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PREDICTION OF GROUND MOTION FROM UNDERGROUND NUCLEAR WEAPONS TESTS AS IT RELATES TO SITING OF A NUCLEAR WASTE STORAGE FACILITY AT NTS AND COMPATIBILITY WITH THE WEAPONS TEST PROGRAM

Luke J. Vortman, 1111

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Luke J. Vortman
Ground Motion & Seismic Division 1111
Sandia National Laboratories
Albuquerque, New Mexico 87185

ABSTRACT

This report assumes reasonable criteria for NRC licensing of a nuclear waste storage facility at the Nevada Test Site where it would be exposed to ground motion from underground nuclear weapons tests. Prediction equations and their standard deviations have been determined from measurements on a number of nuclear weapons tests. The effect of various independent parameters on standard deviation is discussed. That the data sample is sufficiently large is shown by the fact that additional data have little effect on the standard deviation. It is also shown that coupling effects can be separated out of the other contributions to the standard deviation. An example, based on certain licensing assumptions, shows that it should be possible to have a nuclear waste storage facility in the vicinity of Timber Mountain which would be compatible with a 700 kt weapons test in the Buckboard Area if the facility were designed to withstand a peak vector acceleration of 0.75 g. The prediction equation is a log-log linear equation which predicts acceleration as a function of yield of an explosion and the distance from it.

PREFACE

The text of this report is the same as that of SAND80-1020/2, which also includes appendices containing the classified weapons test data which support the arguments contained in the text.

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Introduction and Purpose

Subtask 1.1, Data Processing and Analysis (of ground motion data), of the Nevada Nuclear Waste Storage Investigation (NNWSI) has the following objectives:

1. To develop a capability for predicting ground motion from underground nuclear weapons tests which would be imposed on a nuclear waste storage facility at NTS during continued weapons testing.
2. To determine the effect of depth and geology on ground motion from weapons tests.
3. To develop an understanding of seismic amplification at NRDS as observed on past weapons tests, and to evaluate the implications of that amplification on siting of a nuclear waste storage facility.
4. To provide a data bank of ground motion from weapons tests which will become the background base from which NRC licensing decisions can be made.

This report treats only the first objective. By making certain assumptions with regard to NRC licensing, the equations developed here lead to conclusions regarding compatibility of a waste facility with continued nuclear weapons tests. The first objective has two facets. The first is that a terminal waste facility located at or near the NTS must be designed to withstand ground motion from nuclear tests at whatever level and margin of safety is to be specified by NRC. The second facet is that siting based on the ground motion criteria used in the design of a terminal waste storage facility must not result in its being so close to test areas as to impose limitations on weapons testing, either now, or in the future. Although weapons tests are now conducted with a 150 kiloton limit imposed by the Threshold Test Ban Treaty, and although a lower limit could be imposed by a

Comprehensive Test Ban Treaty, the siting of a terminal waste facility at or near NTS should not constrain testing to yields below those limits which have been set by possible off-site damage. These limitations are 1000 kilotons for Pahute Mesa, 750 for Buckboard Mesa area, and 300 for Yucca Flat and Frenchman Flat.[1] Because current emphasis of the NNWSI is on locations along the western boundary of NTS, this report will treat the Buckboard Mesa and Pahute Mesa areas and not the more distant Yucca and Frenchman Flats where lower yields are tested.

To date no nuclear events have been detonated in the Buckboard Mesa area. It is assumed that data from current and past tests on Pahute Mesa are applicable to the Buckboard Mesa area with appropriate allowance for the differences in the yield limits of the two areas. It should be emphasized that with current tests limited to 150 kilotons only data acquired on past (prior to the origin of the NNWSI) tests are available for larger yields. Further, it is important to recognize that these earlier measurements were made for other programs with other goals, and are not at locations which would be chosen for measurements with siting of a terminal waste storage facility in mind. Also, because data from large-yield events as early as 1966 are being used, the measurements systems used then did not have characteristics as good as systems would be chosen today.

Possible Criteria for NRC Licensing

Equations predicting ground motion from nuclear weapons tests are not alone enough to evaluate the compatibility of the weapons test program with a nuclear waste storage facility. The level of compatibility depends also on the design response criteria required by NRC. Since those criteria have not been established, it is necessary here to make some assumptions as to the criteria it might be reasonable to expect.

For design of nuclear power plants only motions from natural earthquakes are of concern. These designs consider two levels of earthquakes: a Safe Shutdown Earthquake (SSE), which has also been called the Design Basis Earthquake (DBE), and an Operating Basis Earthquake (OBE).

An understanding of the way in which these levels are applied is seen in the following quote from Reference 2.

> "III. (c) The "Safe Shutdown Earthquake" is that earthquake which is based upon an evaluation of the maximum earthquake potential considering the regional and local geology and seismology and specific characteristics of local subsurface material. It is that earthquake which produces the maximum vibratory ground motion for which certain structures, systems, and components are designed to remain functional. These structures, systems, and components are those necessary to assure:
>
> (1) The integrity of the reactor coolant pressure boundary,
>
> (2) The capability to shut down the reactor and maintain it in a safe shutdown condition, or
>
> (3) The capability to prevent or mitigate the consequences of accidents which could result in potential offsite exposures comparable to the guideline exposures of this part.
>
> (d) The "Operating Basis Earthquake" is that earthquake which, considering the regional and local geology and seismology and specific characteristics of local subsurface material, could reasonably be expected to affect the plant site during the operating life of the plant; it is that earthquake which produces the vibratory ground motion for which those features of the nuclear power plant necessary for continued operation without undue risk to the health and safety of the public are designed to remain functional."(2)

It is further specified that "The maximum vibratory ground acceleration of the Operating Basis Earthquake shall be at least one-half the maximum vibratory ground acceleration of the Safe Shutdown Earthquake."(2)

The design procedure begins with the applicant undertaking a siting investigation in which the seismicity of the site is evaluated. The maximum ground motion from earthquakes is defined by the applicant. That motion is used with design response criteria prescribed by NRC.(3,4) (See Figures 1 and 2.) The design response spectra have been normalized to 1.0 g for maximum vertical and horizontal accelerations. The spectra were arrived at by enveloping spectra measured from a representative set of earthquakes.(5) The mean plus one standard deviation, or the 84.1% probability level, was chosen as the design spectrum probability level. It is worth noting that Japan, with many real time earthquake records, uses a real time record appropriate to the site without the added conservatism of plus one standard deviation.(6)

It should be emphasized that the current nuclear regulations are for surface nuclear reactors subject to natural earthquakes and surface structures of a waste facility are quite different. An additional risk analysis needs to be done considering how the surface structures of a waste facility differ from reactor structures in vulnerability to ground motion and in risk associated with the response to ground motion and also considering the below-ground portions of a waste repository. It is anticipated that the criteria would also take into account the fact that a waste facility at NTS is under control of the federal government and that the surrounding area has very low population density. It is expected that in the United States a technical approach similar to that developed for nuclear reactors, but with different criteria, would be used for design of nuclear waste storage facilities with respect to natural earthquakes. For example, the same earthquake data base will probably be used for both. It is a premise here that the design response criteria will be different and less restrictive.

There are four significant differences between predicting ground motion from natural earthquakes and that from nuclear weapons tests. First, tests are scheduled and earthquakes are not. Second, the seismic source location for ground motion from nuclear weapons tests is precisely known. Third, an upper limit (and a very conservative one at that) on the explosion energy has been predetermined. Fourth, the safety aspects both on-site and off-site of a nuclear detonation

