APPENDIX III 403479

Radiation Dose Prediction for Underground Nuclear Detonations

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Introduction

The detonation of a nuclear device beneath the earth's surface may be accompanied by a release of radioactivity to the atmosphere. Whether a release will or will not occur depends on a number of factors. Experience has shown that for certain types of device emplacements, releases are to be expected, e.g. cratering detonations. For other types of emplacements, releases are not expected and do not normally occur. The quantities of radioactive materials which have been released from individual underground explosions have varied over many orders of magnitude. The physical characteristics of the releases and the composition of the released materials have also varied greatly. In some instances only small releases, or seepages of primarily noble gases have been observed. On the other hand, releases of large quantities of radioactive material have been experienced, consisting of both gaseous and refractory materials, resulting in considerable local radioactive fallout and in airborne activity being detected at great downwind distances. A radionuclide of particular interest is radioiodine, particularly iodine-131. The quantities of this nuclide released during a seepage is rather small and does not constitute an off-site hazard. For prompt massive ventings, however, relatively large quantities may be released, later appear in the milk of dairy cattle, and potentially result in exposures to the thyroids of those who consume the milk. It is this latter type of release and the prediction of its related potential exposures to man which is the subject of what follows.

The Fallout Fraction

When radioactive materials are released to the atmosphere during a prompt massive venting of an underground nuclear detonation, part of the radioactive debris falls rather rapidly to the earth's surface and is commonly referred to as local fallout. The remaining radioactivity, that in gaseous form or associated with very small particles, is carried to much greater downwind distances. That portion of the total activity produced by the nuclear explosion which is deposited in the local fallout pattern is referred to as the fallout fraction. Within certain limits the fallout fraction is a function of the scaled distance of the device beneath the earth's surface. It is also a function of other variables such as the water content of the medium surrounding the device. Experimental data show that for devices detonated within the range of scaled depths from about 15 $W^{1/3}$ to 150 $W^{1/3}$ the associated fallout fractions range from about 80% downward to a few percent, respectively. These data form the basis for an empirical relationship which provides useful estimates of the fallout fractions to be expected from detonations in this range of scaled depths. Data also indicate that for larger scaled depths of burial, the fallout fraction approaches zero as the scaled depth asymptotically approaches a value of about 350 $W^{1/3}$, sometimes referred to as the asymptote of no venting. Unfortunately, experience has also shown that unexpectedly large fallout fractions have indeed occurred at even greater scaled depths of burial.

Data exist which perhaps indicate that a reasonable upper limit to the fallout fraction which might result from an accidental massive venting of an underground detonation designed for complete containment is on the order of 5%. During the 1957 PLUMBOB and 1958 HARDTACK II series at the Nevada Test Site a number of small yield nuclear devices were detonated at the bottom of drilled holes. In contrast to the stemming practices of today these holes only contained one or more cement plugs between the device and the ground surface. Four of these events, PASCAL A, OTERO, BERNALILLO, and VALENCIA had scaled depths of burial ranging from 3800 $W^{1/3}$ to 1360 $W^{1/3}$. (Use of scaled depth may not be strictly appropriate here). The maximum fraction of the total activity produced by these detonations which was deposited in the local fallout pattern was about 5.5%. Fallout fractions resulting from accidental ventings of detonations designed for complete containment, including line of sight and tunnel events, have not exceeded this number. (Final determination of the fallout fraction for BANEBERRY has not as yet been completed).

The occurrence of a massive venting of an underground detonation designed for complete containment is accidental and unpredictable. For safety reasons, therefore, it has been the practice for many years, and currently is common practice, to assume that for essentially all underground detonations of this type, a prompt massive venting is credible. Current fallout prediction procedures are based upon this assumption.

