

CHAPTER VI

LONG-TERM METEORITE HAZARDS TO BURIED NUCLEAR WASTEReport 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 2.5×10^{-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

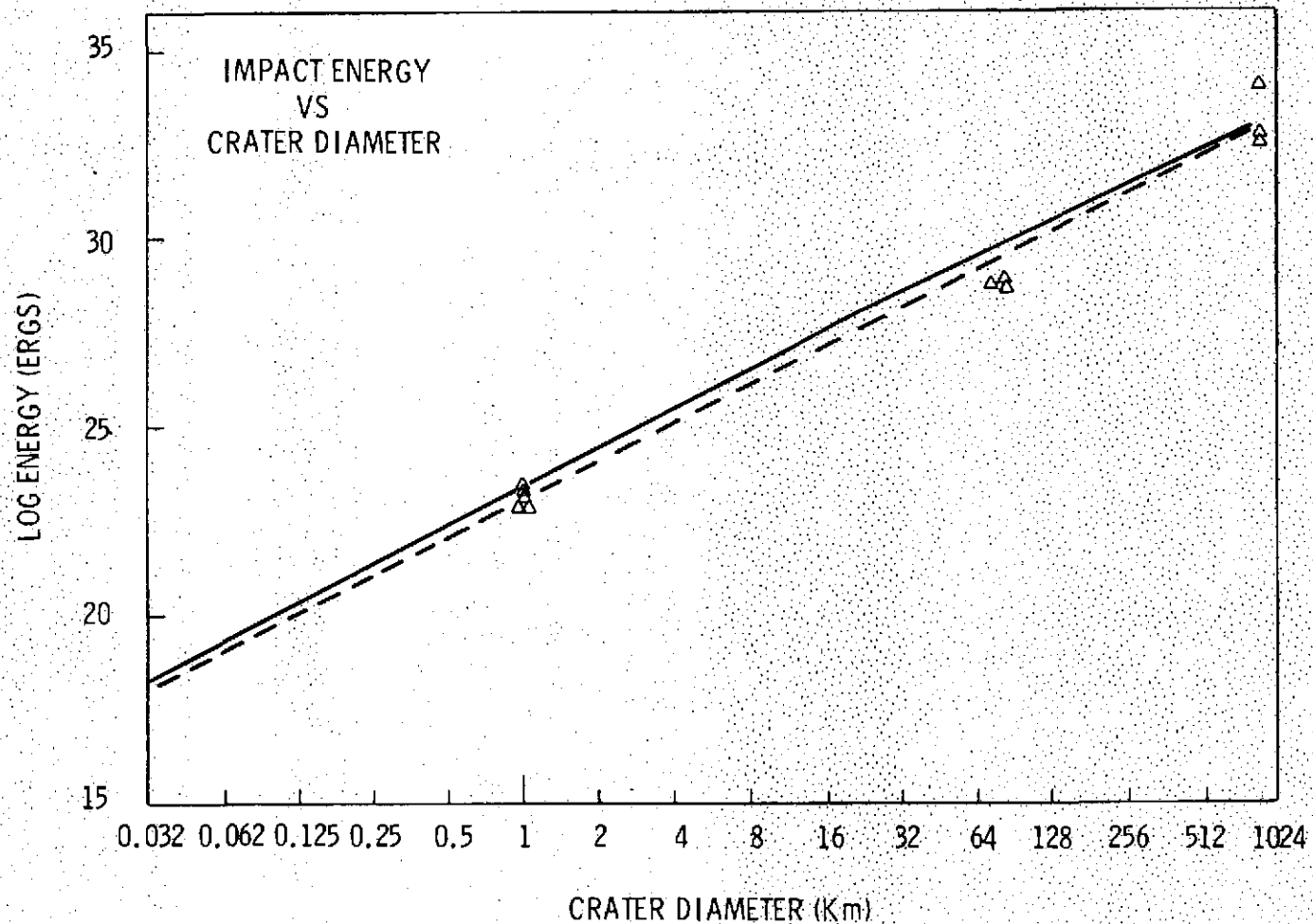


FIGURE VI-1. Relation of Total Kinetic Energy of Meteorite on Impact with Diameter of Resulting Crater. Solid line gives equations developed by Baldwin (1963). Xs give estimates for different-sized craters in recent summary by Croft (1978). Dashed line is analytic equation developed here (Equation 1).