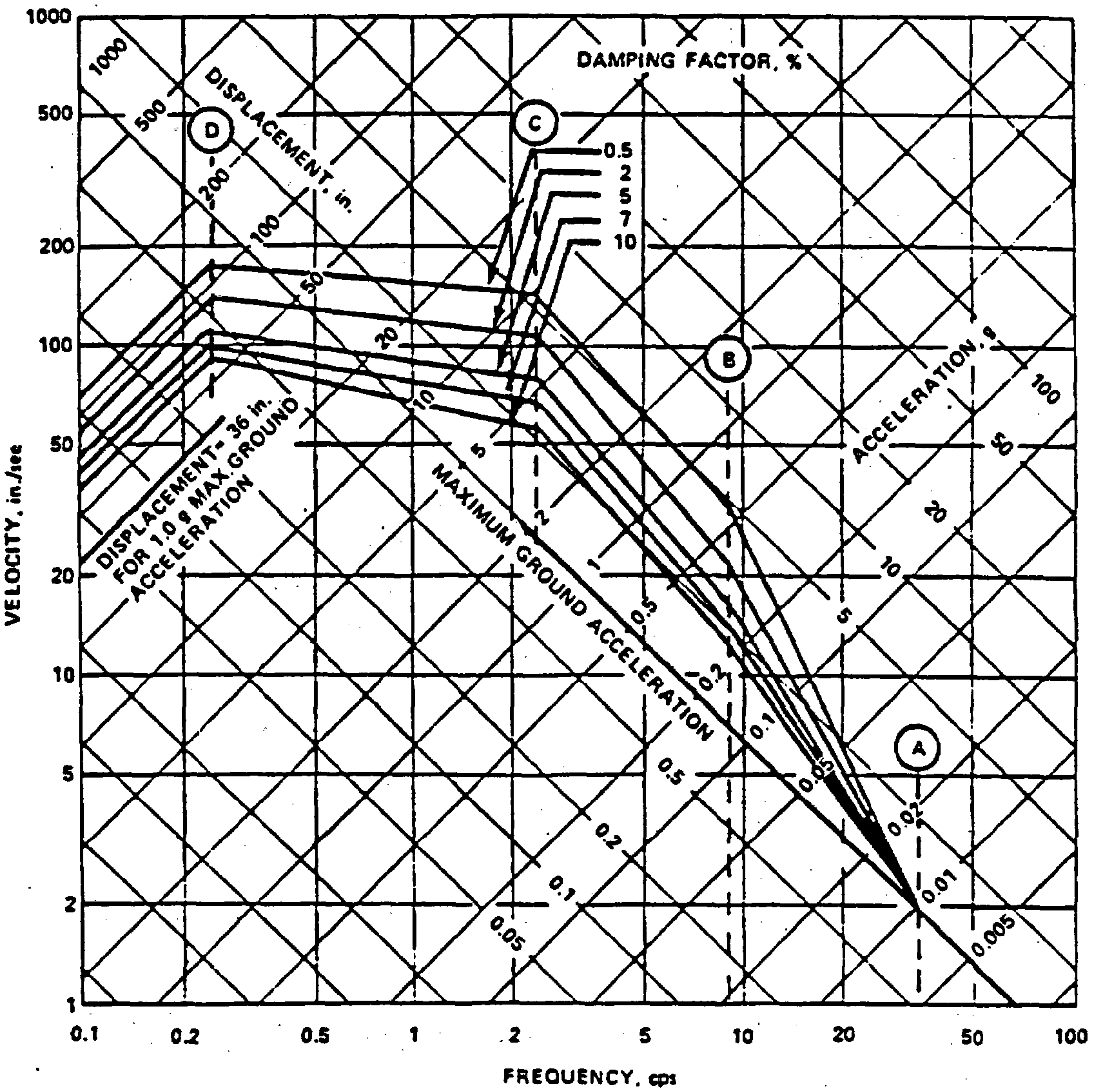

FIGURE 1. HORIZONTAL DESIGN RESPONSE SPECTRA – SCALED TO 1g HORIZONTAL GROUND ACCELERATION

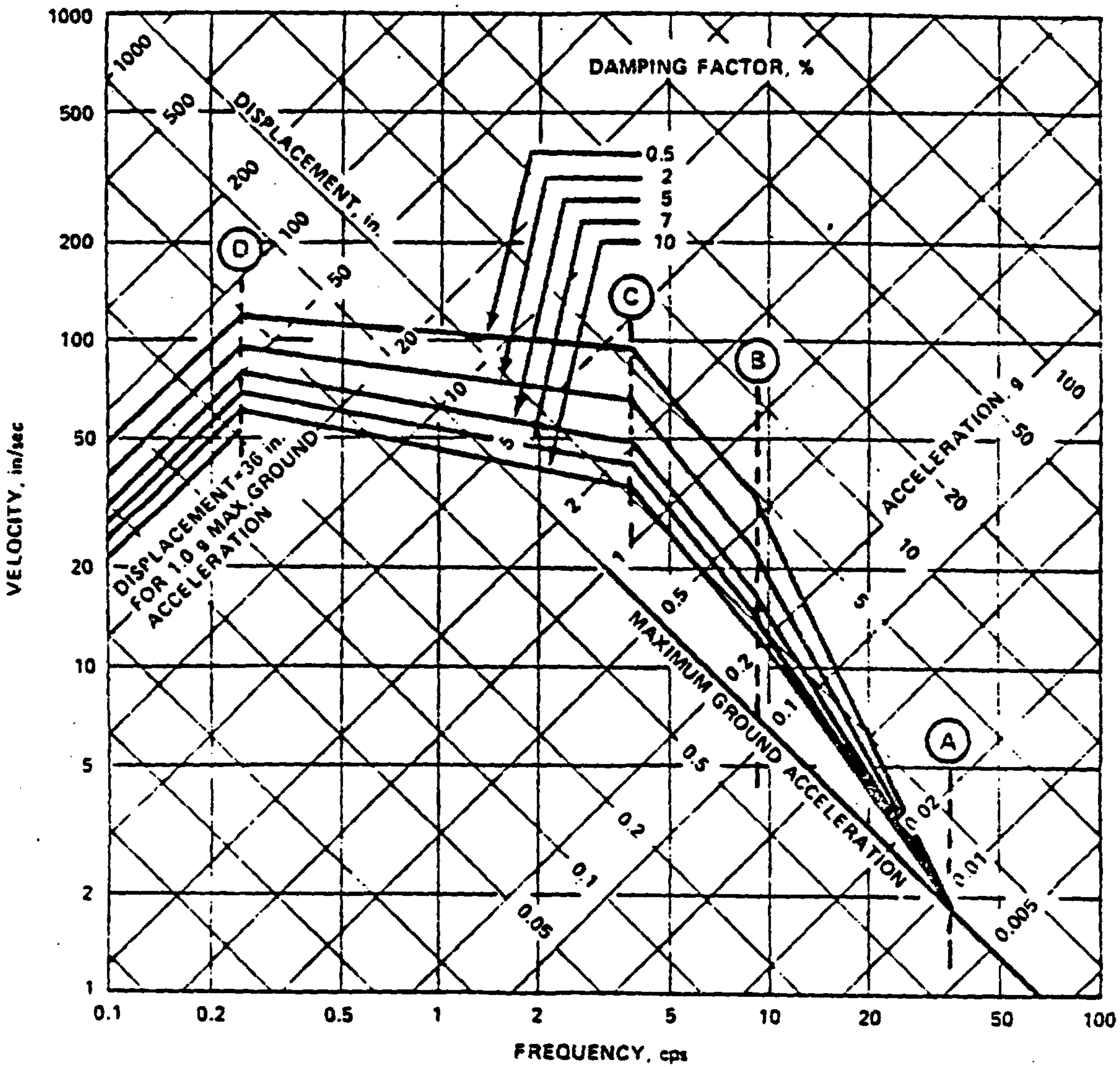

FIGURE 2. VERTICAL DESIGN RESPONSE SPECTRA – SCALED TO 1g HORIZONTAL GROUND ACCELERATION

are under control of an experienced test organization. It is in order to examine how these four differences interact with the operational options of a nuclear waste storage facility. A lower and an upper limit in terms of ground motion level will be considered, the former where earthquake motion controls design, the latter where weapons-test-induced motion controls.

If a waste storage facility is located at a sufficient distance from the weapons testing area that predicted ground motions from testing do not exceed the levels for which the facility must be designed for natural earthquake ground motion, then motion from nuclear tests need not be a significant consideration. That is, no action with respect to the structure of the facility need be taken in anticipation of a test. Whether operating personnel would be permitted to remain underground during a test would be determined by NV policy. Currently that policy requires evacuation of mines within about 50 miles of a test of approximately 80 kt or larger. This restriction obviously applies only during the operational phase of the waste facility.

If a waste facility is to be located relatively close to a weapons testing area, then the four differences pertaining to a controlled seismic source dictate the design response criteria, and earthquake motions are no longer a consideration. Here, evacuation of operating personnel would most certainly be required. This action reduces to zero the probability of personnel injury. Further, any structure, component, or content which would be susceptible to damage from ground motion could be secured. By design, the limiting factor can be made to be the shafts and drifts, where some minor cracking and minor loosening of rock, which could be easily repaired, could be allowed. Waste, after emplacement in the repository, is expected to withstand more than 1 g and if necessary waste could be held away from the facility so as not to be at the facility, and short of final emplacement, at shot time. A close location may also require some flexibility in the location of a specific weapons test, i.e., the maximum yield predicated on off-site safety need not necessarily be detonated at the point in the test area closest to a waste facility.

It is important to emphasize that the four differences between earthquake and weapons-test-generated ground motion mean that there is less need to be as conservative with regard to design response criteria for weapons-test-generated ground motion than for that generated by natural earthquakes. Also, there is no need for an equivalent of an SSE or an OBE. There may, of course, be a Design Basis Earthquake (DBE), but it should be predicated on the response and risk of nuclear waste storage structures rather than merely copied from those used for nuclear reactors.

There is reason to avoid subjecting a waste storage facility to much more than +1 g vertically at the surface from an underground nuclear test. In the vicinity of the epicenter of an underground nuclear explosion the shock wave arrives at the surface as a compression wave whereupon it is reflected downward as a tensile wave.

Close to the surface the head of the downward-moving tension wave is not appreciably greater in amplitude than the portion of the upward-moving compression wave it encounters. But as the tension wave continues downward it encounters the decaying portion of the compression wave. Eventually the tension wave reaches a depth at which its amplitude exceeds that of the tail of the upward moving compression wave plus overburden pressure by an amount greater than the tensile strength of the medium. At that point a tensile failure occurs (usually at a bedding plane), the material above spalls off, and a spall gap opens. For the contained explosions of concern here, the spall gap is not expected below the upper one-third of the burial depth. The spall gap can be characterized as a half-lens, flat on the bottom and convex on the top. To locate a waste facility so that the top of a shaft was within the spall zone would be to invite heavy damage at and near the region of the spall gap. Past experience at NTS has characterized the nature of this type of damage.(7)

Spall has been observed on Pahute Mesa to about 2000 $kt^{1/3}$ (feet) range from surface zero for normally buried events, or about 5.4 km from a 700 kt explosion. Figure 3 shows a vertical surface acceleration within the spall zone for a case involving multiple spall.