Current Fallout Prediction Procedures

The currently employed fallout prediction technique was derived by modification of a method originally developed by the Special Projects Section , U. S. Weather Bureau, in 1955. The original method was based primarily on fallout data from tower shots in Nevada and has been described by Nagler, Machta, and Pooler (1). The modification of this method has been reported in detail by Cluff and Palmer (2) and its application has been discussed by Mueller (3,4) and Morrell (5).

Most fallout prediction models require as input rather detailed specification of the total amount of fallout and the distribution of activity as a function of particle size and height in the initial stabilized radioactive cloud. The more simplified method currently employed is a scaling technique which does not require explicit definition of the distribution of activity as a function of particle size and height in the initial cloud. Rather, the assumption is made that an appropriate analog event can be chosen whose particle size-activity distribution will adequately approximate that of the event for which a prediction is being made. The scaling method consists of a ratio technique whereby the parameters which determine hotline fallout intensities and the location of these fallout intensities in their respective fallout patterns are related, and then used in conjunction with the empirical results of a previous event for prediction purposes. Exposure rate levels are normalized to one hour after the detonation at all downwind distances to account for radioactive decay. This technique is used to provide predictions of: (a) external gamma exposure from deposited activity along the fallout hotline; (b) external gamma exposure along the hotline from immersion in the passing radioactive cloud; and (c) dose to the thyroid potentially resulting from ingestion of I-131 contaminated cow's milk, again, along the fallout hotline.

The form of the scaling equations, where the unprimed symbols refer to the analog event and the primed symbols refer to the forthcoming event, are as follows:

$$A' = A\left(\frac{\theta}{\theta'}\right)\left(\frac{h}{h'}\right)^2\left(\frac{V}{V'}\right)^2\frac{f'Y'}{f\,Y} \qquad \text{(Eq I)}$$

where:

A, A'	are the gamma exposure rate levels as a function of distance along the fallout hotline for an H+1 hour reference time (R/hr)
θ, θ'	are the directional shears in the fallout hodograph from the surface to the top of the radioactive cloud (degrees)
h, h'	are the radioactive cloud depths (feet)
V, V'	are the resultant mean transport speeds from the surface to an appropriate altitude in the radioactive cloud (mph)
f, f'	are the fallout fractions (%)
Y, Y'	are the fission or fission equivalent yields of the nuclear devices (kt)

the exposure rate level (A'), when computed, is applicable at the downwind distance

$$X' = X\left(\frac{h'}{h}\right)\left(\frac{V'}{V}\right) \qquad \text{(Eq II)}$$

where:

X, X' are downwind distances along the fallout hotline (statute miles)

h, h' and V, V' are defined as in Eq I above. (Note: Eq II is reversed in practice to solve for X rather than X' thereby facilitating computational procedures).

The unprimed quantities are obtained for the analog event by an analysis of observed exposure rate levels, meteorological conditions, and radioactive cloud dimensions. All yield information is obtained from the nuclear laboratory executing the detonation. If a reliable method of predicting the fallout fraction f' were available the value of this parameter could be a variable. Estimates of f' for cratering experiments can be made, however, for containment-designed detonations it is the practice to assume that $f' = f$. Thus, if meteorological conditions and radioactive cloud dimensions were identical for the analog and new events the predicted exposure rates would simply be proportional to fission yield. A discussion of the subjective estimation of the vertical cloud dimension (h') and a detailed description of the mechanics for obtaining values of (V') and (θ') are given in reference 5.

The initial result of the scaling process is the predicted H+1 hour gamma exposure rate levels as a function of downwind distance along the fallout hotline. To obtain exposures, an appropriate radioactivity decay rate is applied to the H+1 hour exposure rates. If significant quantities of induced activities are involved, their potential effect on the gross gamma decay rate must be considered.

