLE VI-1. Results from Equation (6) and Comparison with Data From Previous Work

Excavation Depth (d) (m)	Fracture Depth (d_f) (m)	Crater Diam. (D) (km)	Log A	Log A Value from Previous Work	Years Required to Cover 60% of Area with Craters of Diameter D (= 1/A)
10	40	.05	-11.5	-9.4[a]	3 (11)
33	132	.19	-11.6	-11.5	4 (11)
100	400	.64	-11.6	-11.5	4 (11)
333	1332	2.5	-11.7	-11.6	5 (11)
1,000	4,000	9.2	-11.8	-12.1	6 (11)
3,333	13,332	38.7	-12.0	-12.4[b]	1 (12)
10,000	40,000	128	-13.0	-12.4[b]	1 (13)

(a) This value is considerably higher than that in the new calculation, because it takes into account the abundant secondaries, whereas the present calculation neglects them. They appear so shallow that they are not a serious part of the total hazard.

(b) These values are somewhat higher than the older values because of a difference in the diameter distribution of craters assumed in the two studies. The new distribution, based on a least squares fit to crater count data, appears more accurate. The risk is so small from these rare, large-D craters that the difference appears unimportant. Agreement at other diameters is quite good.

The time required to cover any given fraction of the U.S. (or any other area) with craters larger than D can be easily computed. The inverse of A, i.e., 1/A, gives the timescale needed to cover a large fraction (some 60%) with craters. For example, A for 2.5 km craters, which excavate to 100 m and fracture to 400 m, is found to be 2.06 x 10^{-12}/year. One would have to wait 1/A = 5 x 10^{11} years to accumulate enough area to cover most of the ground. To get a 1% chance of penetration or fracturing to the depths indicated, one would have to wait 5 x 10^{9} years. Other probabilities can be similarly scaled.

Because the repository studied in the July 1977 Battelle workshop is considered to be 600 m deep with a proposed lifetime of 1 million years, it is possible to estimate from equation (6) or Table VI-1 that the probability of penetration in 10^{6} years is about 10^{6}/4 x 10^{11}, or 2.5 x 10^{-6}, and the time to increase the probability of penetration by fractures to near 100% would be roughly 4 x 10^{11} years.

NOTE ON CONSTANCY OF CRATERING RATE

Analyses of cratering, both by empirical Apollo evidence and celestial mechanical theory of asteroid orbits, indicates that the cratering rate in the current 10^{8} year period is nearly constant and may be declining slightly on the long term as interplanetary debris are swept up. Although there is always a chance of some new debris being injected into our part of the solar system by perturbation of material in other regions, it appears unlikely that a strong surge of meteoritic cratering could seriously affect the hazard to nuclear wastes in the next 10^{6} years.

METEORITE IMPACTS AS SEISMIC ENERGY SOURCES - ANALYTIC TREATMENT

An impacting meteorite carries a certain amount of initial kinetic energy. In addition to being dissipated by crushing and accelerating rock to make the crater, this energy is partly dissipated in the form of seismic waves. Therefore, it appears appropriate to treat the meteorites not only as an excavation hazard, but as a source of seismic disturbances randomly distributed in time and space.

This equation gives the seismic energy dissipated during formation of a crater of size D. The frequency N (events/km^2/yr) is given by equation (5) as:

$$\begin{aligned} \log N &= -1.80 \log D - 12.74 \\ &= -1.80\ (0.288 \log SE - 6.115) - 12.74 \\ &= -0.518 \log SE - 1.73 \\ &= \log\ (\text{no. seismic events/km}^2\text{/yr}) \end{aligned}$$

where

$$SE = \text{energy of seismic source in ergs.} \tag{8}$$

This formulation should permit meteorite impacts to be treated in the release scenario analysis as a form of earthquake with the random frequency specified by equation (8). It will admittedly be small but might be significant in geological areas that are otherwise thought to be very stable and seismically quiet.

EXTENDED VS. "POINT" REPOSITORIES

Equation (6), giving the rate at which areas are excavated to depth d(D) or fractured to depth $d_f(D)$, was formulated to allow evaluation of meteorite hazards in the case where a repository has a surface dimension $<<$D. In this case, such as a repository in the form of a shaft a few meters wide, the repository was viewed as a point and the question was asked, simply, how long will it take until one of the sufficiently large craters overlaps that "point?"