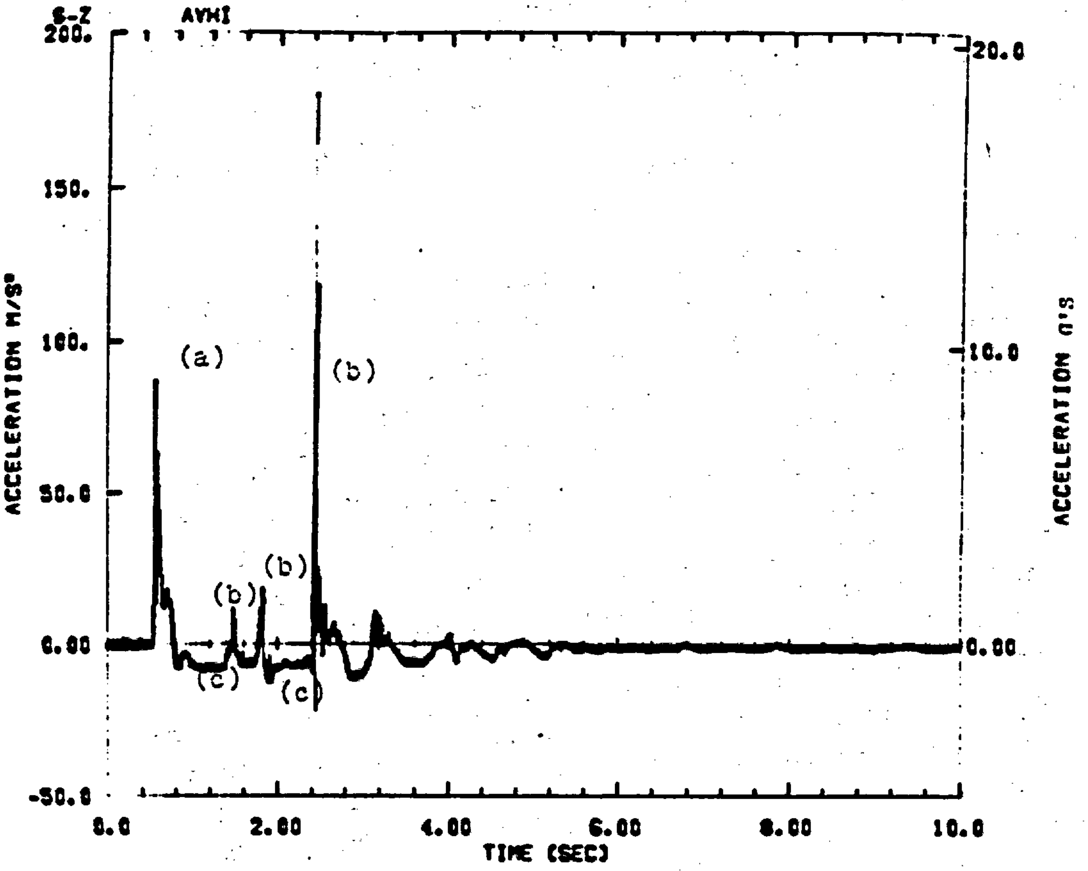

Figure 3. Vertical acceleration measured at surface zero showing (a) the initial pulse, (b) multiple spall closure spikes, and (c) the minus 1 g free-fall.

There is (a) the initial pulse followed by (b) a period of freefall (minus 1 g) which is in turn followed by (c) one or more spall-closure spikes. These generally have an amplitude greater than the initial pulse. As the point of observation moves outward toward the edge of spall the time interval of freefall (-1 g) decreases; and the amplitude of the spall-closure spikes approaches 1 g. (See Figure 4.) Beyond the spall limit the three constituents lose their separate identifies as they merge into the wave train. Beneath the edge of spall as defined at the surface and at a depth of burst for a contained explosion or suitable depth for a storage facility, it may be possible to experience more than 1 g horizontal acceleration, but, of course, there would be no spall.

One of the events detonated at the Pahute Mesa test area had a yield of about 700 kt which is near the upper limit for the Buckboard Area. There was one surface station beyond the spall limit where the peak vector (square-root of sum of squares of the three orthogonal components in a time series) acceleration had a value of 0.608 g. If one assumes a DBE of 0.75 g, the Design Response Spectrum would be as shown in the upper (solid) line of Figure 5 for the vertical component. (The scales on the figure are reversed from those of Figures 1 and 2 and the scales are metric.) The dashed line is the boundary of the individual peak values of vertical acceleration, velocity, and displacement as shown in the block above the plot. The measured spectrum falls between. Both the Design Response Spectrum and the measured spectrum are for 5% damping. Similar information for the two horizontal components is shown in Figures 6 and 7. Note that the square root of the sum of the squares of the measured acceleration peaks for the three components (where the peaks of each are not necessarily at the same time) is 0.647 g, slightly larger than the measured time-series peak vector sum of 0.607 g. These spectra illustrate that a Design Response Spectrum approach similar to that used in Regulatory Guide No. 1.60(3) is appropriate for ground motion from nuclear weapons tests.

There is even more conservatism involved in the above approach. If the DBE is 0.75 g, for example, the peak vector sum is approximately 1.4 times the largest component. (For Figures 5 - 7 the vector sum is from 1.30 to 2.45 times larger than the individual components.)

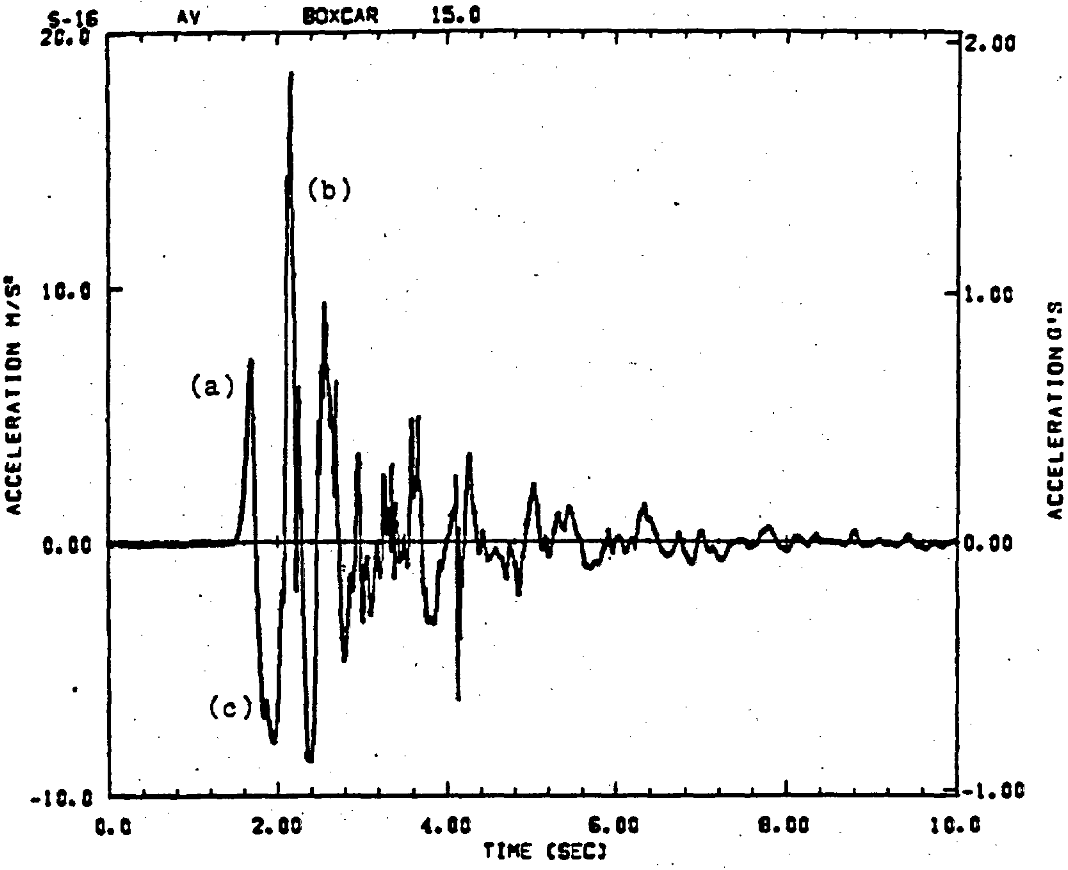

Figure 4. Vertical acceleration measured on the surface near the limit of spall showing (a) the initial pulse, (b) vestigial spall closure spike, and (c) vestigial free-fall.