Estimates are also made of the immersion exposure occurring during cloud passage along the fallout hotline. These estimates are made on the basis of the relative contribution to centerline exposure from cloud passage and fallout observed with the analog event. It is assumed that the relative contributions as a function of downwind distance for the new event will be similar to those of the analog event. Dose rate profiles from the routinely applied analog have been examined and current practice is to assume an infinite fallout to cloud passage centerline exposure ratio of 2:1. The exposure during cloud passage includes contributions from both the airborne debris and the debris deposited during cloud passage. This provides an estimate, for example, of the exposure which could be avoided by evacuation prior to cloud passage. This ratio would, of course, be altered if the new event decay rate were significantly different from that of the analog.

Estimates of the potential dose to the thyroid from ingestion of I-131 contaminated cow's milk are made utilizing an empirical relationship between gamma fallout field intensities and I-131 peak concentration in cow's milk developed by Knapp [6]. Knapp found that after a single dry deposition of radioactive fallout on pastureland the level of I-131 in the fresh milk of dairy cattle reached a maximum value within 4 days and thereafter decreased exponentially with a half reduction time of about 5 days. The maximum level of I-131 in the fresh milk, I_{max}, was related to the external gamma radiation level by the relation

$$I_{max} = (26{,}000\,\gamma_o) \text{ to } (96{,}000\,\gamma_o) \text{ pci/l}$$

where γ_o is the open field, external gamma dose rate at 3 feet above the ground surface, 24 hours following detonation, expressed in mr/hr. Further, by assuming the mass of the thyroid to be 2 grams (1 year old child), the child consumes 1 liter of contaminated cow's milk per day, the fraction of ingested I-131 reaching the thyroid is 0.3, and the half reduction time of I-131 in fresh milk is 5 days, Knapp provides the following relation between the maximum I-131 level in the milk and the dose to the thyroid

$$D = (1.71 \times 10^{-4})\, I_{max} \text{ rads}$$

Thus, if I_{max} lies in the range of $(26{,}000\,\gamma_o)$ to $(96{,}000\,\gamma_o)$ then

$$D = (4.4\,\gamma_o) \text{ to } (16.4\,\gamma_o) \text{ rads}$$

Since the gamma exposure rate at H+1 hour, rather than at H+24 hours, is normally obtained in the scaling technique, the above equations have been modified, assuming a $t^{-1.2}$ decay dependence, to the following

$$I_{max} = (580\ \gamma_1) \text{ to } (2,100\ \gamma_1) \text{ pci/l}$$

and

$$\bar{D} = (0.1\gamma_1) \text{ to } (0.37\gamma_1) \text{ rads}$$

where γ_1 is the open field, external gamma dose rate one hour following detonation, expressed in mr/hr. Current conservative practice is to use the upper limit of the dose range.

The dose estimated by this technique is reduced by a factor of 5 if dairy cattle are only consuming contaminated dry feed. Also, only the fission yield of a device is used to estimate the H+1 hour gamma exposure rate, neglecting any induced activity.

Evaluation of Prediction Techniques

A limited examination of the ability of the fallout scaling technique to reproduce observed data has been performed on a number of cases in three different categories of events. The three categories of events include tower shots, excavation experiments, and ventings of underground detonations designed for complete containment. Observed exposure rate or exposure versus distance curves along the fallout hotlines for the several events in a given category have been normalized to an arbitrary set of conditions utilizing the scaling technique. If each event in a given category is a reasonable analog of the others in that category and if the parameters in the scaling equations are known accurately then the normalization should hopefully result in a tightly grouped set of curves.

Three events, Hamilton, Humbolt, and Rio Arriba were chosen from the Hardtack II Test Series. Each of the devices was detonated on a wooden tower. These events were chosen because the fallout documentation was adequate to reasonably determine the exposure rate-distance curves and the fallout fractions. Their yields ranged from 1 to 92 tons, fallout fractions a factor of about 3, and tower heights from 25 to 72 feet. Fallout hodograph shears ranged from about 2° to 30°, mean wind speeds from 2 to 29 knots, and initial cloud tops from about 2900 to 9400 feet. The normalized exposure rate-distance curves are shown in Figure 1 where the maximum separation between any two curves is seen to be a factor of about 2.2 at one mile downwind, with less separation at all greater distances.