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:

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

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/km²) by the average age of the flows (in years) to get craters formed/km²/yr.

A comparison of actual crater counts of different Apollo landing sites with the measured rock ages at these sites provides information on the rate of change of cratering rate with time. This comparison has been done with early data and, more recently, with updated data (Hartmann, 1972; Hartmann et al., in preparation). Two results are that (1) it is possible to show that the crater production rate was declining during formation of the lunar lavas, up until about 3×10^9 years ago, and (2) it is possible to estimate the figure applicable at the present time by fitting the lunar data to terrestrial data derived from craters in geologic provinces such as the Canadian Shield and eastern U.S., where dozens of eroded craters have been found. Thus, the time dependence can be sketched throughout a time interval from about 3.5 to less than 1 billion years ago. The results indicate that the cratering rate has been relatively constant (within a factor of perhaps 3) in the last 2.5 billion years, even though it was much larger earlier.

In this way it is found that impact craters larger than 4 km diameter are currently being formed at about a rate of

$$N_4 = 1.5 \times 10^{-14} \text{ craters of } D > 4 \text{ km/km}^2/\text{yr.} \quad (2)$$

From the same data (craters on the lunar maria, primarily) a least squares solution of crater diameter distribution has been found to be:

$$N = C D^{-1.80} \quad (3)$$

From equations (2) and (3), we have the constant,

$$C = 1.82 (10^{-13}) \quad (4)$$

so that

$$N_D = 1.82 (10^{-13}) D^{-1.80} \text{ craters/km}^2/\text{yr} \quad (5)$$

where

$$N_D = \text{formation rate of craters of diameter } > D \text{ km (craters/km}^2/\text{yr)}$$

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 determining 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:

$$\begin{aligned} dA &= \pi (D/2)^2 dN = \frac{\pi}{4} D^2 dN \\ &= \frac{1.80\pi C}{4} D^{-0.8} dD \end{aligned}$$

Therefore the cumulative area of craters bigger than D is:

$$\begin{aligned}
 A &= \int_{D_{\max}}^D dA = - \frac{1.80 C}{4} \int_{D_{\max}}^D D^{-0.8} dD \\
 &= - \frac{1.80\pi C}{4} \left(\frac{1}{0.2} \right) \int_{D_{\max}}^D D^{+0.2} \\
 &= 1.29 (10^{-12}) \left[D_{\max}^{+0.2} - D^{+0.2} \right]
 \end{aligned}$$

The resulting number is fairly insensitive to the value chosen for D_{\max} , which in the case of the lunar lava plains is about 181 km. Using this number for D_{\max} , we have:

$$\begin{aligned}
 A &= 1.29 (10^{-12}) [2.8 - D^{+0.2}] \quad (6) \\
 &= \text{area excavated by all craters larger than } D \text{ km/km}^2/\text{yr} \\
 &= \text{fractional area excavated /yr.}
 \end{aligned}$$

Table VI-1 gives some tabular examples of the rate of area coverage by craters of different diameters D and depths d, and shows that the results from Equation (6) are reasonably consistent with the graphical results derived in previous work.

To evaluate the probability of an impact penetrating deeper than depth d, or causing fractures to depth d_f , one simply chooses the depth with which one is concerned, determines the minimum diameter crater (D) that affects this depth, and then solves equation (6) for that D-value to get the rate at which surface area is chewed up to that depth. The relation of crater depth d, fracture depth d_f , and crater diameter D is graphically shown in Figure VI-2.

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.