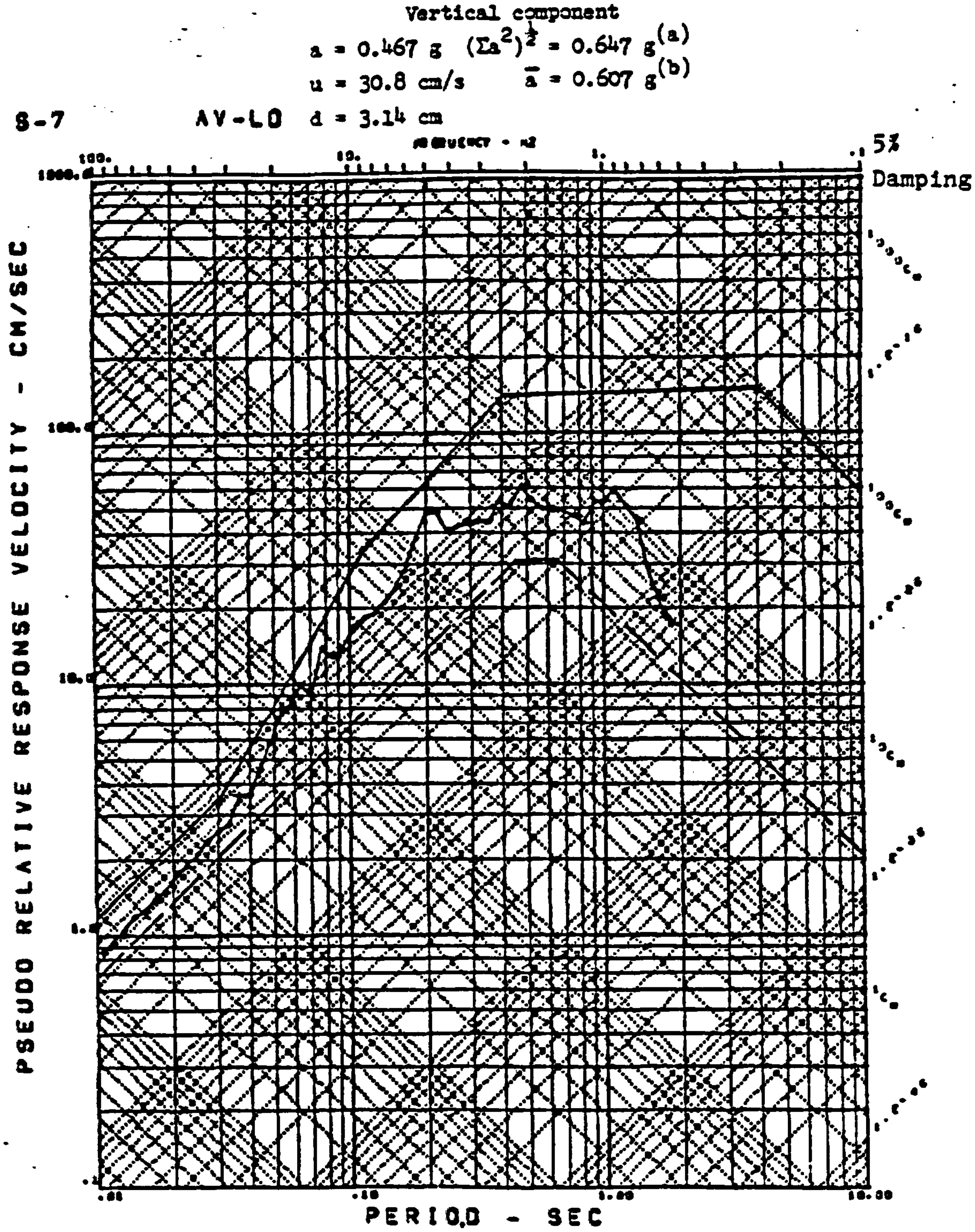

Figure 5. PSRV for vertical component

Notes: (a) square-root of sum of squares of peak values of each of the three components without regard for time of peak.

(b) peak resulting from square-root of sum of squares of the three components in a time series.

Radial component

a = 0.246 g $(\Sigma a^2)^{\frac{1}{2}}$ = 0.647 g[(a)]

u = 14.2 cm/s $\bar{a}$ = 0.607 g[(b)]

S-7 UR d = 3.64 cm

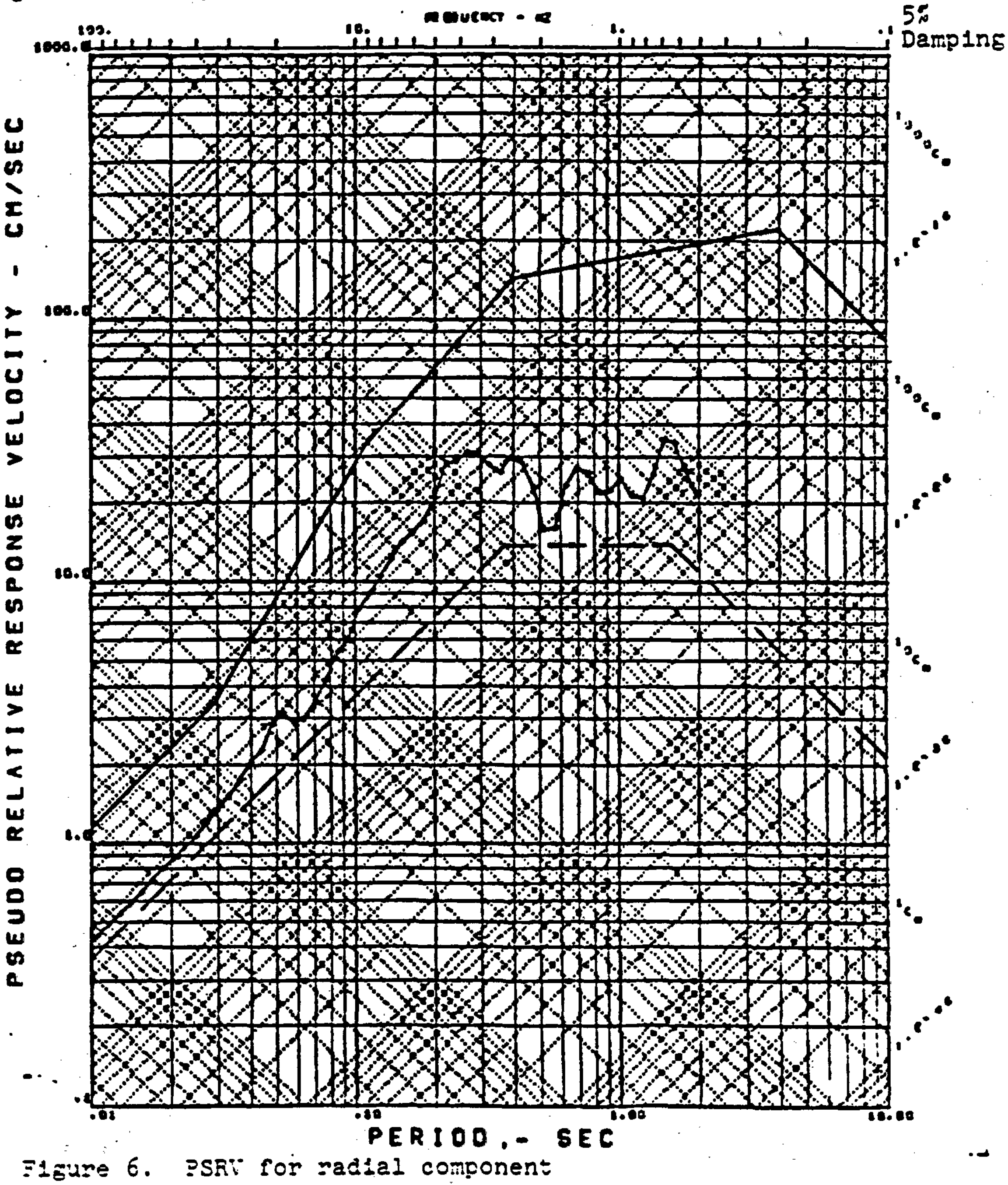

Figure 6. PSRV for radial component

Notes: (a) square-root of sum of squares of peak values of each of the three components without regard for time of peak.
(b) peak resulting from square-root of sum of squares of the three components in a time series.

Tangential Component

$a = 0.375$ g $(\Sigma a^2)^{\frac{1}{2}} = 0.647$ g$^{(a)}$

$u = 24.9$ cm/s $\bar{a} = 0.607$ g$^{(b)}$

$d = 5.15$ cm

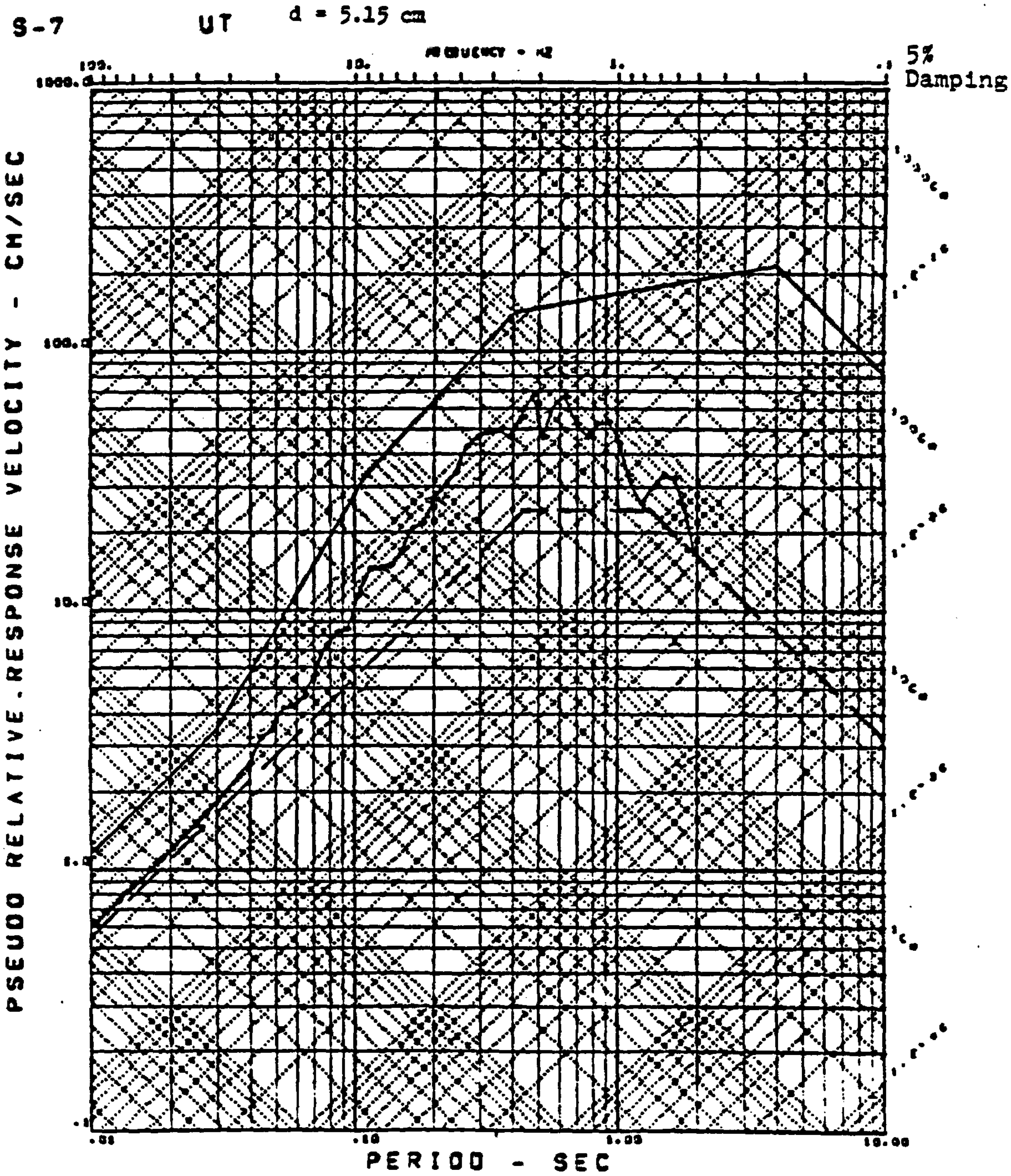

Figure 7. PSRV for tangential component

Notes: (a) square-root of sum of squares of peak values of each of the three components without regard for time of peak.