In the June 1978 workshop at Battelle, several participants referred to an extended repository area, perhaps encompassing over 10 km^2 or more. The entire area would need to be kept free from disturbance. A breach or disturbance is assumed to occur if any part of this area is penetrated to the critical burial depth (usually taken as 600 m).

In this case a new methodology is needed. Equation (6) is no longer useful, but equation (5) permits easy evaluation of the hazard. One simply selects the crater diameter D viewed as constituting a threat. For example, from Figure VI-2, D must be = 6 km in order to excavate to 600 m, and D must

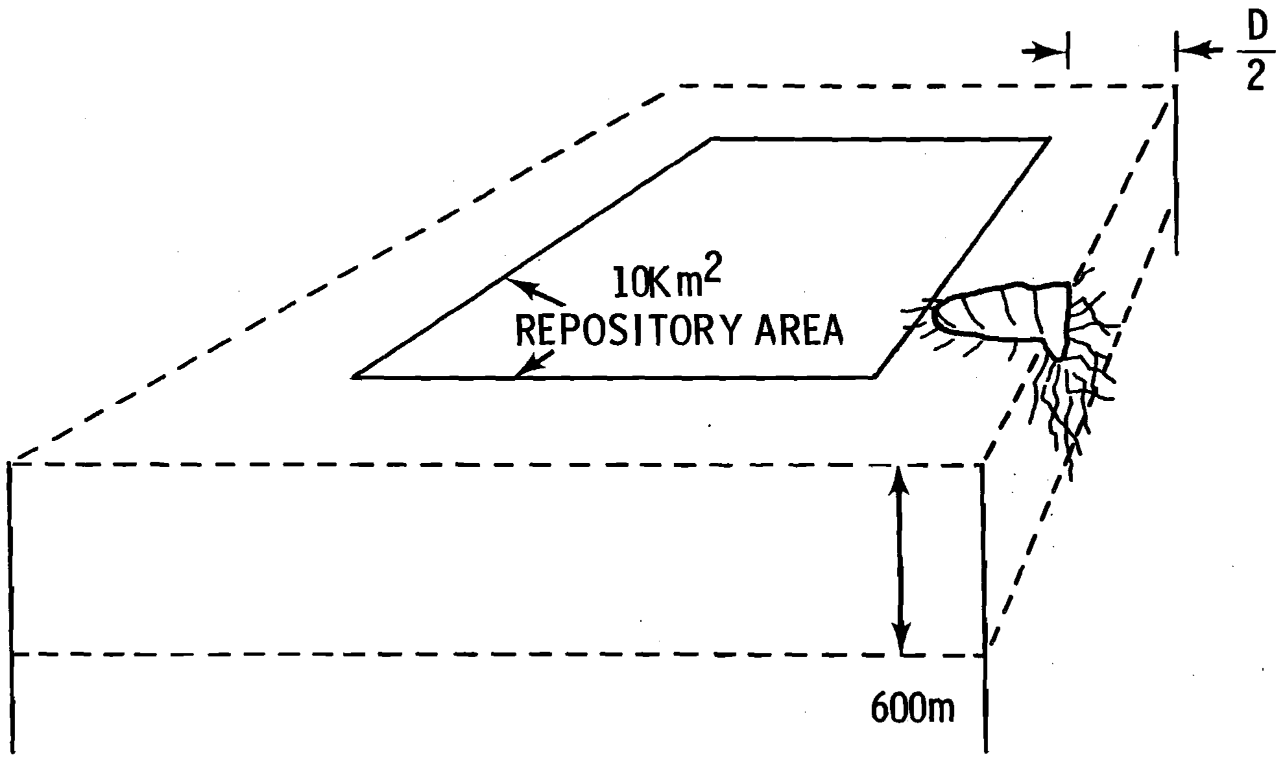

FIGURE VI-3. Sketch of Repository Surface Area (solid lines) Showing Damage Extending into Repository from an Impact Crater Lying in a Zone Just Outside Repository (dashed line). Critical area is thus given by width of repository plus a zone of D/2 on each side. Impact anywhere in this larger zone, as evaluated in text, causes damage in repository if crater diameter is larger than the D value specified.

From Figure VI-2, D = 1 km for d_f = 600 m

From Figure VI-3, the critical area is $(\sqrt{10} + 1)^2 = 17\ km^2$

From Equation 9,

$$\text{No. craters} = N_D AT = 1.82\ (10^{-13})\ (1)\ 17\ (10^6)$$
$$= 3 \times 10^{-6} = \text{probability.}$$

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