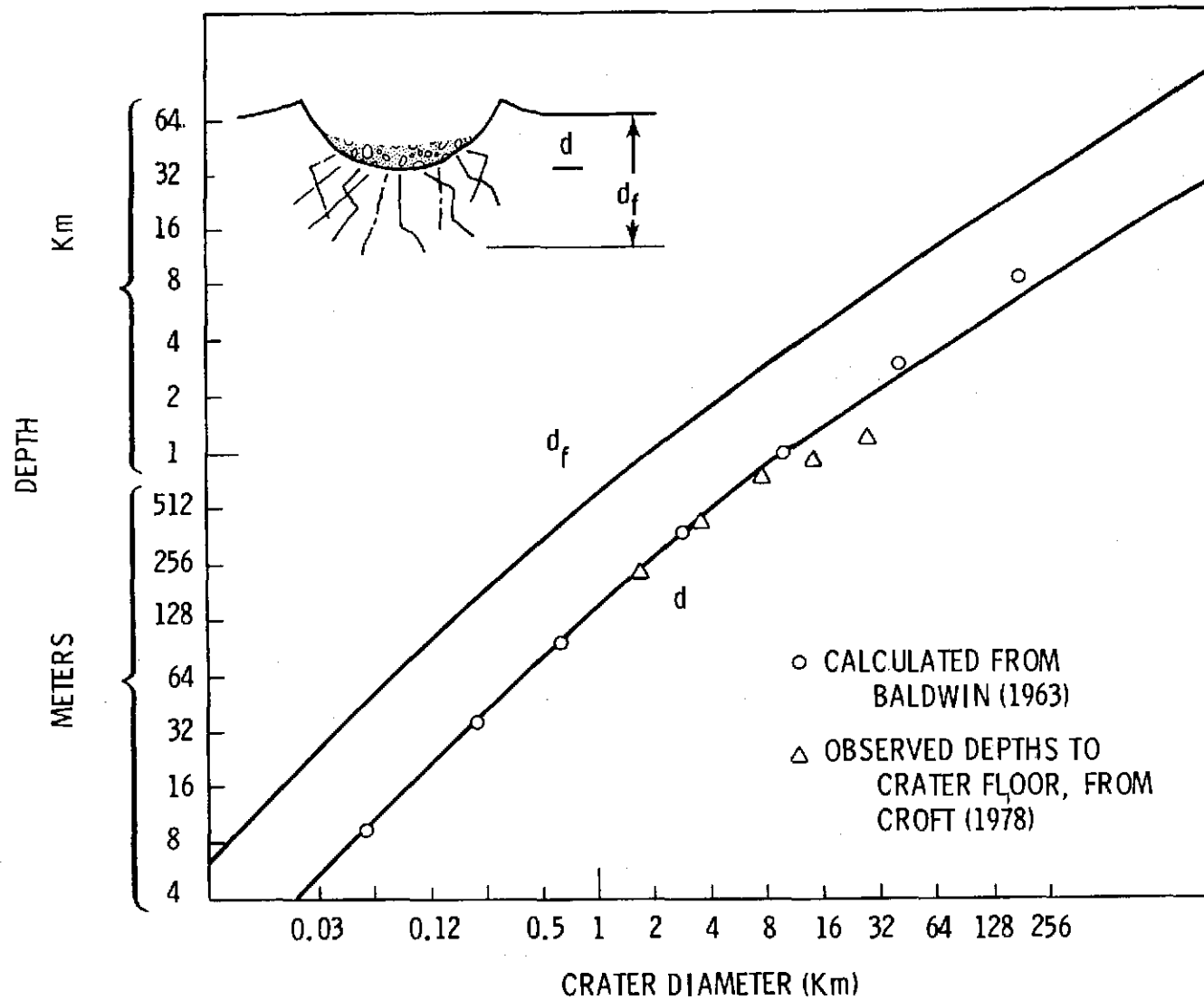


FIGURE VI-2. Relation Between Crater Diameter (D) and the Depth of Excavation (d) and the Depth of Fracturing (d_f)

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 2.06×10^{-12} /year. One would have to wait $1/A = 5 \times 10^{11}$ 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 5×10^9 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 $10^6/4 \times 10^{11}$, or 2.5×10^{-6} , and the time to increase the probability of penetration by fractures to near 100% would be roughly 4×10^{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.