(b) peak resulting from square-root of sum of squares of the three components in a time series.

Yet, as described below, equations for prediction of accelerations are based on peak vector sums. Thus, if a DBE of 0.75 g vertically were to be used, it would correspond to a peak vector value of over 1 g, and that 1 g vector will be shown later to remain beyond the limit of spall which is defined by a vertical acceleration of 1 g. A choice of a vector sum value of 0.75 g from the prediction equations will also be shown to be essentially equivalent to choosing a +1σ value for an individual component for which the design response spectra have been formulated.

Factors Affecting Sigma

Figure 8 is a block diagram of the factors from source to detector and recorder which affect ground motion. Each of these contributes to the variation in σ. It is in order to comment on each.

a. Yield - Yield is most often quoted as ±10%. This has no rigorous statistical meaning. Confidence in yield determination is a function of device design and diagnostic measurements made. For some events there is greater accuracy and for some less. It is a subjective judgment of those responsible for yield determination at LASL and LLL that the ±10% corresponds roughly to a 1 σ value.

b. Coupling - The effectiveness with which the explosion energy is coupled to the earth is a function of medium properties in the immediate vicinity of the explosion. Events detonated in granite couple energy very well while those in dry porous media show considerable decoupling. Coupling is further increased when the shot point is below the water table. Efforts later will attempt to define the effects of coupling on σ.

c. Transmission - Motion close to the shot is essentially a compression wave. At around two shot depths from surface zero, waves refracted from various geologic layers become significant. At larger distances the wave train at the surface is made up of refracted signals arriving from many different paths. Usually those refracted waves traveling through high velocity deeper

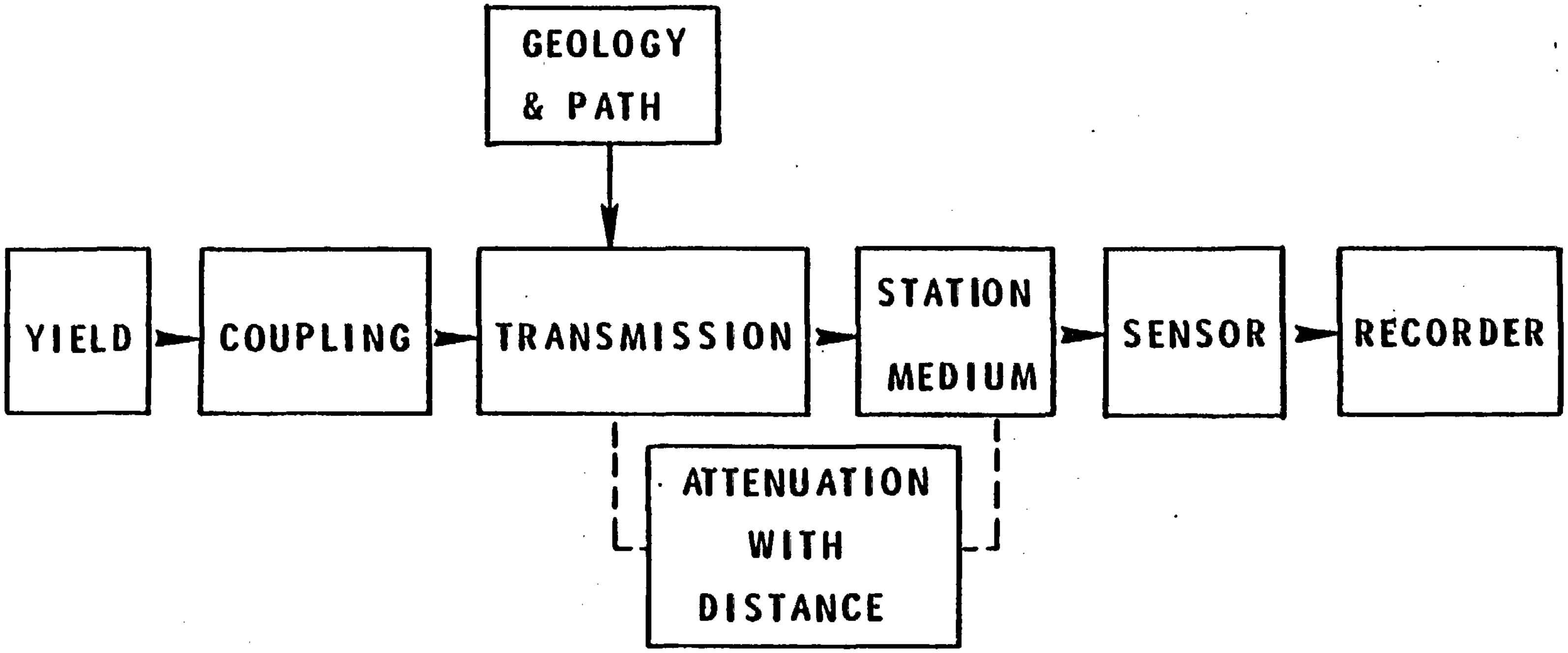

Figure 8 Factors from source to detector and recorder which affect ground motion σ.

structures arrive first, followed by surface waves. The path of the waves is determined by the geology encountered. This is illustrated by the fact that there is considerable azimuthal variation. For example, Boxcar, which had stations at a number of azimuths shows $\sigma_a = 1.49$, while Muenster with all measurements in a single direction had $\sigma_a = 1.16$.

d. Station Site Medium - Peak ground motion amplitude also depends on the medium at the point of measurement. It has been shown(8) that peak velocities at certain frequencies can be factors of 4 to 6 higher where the station at which the measurement is made is on soil (soil over rock) than where the station is on rock. Similar amplifications occur for acceleration. Whereas the measurements included in this data set have been made at sites on both soil and rock, a waste storage facility will represent only soil or, more probably, rock. Data from stations on both soil and rock results in σ from the prediction equations being larger than would be observed if measurements were confined to one or the other.

Transmission and station site medium (c and d above) combine to determine the attenuation of motion with distance. Station site medium is of little consequence where close-in measurements are made, but it is very important at the greater distances. This is because close to the epicenter the maximum motion is from the direct wave whereas at greater distances reverberations within the surface layer of soil produce the maximum motion. Since motions measured at rock sites are less than those measured at alluvium (soil) sites, an event with all measurements on rock only will show an attenuation rate appreciably greater than if all the distant measurements had been on alluvium. If the distant stations are mixed between rock and alluvium station sites there will be an intermediate attenuation rate, but fitted equation will have a larger σ.

One point should be emphasized. The scatter in data used for the general prediction equations results from measurements made at many locations. It has been found(8) that when measurements are made at a single site of motion from events at several locations that the scatter is significantly reduced. For example, for the general prediction equation for events on Pahute Mesa, $\sigma = 2.30$. For specific recording sites the results were:

Las Vegas (SE-6)	$\sigma = 1.29$
Las Vegas (Squires Park)	$\sigma = 1.23$
Tonopah Church	$\sigma = 1.48$
Tonopah Motel	$\sigma = 1.45$

Once final selection of a waste facility site has been made, it should be expected that the scatter of measurements made at that site would be significantly less than from a general prediction equation. No effort should be made to use the numbers above from distant stations such as Las Vegas and Tonopah to deduce the reduction which would occur at on-site locations.

The same point manifests itself in the data set used here in the following way. Measurements made at the Climax Stock in the current set of measurements give peak vector accelerations which are typically factors of three below the mean for an event. Measurements made at Engine Test Stand 2 in Jackass flats typically run from 2 to 5 times the mean. Including these data in the data set exaggerates σ with respect to what it would be if all measurements made at those individual stations were considered separately.

e. Sensors and Recorders - Data used in this program was obtained from three systems and data from the three systems have been intermingled. On more recent events measurements were made by Sandia Laboratories, Albuquerque (SLA) with Kistler Model 303 servo accelerometers. This was the case on Events M, Q, and [illegible] (see Figure 9). On Event J the same accelerometers were used at six distant stations and combined with LASL data at four close-in stations where Endevco Model 2262-25 accelerometers were used. On two of the earlier events, C and T, Pace variable reluctance mass-spring accelerometers were used for 1 or 2 vertical measurements and Spartan DX variable reluctance pendulum velocity transducers were used for three components of velocity. Records from the latter were differentiated digitally to obtain acceleration. For the balance of the events these same gages were used together with data from USGS at 1 or more distant on-site or near off-site locations using L-7 seismometers. These measure acceleration but have an integrating circuit and record velocity-time. Records were differentiated digitally to obtain acceleration.