Normalized exposure rate-distance curves for the four excavation experiments, Johnnie Boy, Sedan, Teapot Ess, and Danny Boy are shown in Figure 2. The range in total yield of those detonations was a factor of about 240 and the range in fallout fraction was a factor of about 13. Observed wind speeds, shears, and cloud heights, as expressed in the scaling equations, also varied considerably. The separation between the normalized curves is a factor of about 3 at shorter distances, decreasing with increasing distance to a factor of about 1.8 at 120 miles downwind.

Only two cases of ventings of underground detonations designed for complete containment are available which are reasonable analogues. These are the Pike and Pinstripe events. Both ventings were of short duration and had rather similar early-time cloud rises. Yields, as well as fallout fractions, differed by about one order of magnitude. Shears and mean wind speeds were similar. The normalized exposure-distance curves for these two events are shown in Figure 3. A maximum separation between the two curves is a factor of about 2.6 at a downwind distance of 80 miles, however, the separation is considerably smaller at all other distances.

It appears, from the foregoing examples, that the scaling technique performs reasonably well for a variety of types of nuclear detonations. Obviously, the accuracy of this prediction method, as well as any other fallout prediction method, depends ultimately on accurate predictions of input parameters.

Some radiological data are available with which to examine the performance of the Knapp relationship for both the Pike and Pinstripe events. The downwind distance to the dairies were 85 miles in the case of Pike and 63 miles in the case of Pinstripe. In both instances the dairy cows were on green feed and the deposition was dry. Fallout data for both events have been analyzed and dose rate patterns for an H+1 hour reference time were constructed using observed gamma decay rates. These gamma dose rates at the locations where radioiodine was observed in cow's milk were used to determine the peak concentration of I-131 which would be predicted by means of the Knapp relationship. The results of this calculation are as follows:

	Maximum Concentrations (pci/l)	
Event	Predicted Range	Observed
Pike	174 to 630	420
Pinstripe	3500 to 12,600	4800

Application of the upper end of the range results in overestimates by a factor of 1.5 for Pike and 2.6 for Pinstripe. Application of the middle of the range still results in an overestimate by a factor of 1.7 for Pinstripe but only a 4% underestimate for Pike.

References

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2. Cluff, F. D. and T. R. Palmer, "A Fallout Scaling Model for the Prediction of Gross Gamma Dose Rates From Earth Cratering Detonations", unpublished manuscript, ESSA, ARFRO, Las Vegas, Nevada, 1964.

3. Mueller, H. F., "Local Fallout and Diffusion of Radioactive Material", Technical Discussions of Off-Site Safety Programs for Underground Nuclear Detonations, NVO-40, USAEC, pp. 216-225, 1968.

4. Mueller, H. F., "Meteorological Requirements and Operational Fallout Prediction Techniques for Plowshare Nuclear Detonations", Procedures for the Symposium on Public Health Aspects of Peaceful Uses of Nuclear Explosives, U. S. Public Health Service, S.W.R.H.L., Las Vegas, Nevada, April, 1969.

5. Morrell, J. R., "The NTS Radiation Prediction Model", unpublished manuscript, NOAA, ARL-Las Vegas, Nevada, 1971.

6. Knapp, H. A., "I-131 in Fresh Milk and Human Thyroids Following a Single Deposition of Nuclear Test Fallout", USAEC, TID-19266, June 1, 1963.