There is some controversy in the cratering literature about how much energy finally dissipates in the form of seismic waves, because a certain fraction is lost in heating and crushing the target rock layers. The accelerated ejecta eventually returns to earth, so that a certain part of its kinetic energy ultimately appears as seismic waves, in addition to the seismic waves from the impact site. O'Keefe and Ahrens (1977) have recently studied the partitioning of energy during impact and have compared their results (which are essentially theoretical) with earlier small-scale experiments. They found that about 40% of the energy in high-speed (5 km/sec) impact is lost in heating of the target, compared to an earlier finding from small-scale lab impacts (6.2 km/sec) of roughly 30%. The two studies disagree on how the remaining 60-70% of the initial energy is distributed. O'Keefe and Ahrens suggest 50% goes into crushing or plastic deformation of rock and 10% into ejecta kinetic energy. The earlier study (Gault and Heitowit, 1963) puts these two percentages at about 15% and 55%, respectively. In any case, it appears that the ultimate amount of energy dispersed as seismic waves is unlikely to be more than 30% of the initial total and may be as small as a few percent. We will take 30% as the upper bound for the purposes of the hazard study.

We therefore have:

$$SE = 0.3 KE$$

where

SE = energy dispersed as seismic energy

KE = initial total kinetic energy of impact.

From equation (1), we have:

$$\log D = 0.288 \log (3.33 SE) - 6.637$$

Therefore,

$$\log D = 0.288 \log SE - 6.115 \tag{7}$$

This equation gives the seismic energy dissipated during formation of a crater of size D. The frequency N (events/km²/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

$$SE = \text{energy of seismic source in ergs.} \quad (8)$$

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 $\ll D$. 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 km² 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

be = 1 km in order to fracture to 600 m. From equation (5), we see that the number of craters expected in a critical area A, during time T (T = 10⁶ years in the Battelle study) is:

$$\text{No. craters (size D)} = N_D A T \quad (9)$$

As shown in Figure VI-3, the critical area A must be calculated from the width of the repository plus a zone of width D, because an impact centered just outside the repository could penetrate into it.

In typical applications, the number of craters calculated in equation (9) comes out to be far less than 1. The calculated number is interpreted as a probability of breach or disturbance during time T.

EXAMPLES

1. What is the timescale for formation of craters larger than D = 1 km in North America (where impact craters have been relatively well-cataloged geologically)?

Equation (5) gives formation rate

$$N_D = 1.82 (10^{-13}) D^{-1.80} \text{ craters/km}^2/\text{yr}$$

Area of North America is $2.4 \times 10^7 \text{ km}^2 = A$.

$$\begin{aligned} \text{Thus, No. of craters/yr} &= N_D A \\ &= 1.82 (10^{-13}) (1) (2.4) (10^7) \\ &= 4 \times 10^{-6} \text{ craters/yr} \end{aligned}$$

This number indicates that the time required to get a high probability of one crater is about 200,000 years. North America may have two craters in this interval of time. The famous Arizona crater (D = 1.2 km) is estimated to be roughly 20,000 years old. The New Quebec crater in Canada (D = 3.4 km) is probably somewhat older.