The largest factor in instrument variation has to do with accuracy of gage calibration and the stability of the calibration with time subsequent to the laboratory calibration. Accelerometers are given a ±1 g field check prior to every installation, but small departures from the 1 g can be detected only in a laboratory calibration. No analysis of calibration effects on accuracy have been made in connection with this program. An analysis made on accelerometers used for close-in measurements on a prior program showed peak velocity from integration of acceleration records from Pace accelerometers had fifty percent of the measurements fall within ±4 percent of the average peak velocity measured by two other gages. Peaks from DX velocity gages had 50 percent fall within ±12 percent. The latter gage is calibrated only statically at 1 g, and the gage contains a viscous damping fluid which requires measurement of temperature at time of use to obtain a valid calibration. There appeared to be no significant bias on the positive or negative side of the average peak. Since vector sums are being used for this program, the variance caused in the vector sums will be less than the percentages noted above. No values are available for the Kistler accelerometer, but the accuracy is certain to be better than that of the Pace accelerometer. The L-7 seismometer has a variation of about ±5 percent immediately after calibration to possibly ±10 percent at some later time. DX velocity gage data have been differentiated to obtain acceleration-time records used for vector sums. In view of the greater variation noted for the DX velocity gage data, it is clear that differentiating those records further increases the variation. Where available, a vertical component from the Pace accelerometer has been used with two horizontal components from the DX velocity gage, resulting in some decrease in the variation. It is important to emphasize the following points with regard to use of data from the DX velocity gages, and to a lesser extent with regard to the Pace accelerometer data:

1. Because the potential exists for the NTS to return to testing weapons to yields limited to those which would cause unacceptable off-site damage, these yields must be considered in an evaluation of compatibility of a waste storage facility with weapons testing.
2. Since the advent of the NNWSI, only yields less than 150 kt have been detonated.
3. In order to base compatibility evaluation on larger yields, data from earlier shots _must_ be used.
4. In using these larger yields, there is no alternative to accepting data from Pace accelerometers, DX velocity gages, and L-7 seismometers.

f. _Data Processing_ - There is no significant scatter contributed by the recording system or the data processing techniques, _per se_. The scatter, and the accompanying increase in σ, brought about by having differentiated velocity-time measurements from velocity gages which have greater variance than accelerometers properly belongs in e. above. The data processing, in this case differentiation, does not increase the variance.

g. Number of Stations - Events used in this data set did not all have the same number of stations. The number ranges from 6 to 25. Thus, in a multiple regression analysis an event with a large number of stations would weigh more heavily than events with a smaller number. If all other factors contributing to variations in σ were the same this would make little difference. If, however, the event with the larger number of stations were relatively more strongly or weakly coupled than other events, its having more stations would bias the mean in that direction.

h. Distribution of Stations - For a more idealized data set is would be desirable to have the same number of stations for each event and to have that number at an equal logarithmic spacing away from ground zero. Figure 9 shows for the 21 events in the data set the number and location of stations. As significant as number, is the distribution of stations with distance. A more ideal measurements program would have had stations equally spaced on a logarithmic scale. Event I most nearly approaches such a spacing. Event Q has no stations closer than 9 km and Event T has none beyond 3.5. Several events (B, G, H, K, L, O, and P) have only one station beyond 10 km. These single distant stations exert a disproportionate influence on the attentuation rate with distance, depending especially on whether the station was located on soil or rock.

Rough estimates of the contributions to σ of items a through e above would be about:

			x	x^2
a.	Yield	10%	.1	.01
b.	Coupling	30%	.3	.09
c.	Transmission	50%	.5	.25
d.	Station Site Medium	50%	.5	.25
e.	Sensors and Recorders	10%	.1	.01

$$\Sigma x^2 = .61$$

$$(\Sigma x^2)^{1/2} = .78$$

$$.78 + 1 \approx \sigma$$

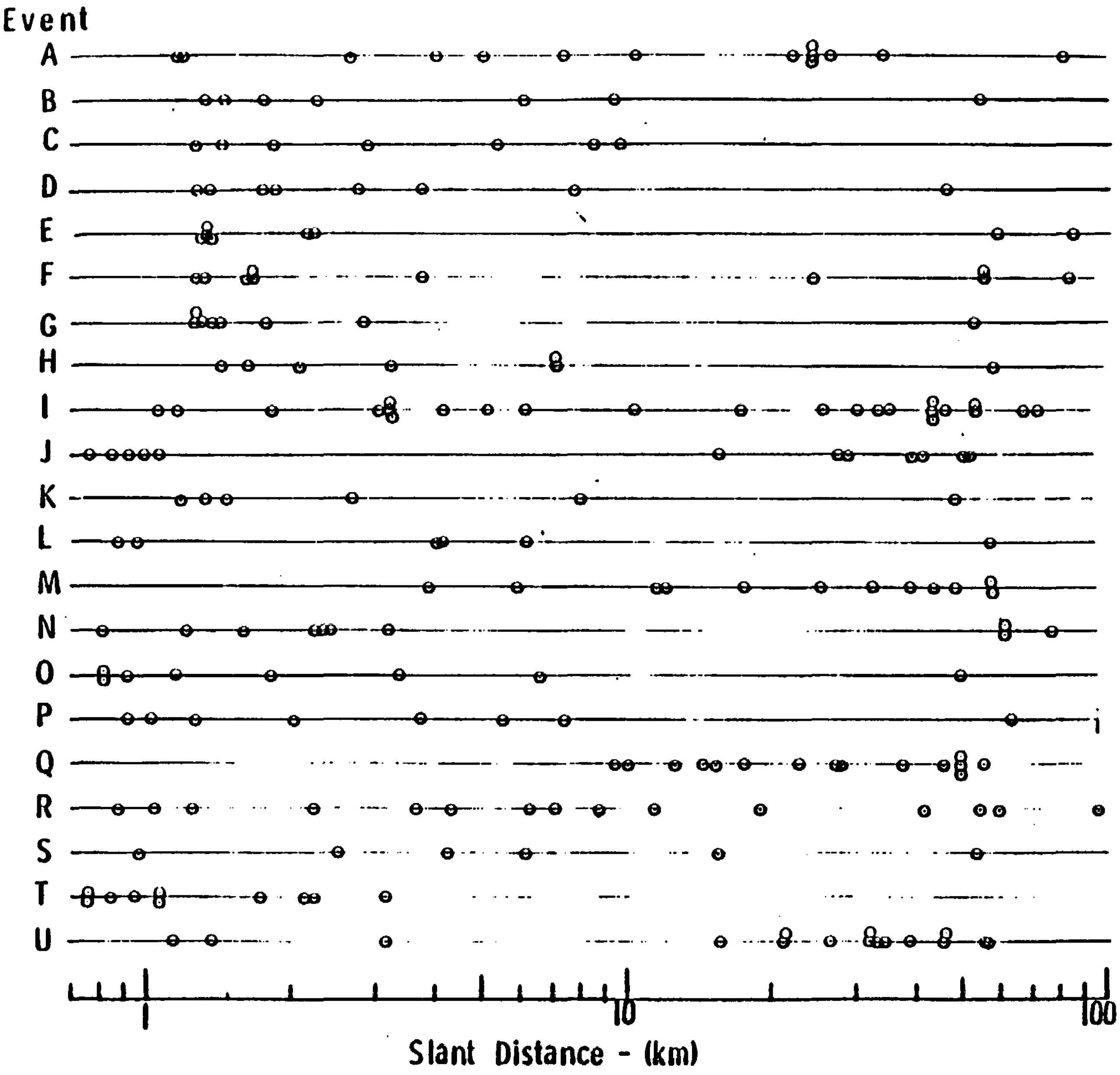

Figure 2 [illegible]

A σ derived from a multiple regression equation of the form

$$a = K W^{n} R^{-m}$$

will contain contributions from all five elements. A σ derived from a simple regression equation of the form

$$a = k R^{-\mu}$$

does not contain the contributions of elements a and b. The contributions of c and d are not easily separable except by estimating from a multiple regression analysis using first stations on alluvium only and separately those on rock only.

Ground Motion Dependence on Yield and Distance

The functional form used by Environmental Research Corporation (ERC)[8,9,10] to relate acceleration to yield and distance is

$$a = KW^{n}R^{-m} \tag{1}$$

where K, n, and m are constants. They further observe that if cube-root scaling were to prevail, then

$$n = \frac{m - 1}{3} \tag{2}$$

where 3 is the denominator in the scaling exponent 1/3 in

$$\frac{a_1}{a_2} = \left(\frac{W_2}{W_1}\right)^{1/3} \tag{3}$$

where subscript 1 refers to an event yield, and 2 refers to a yield to which data are scaled. If, in Equation (2), we replace 3 with α, then

$$\alpha = \frac{m - 1}{n} \tag{4}$$

and can be evaluated using m and n from Equation (1). Then α can replace the 3 in the denominator of the scaling exponent of Equation (3).

With such a prediction equation, data from any event may be scaled to another yield using

$$\frac{a_1}{a_2} = \left(\frac{W_2}{W_1}\right)^{1/\alpha} \tag{5}$$

Later examples are shown which separate a yield effect from coupling effects and allow coupling to be assessed separately. The argument which will be explored further is that a markedly decoupled shot can add appreciably to σ, and should not be used when the concern is with the strongly coupled shot. There is no a priori reason to expect a decoupled shot to be offset by a shot as strongly coupled with respect to the mean of the data set.