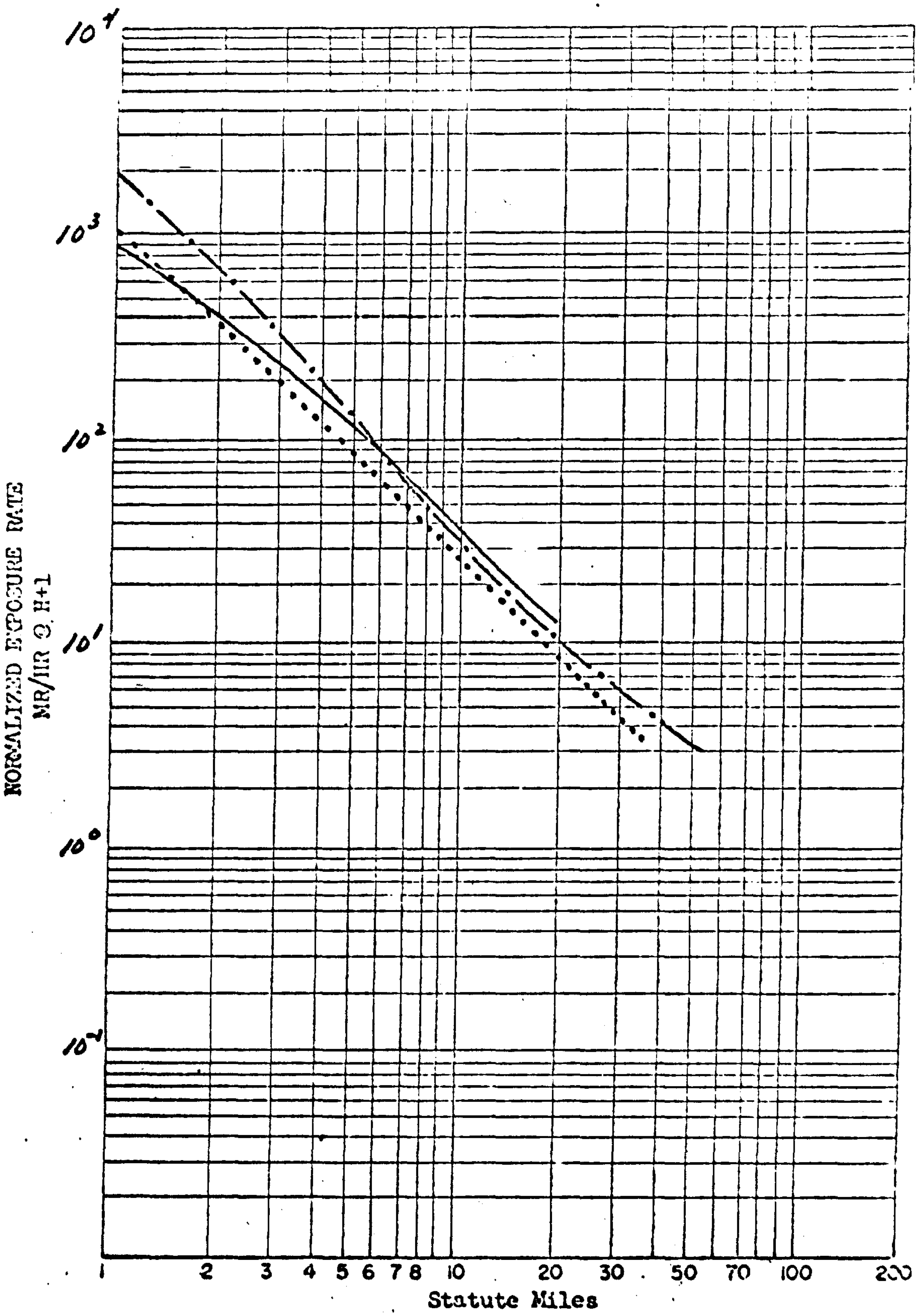

FIGURE 1. TOWER SHOTS