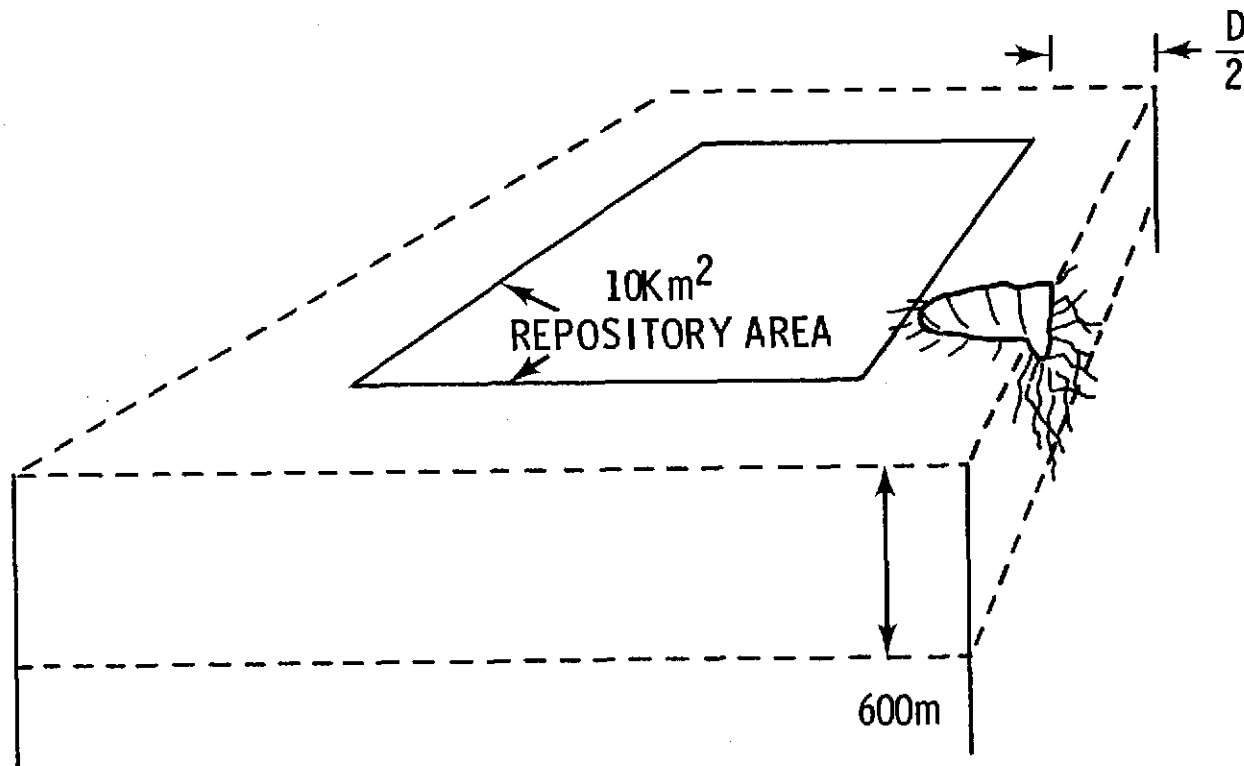


FIGURE VI-3. Sketch of Repository Surface Area (solid lines) Showing Damage Extending into Repository from an Impact Crater Lying in a Zone Just Outside Repository (dashed line). Critical area is thus given by width of repository plus a zone of $D/2$ on each side. Impact anywhere in this larger zone,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

2. How many craters larger than $D = 10$ km would be expected to have formed in the Canadian Shield during the roughly 10^9 yr during which its surface rocks have been exposed and stable?

$$\text{Area of Canadian Shield} = A = 3.7 \times 10^6 \text{ km}^2$$

Using the same formulation as above, we have

$$\text{No. craters} = N_D A T = 1.82 (10^{-13}) 10^{1.80} 3.7 (10^6) (10^9) = 11$$

Work done by M. Dence and W. K. Hartman indicates that there are actually about 10 very probable impact craters in this size range known in the Canadian Shield area. These craters are identified by circular structures and shock metamorphism indicative of impact. These craters range in diameter from 12.5 km (Nicholson Lake) to 70 km (Manicouagan), and in age from about 15 m.y. (Haughton Dome) to about 485 m.y. (Carswell Lake). The age range suggests that the true number should be more than 10, perhaps 20, for a 1 b.y. time period.

3. What is the probability of a catastrophic impact that would completely exhume part of a repository with area of 10 km^2 , buried 600 m deep, during a 1 million year interval?

From Figure VI-2, $D = 6$ km for $d = 600$ m

From Figure VI-3, the critical area is $(\sqrt{10} + 6)^2 = 84 \text{ km}^2$

From Equation 9,

$$\begin{aligned} \text{No. craters} &= N_D A T = 1.82 (10^{-13}) 6^{-1.80} 84 (10^6) \\ &= 6 \times 10^{-7} = \text{probability.} \end{aligned}$$

4. What is the probability of an impact that would extend fractures to the burial depth of 600 m occurring in a repository with area 10 km^2 within 1 million years?

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

From Figure VI-3, the critical area is $(\sqrt{10} + 1)^2 = 17$ km²

From Equation 9,

$$\begin{aligned}\text{No. craters} &= N_D A_T = 1.82 (10^{-13}) (1) 17 (10^6) \\ &= 3 \times 10^{-6} = \text{probability.}\end{aligned}$$

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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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