Convergence of and Effect of Coupling on σ

Two topics are of interest with respect to the prediction of ground motion from nuclear weapons tests. One is the convergence of the σ in the prediction equations as additional data are obtained. The other is the effect of energy coupling on the values for σ. The data used in the arguments involve classified information, and the arguments and data are contained in Appendices A and B which are classified. They are not included with the unclassified version of this report. The following is an unclassified summary of the two topics.

Convergence of σ - The results of the analysis show that as additional data are added to the data set, the change in σ is irregular, increasing more often than decreasing, but gradually approaching an asymptote. Equations for calculating the convergence of σ require that the random variables in the sample are always independent and identically distributed. Such is not the case with this data set since the number of stations on a given event varies from 6 to 25, and the spacing of stations with distance is not comparable. Additional data beyond that in the present data set can be expected to introduce relatively small changes in σ. Present data are sufficient if the final selection of a site is at a location sufficiently far from the testing areas that the maximum motion imposed by weapons tests does not exceed that from natural earthquakes for which the facility must be designed. For a closer site, the adequacy of the data must be a decision by managers of the NNWSI and NRC that the data provide sufficient basis for NRC licensing. This decision must consider that a comprehensive test ban treaty or weapons test moratorium would preclude acquisition of additional data.

Effect of Coupling - If data from 215 stations on 21 events are scaled to 700 kt the equation which fits the data is

$$a = 0.603\ W^{0.446}\ R^{-1.691} \quad (\sigma_a = 1.833,\ \sigma_R = 1.431) \qquad (6)$$

The σ_R for coupling was found in classified Appendix B to be 1.287, and the σ_R attributed to all other contributors to scatter is 1.322. Where σ_R is 1.322 and m is 1.691, σ_a is 1.602. Using data for each shot weighted according to the number of stations on that shot, σ_a was found from the average value to be 1.596. Thus, two approaches give essentially the same answer.

There were five shots which were markedly decoupled and one which was considered anomalous because very weak signals resulted from gages set for strong motion from a closer detonation. Using data from the remaining 15 events (153 stations) the following fit was found

$$a = 1.042\ W^{0.397}\ R^{-1.741} \quad (\sigma_a = 1.731,\ \sigma_R = 1.371) \qquad (7)$$

Thus a small decrease in σ results from discarding data from strongly decoupled shots. Removing the contribution of coupling ($\sigma_R = 1.166$) leaves a residual from other causes, $\sigma_R = 1.332$.

This value (1.332) can be applied to the best-coupled event and compared with the prediction equations above by showing the following distances (km) to the 0.75 g level for 700 kt.

	Mean (km)	$1\sigma_R$ (km)	$2\sigma_R$ (km)	$3\sigma_R$ (km)
Fitting equation for 21 events	4.95	7.08	10.12	14.50
Fitting equation for 15 events	5.38	7.38	10.11	13.86
Best-coupled event, $\sigma_R = 1.332$	6.43	8.56	11.41	15.20

The difference in distance to 0.75 g is relatively small between the fitting equation for 15 events and that for 21 events, and the direction of the difference changes with increased σ. Removing the contribution of coupling from σ and using the residual value with the best-coupled event results in larger distances in all cases, indicating that the reduction in σ is not sufficient to offset the stronger coupling of the best-coupled event.

It is necessary to emphasize that the above distances are conservative in the sense that they exaggerate uncertainty in predicting ground motion. If all gages measured accurately and were exactly calibrated and if yields of all events were known exactly the effect of their contribution to scatter would be a more precise (and smaller) value of σ and a greater accuracy of prediction. Also, once a site has been fixed, measurements made there can be used to determine a site factor, i.e., to determine how measurements there fall with respect to the prediction equation. This permits a further reduction in σ for that site only.

Application

It is in order to put the foregoing into perspective relative to siting a nuclear waste storage facility. It is reasonable to assume that a Design Response Vector appropriate to siting would be 0.75 g, which would have a mean from Equation 7 at 5.38 km (Arrow a, Figure 10). This is almost exactly the maximum distance to which spall has been observed on Pahute Mesa, so some margin is justified. It is a judgment that a $+0.5\sigma$ is sufficiently conservative.

A peak vector acceleration of 0.75 g would occur at the $+0.5\sigma$ distance of 6.30 km (Arrow b). At this distance the mean value for peak vector acceleration would be 0.57 g (Arrow d), and the $+1\sigma$ value 0.99 (Arrow c). Now the degree of conservatism with regard to spall resulting from using a $+0.5\sigma$ criterion can be assessed as it relates to the vertical motion which causes the spall. From data at the top of Figure 5 one finds that the ratio of peak vertical acceleration to peak vector acceleration is 0.467/0.607, or 0.77. If one multiplies the peak vector values at 6.30 km by 0.77 to get peak vertical acceleration, the results are: mean, 0.44 g; $+0.5\sigma$, 0.58 g; $+1\sigma$, 0.76 g, and $+1.5\sigma$, 1.00 g. Thus, at the $0.5\sigma_R$ distance the 1 g limit of spall would be at the $1.5\sigma_a$ probability level for peak vertical acceleration. This is more conservative than the $+1\sigma$ used for vertical acceleration in the design of nuclear reactors.

For purposes of illustration, let it be assumed that a site on Timber Mountain would be considered for a nuclear waste storage facility. In Figure 11 a point on the southeast slope of Timber Mountain pass has been chosen arbitrarily. The map shows an outline of the actual testing areas in the Buckboard Area described by USGS.[11] A 750 kt event in the Buckboard Area would normally be buried at a depth of 1.34 km. A slant distance to 6.3 km would correspond to a horizontal distance of 6.16 km. A circle with a radius of 6.16 km has been drawn with the arbitrary site as the center. A 700 kt explosion (near the maximum allowable for the Buckboard Area) could be detonated anywhere outside the circle without imposing more than 0.75 g vector motion at the 0.5σ probability level and with less than a 1.5σ probability of the site being subjected to spall. Thus, a facility would have to be located closer than the point shown before subjecting the Weapons Test Program to any restrictions.

It was noted in Figure 10 that a Design Basis Vector acceleration of 0.75 g at 0.5σ corresponds to a vertical acceleration of 0.75 at 1.0σ. The hypothetical site illustrated in Figure 11 is 7.9 km from the closest point in the Buckboard Area which has been designated suitable for testing. If a maximum permissible yield were detonated at that closest point, σ would be 1.17, i.e., there would be a 12% change of exceeding the Design basis vector. If the yield at that point were reduced to 475 kt, the chance of exceeding would be 6.7% (1.5σ). For 235 kt the chance would be only 2.3% (2σ). Or, the full 750 kt could be detonated at the closest point if the hypothetical site were moved an additional 0.9 km away for the 1.5σ or an additional 2.4 km for the 2σ case. In view of the risk differences pointed out earlier between reactors and a waste facility at NTS and the fact that only a $+1\sigma$ factor is applied in the Design Response Criteria for reactors the examples cited here seem unnecessarily conservative.

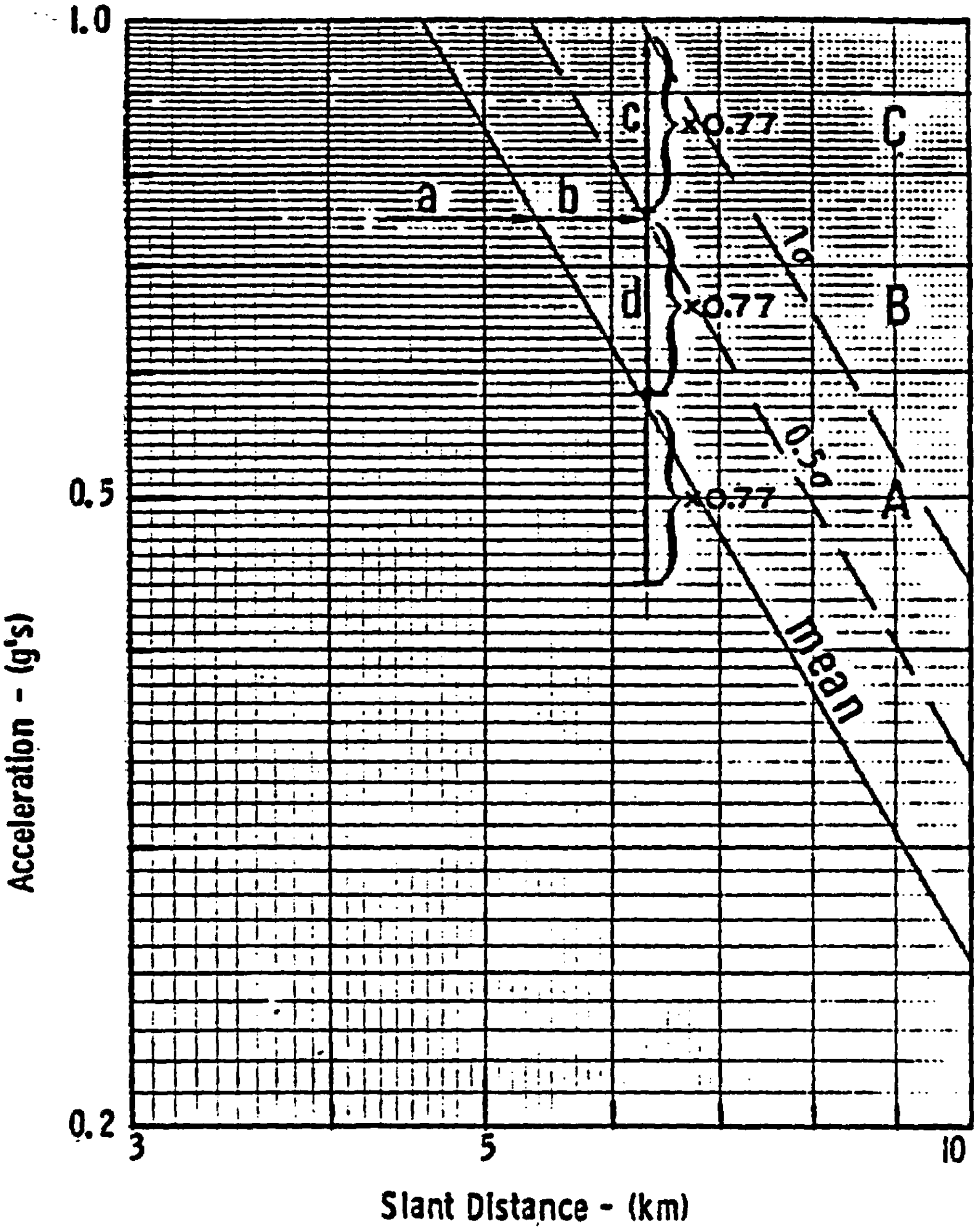

Figure 10 Relation between peak vector acceleration and peak vertical acceleration