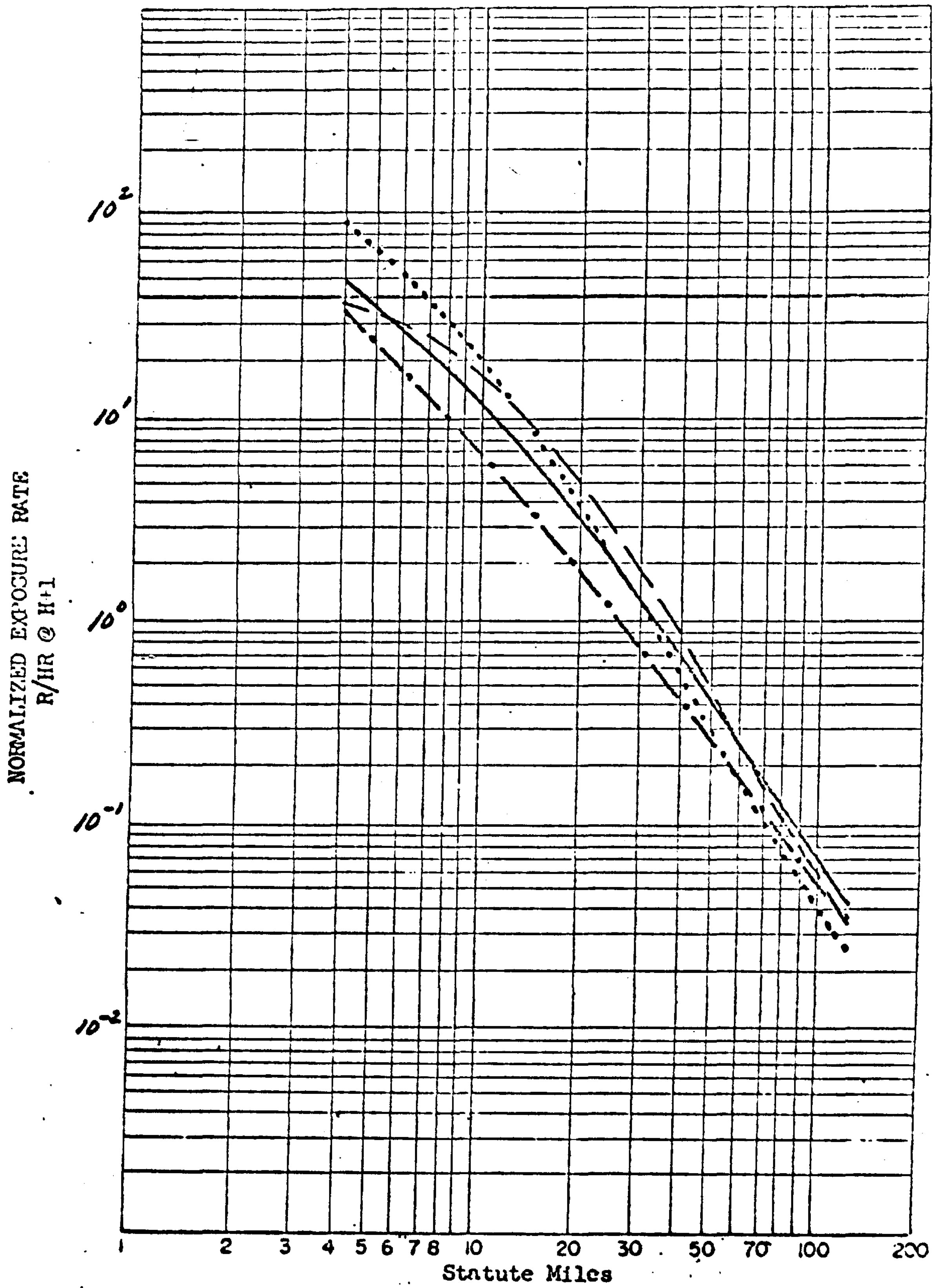

FIGURE 2. EXCAVATION EXPERIMENTS