Alternate Examples

There may be other examples than the 0.75 g from 700 kt used in the example above which encompass the range of options which needs to be considered. In Table I are the slant distances for various values of σ_R for acceleration levels of 0.75, 0.50, and 0.25 g, and for yields of 1000, 700, 400, and 150 kt. The 1000 kt is appropriately used for Pahute Mesa which appears near the top of the map in Figure 11. The 700 kt yield is appropriate for the Buckboard Area. The 150 kt yield was chosen because it is the yield threshold under which present operations are conducted, and 400 kt because it was an intermediate yield. Users of the table should be cautioned that the weapons test program considers it vital that no nuclear waste storage facility be built where it would limit yields tested in the Buckboard Area and Pahute Mesa below the 750 and 1000 kt, respectively, based on off-site safety considerations.

Conclusions

The foregoing leads to a number of conclusions relative to siting a nuclear waste storage facility where it would be subjected to ground motion from underground nuclear weapons tests.

1. If a facility is located sufficiently far from nuclear weapons testing areas, the design criteria for natural earthquakes will control, and weapons-test-induced ground motion will not be a significant factor in design. NV policy may still require that a waste facility be evacuated at the time an explosion is detonated.

2. If a facility is located sufficiently close to nuclear weapons testing areas the design criteria for weapons-test-induced ground motion will control.

3. Underground nuclear detonations are known precisely as to energy, location and time, permitting a close waste facility to be evacuated and secured at shot time.

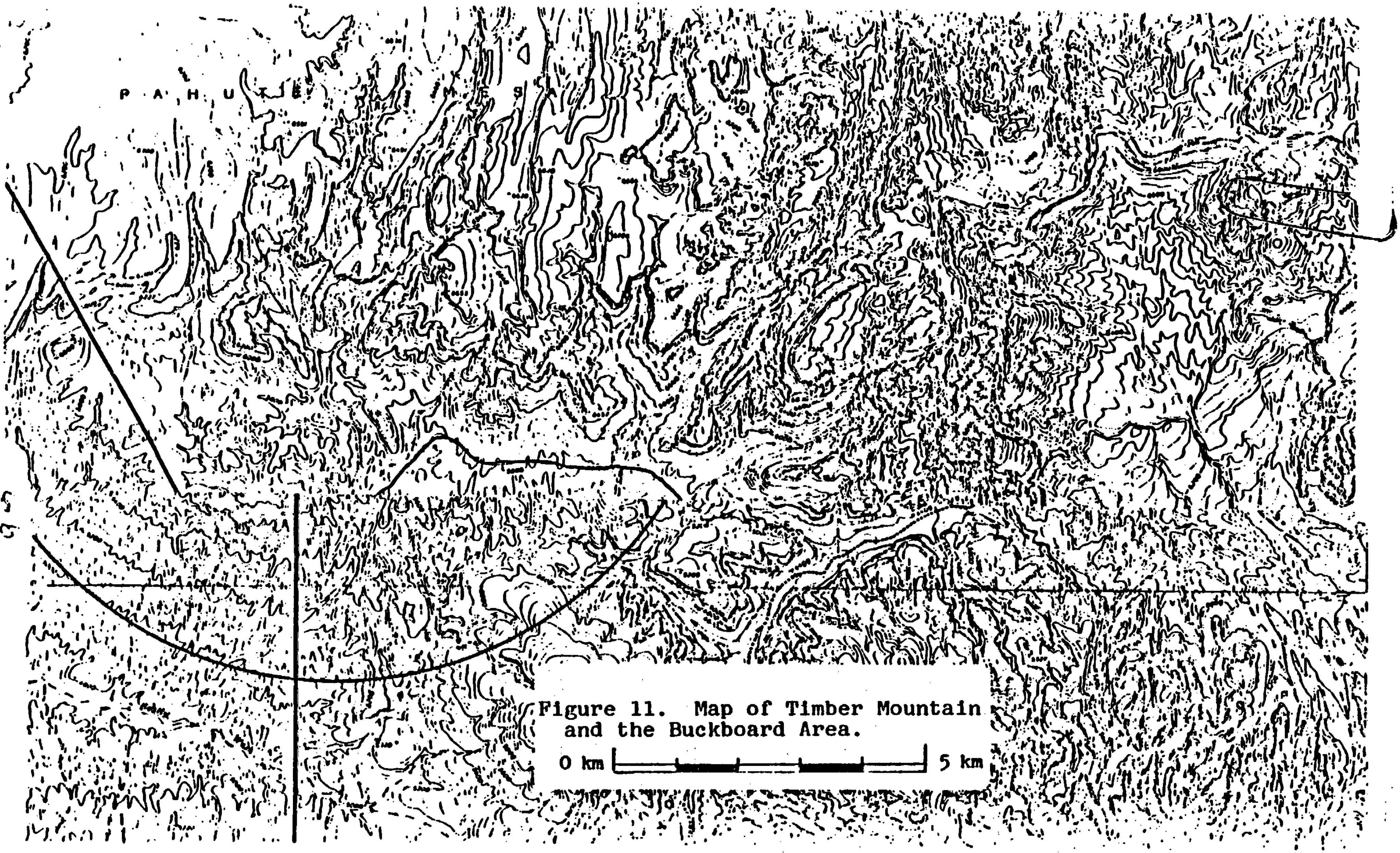

Figure 11. Map of Timber Mountain and the Buckboard Area.

4. Since there is no need for an equivalent of a Safe Shutdown Earthquake or Operating Basis Earthquake as in the design of nuclear reactors, there is less need to be conservative with regard to design response criteria for weapons-test-generated ground motion than for that generated by natural earthquakes.

5. A facility should be located such that the top of the shaft would not be subjected to more than 1 g vertical motion at the surface. This places the facility beyond the limit of spall which would not be expected beyond 5.4 km from a 700 kt explosion.

6. A Design Response Spectrum approach similar to that used for nuclear reactor design is appropriate for siting of a nuclear waste storage facility.

7. An appropriate equation for predicting peak vector ground motion from underground nuclear explosions in the Buckboard Area or Pahute Mesa is

$$a = 1.042\ W^{0.397}\ R^{-1.741} \qquad (\sigma_a = 1.731,\ \sigma_R = 1.371)$$

8. A peak vector acceleration of 0.75 g at a 0.5σ probability level is an appropriate Design Response criterion. A nuclear waste storage facility could be as close as 6.30 km (start distance) to a 700 kt underground nuclear detonation if proper measures are taken to secure the facility. Given the licensing assumptions made, there is little incompatibility from ground motion between the weapons test activities in the Buckboard Area and a waste storage facility beyond 6.30 km. A facility could be located beyond this distance to the south and/or west of the Buckboard Area.

9. The maximum permissible yield for Pahute Mesa is 1000 kt, larger than the 750 kt allowed for the Buckboard Area. The above equation and the same licensing assumptions indicates that a waste facility could be located beyond 7.25 km to the west and/or north of the Pahute Mesa testing area.

10. Tabulated data which permit exploring other ranges of acceleration, yield, and σ_R are subject to the constraint that the off-site safety yield limits of 750 and 1000 kt for Buckboard Area and Pahute Mesa, respectively, not be reduced.

TABLE I

Slant distance (km) to selected values of σ_R at three levels of acceleration and four values of yield.

Peak Vector Acceleration	Yield	Mean	$0.5\sigma_R$	$1.0\sigma_R$	$1.5\sigma_R$	$2.0\sigma_R$	$3.0\sigma_R$
0.75 g	1000kt	5.64	6.83	8.00	9.37	10.97	15.04
	700	5.38	6.30	7.38	8.64	10.11	13.86
	400	4.74	5.54	6.49	7.60	8.90	12.20
	150	3.79	4.43	5.19	6.08	7.12	9.76
0.50 g	1000kt	7.37	8.63	10.10	11.83	13.85	18.98
	700	6.79	7.95	9.31	10.90	12.76	17.50
	400	5.98	7.00	8.20	9.60	11.24	15.40
	150	4.78	5.60	6.55	7.67	8.98	12.32
0.25 g	1000kt	10.97	12.84	15.04	17.61	20.62	28.27
	700	10.11	11.84	13.86	16.23	19.01	26.06
	400	8.90	10.42	12.20	14.29	16.73	22.94
	150	7.12	8.33	9.76	11.42	13.38	18.34

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