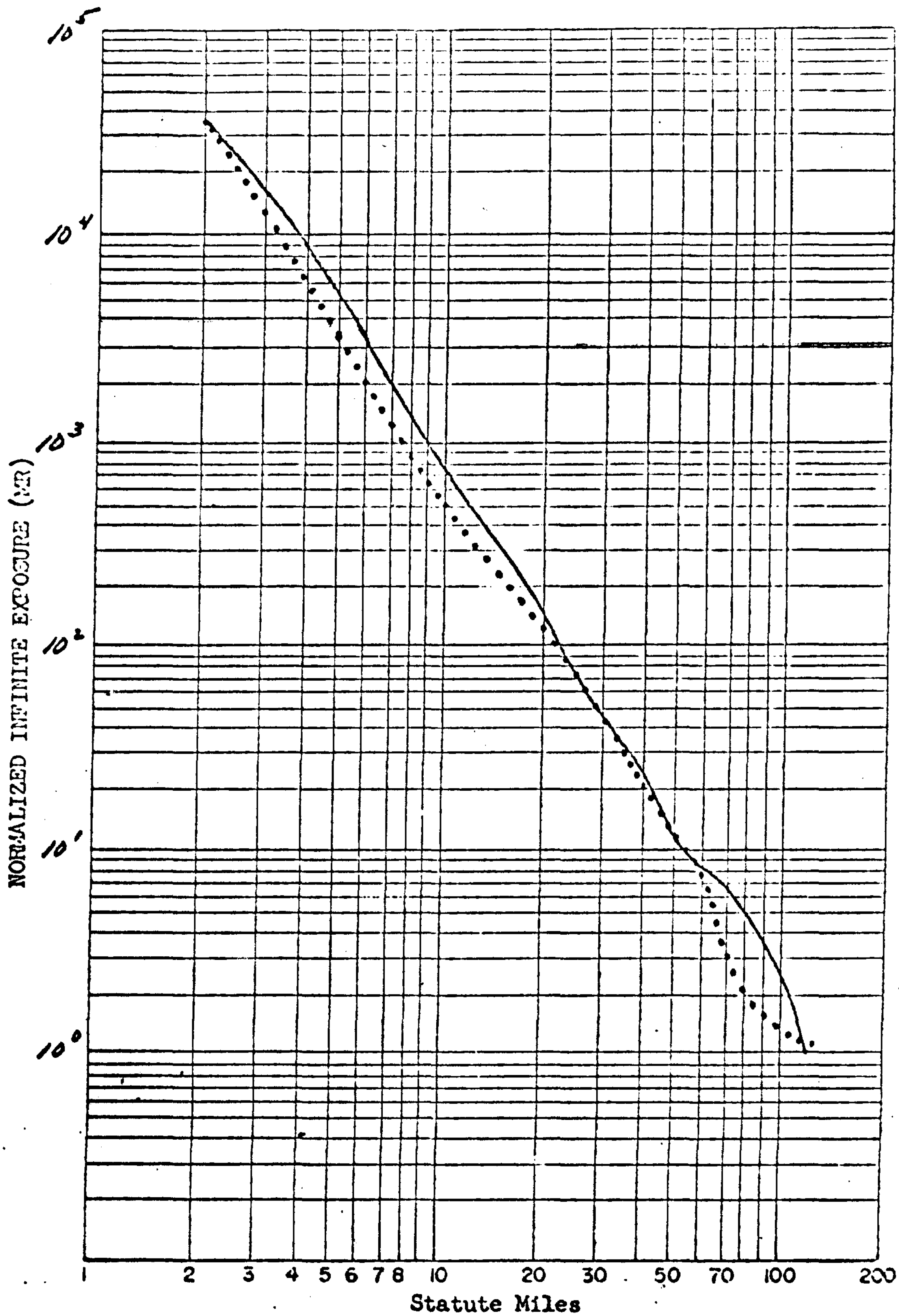

FIGURE 3. VENTING OF UNDERGROUND DETONATIONS