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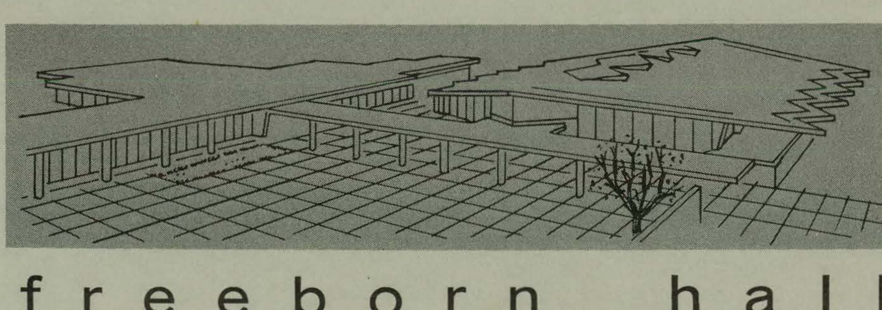

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CALCULATION OF THE SHOCK WAVE FROM AN UNDERGROUND NUCLEAR EXPLOSION IN GRANITE

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Born and reared in Chicago, Illinios, he served in the U. S. Army for three years during WW II. Received his B. S. and M. S. from DePaul University in Chicago. Employed as a physicist by the U. S. Army, Corps of Engineers, doing research on snow and ice from 1952 to 1959. Since 1959, with the Lawrence Radiation Laboratory in Livermore as a physicist with the Plowshare Group.

ABSTRACT

The capability of calculating the close-in effects of the shock wave from an underground nuclear explosion has been demonstrated. Agreement was obtained between calculation and measurements using a spherically symmetric, hydrodynamic, elastic-plastic code called SOC for the Hardhat event, a 5-kiloton nuclear detonation in granite. This capability is dependent upon having a more or less complete description of the elastic and dynamic properties of the materials involved. When this information is available, agreement within the limits of uncertainty of the measurements can be calculated for peak pressures, peak particle velocities, shock wave time of arrival, and pressure pulse shapes.

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INTRODUCTION

In any underground nuclear explosion, the shock front that propagates from the shot point carries with it energy from the explosion, and distributes this energy by doing work on the surrounding material. In the process, the material undergoes changes in both its physical and mechanical states. If enough energy is deposited in the material, it will vaporize or melt thus changing its physical state, or cause it to crush or crack.

During the past few years, special computer codes have been developed for predicting the close-in phenomena of underground nuclear explosions using the laws of physics, and the knowledge of the properties of the materials in which the detonations occur. As a consequence, a better understanding of experimental observations and measurements has evolved.

A spherically symmetric, Lagrangian, hydrodynamic-elastic-plastic code called UNEC (Underground Nuclear Explosion Code)(Nuckolls, 1959), was used in earlier calculations. Presently, a new code called SOC (Seidl, 1964) is being used in making these calculations. SOC is similar to UNEC in that it makes a rather direct use of an experimentally determined shock Hugoniot, but differs in that it uses different equations for calculating elastic-plastic behavior and internal energy. SOC also allows for strain-rate effects such as occur during pressure buildup and decay at the wave front.

Calculations, using the SOC code, were made for the Hardhat event, a 5-kiloton nuclear explosion. The device was detonated at the bottom of a 950-foot-deep, vertical hole in granite at the Nevada Test Site. The Hardhat event was chosen for these calculations first, because a large number of close-in measurements were made through a range extending from the hydrodynamic to the elastic regions; secondly, predictions of peak pressures, pressure histories, and shock wave arrival times had been made using the best available knowledge of the material properties at that time.

MEASUREMENTS

For the Hardhat event, a variety of close-in measurements were made on a horizontal radius from the detonation point. An access shaft and tunnel had been provided, and holes were drilled from the tunnel for instrumentation (Fig. 1).

In the hydrodynamic region, times of arrival of the shock wave were measured with special transducers in the range from 7.35 to 24.1 meters (24 to 79 ft) (Chabai and Bass, 1963). Peak pressure measurements were made in two locations, one of 460 kilobars at 5.51 meters (18.1 ft) (Chabai and Bass, 1963), and another of 664 kilobars at 4.85 meters (15.9 ft) (Lombard, 1963).

In the elastic region, there was an array of accelerometers, velocity and displacement gauges, and stress and strain measurement instruments distributed in the range from 78 to 914 meters (256 to 3000 ft) (Perret, 1963, and Stanford Research Institute, 1962). From this, some measurements are of particular interest here. The time of arrival as determined by the accelerometers are shown in Fig. 2. The average velocity of the shock wave was 5526 meters/second (18,130 ft/sec). With this shock velocity U_s and the peak velocity measurements U_p, peak pressures were determined from the Hugoniot relationship

$$P = U_p U_s \rho_0$$

where ρ_0 is the initial density of the material. Pressure history measurements were made in two locations (Heusinkveld et al., 1962) with

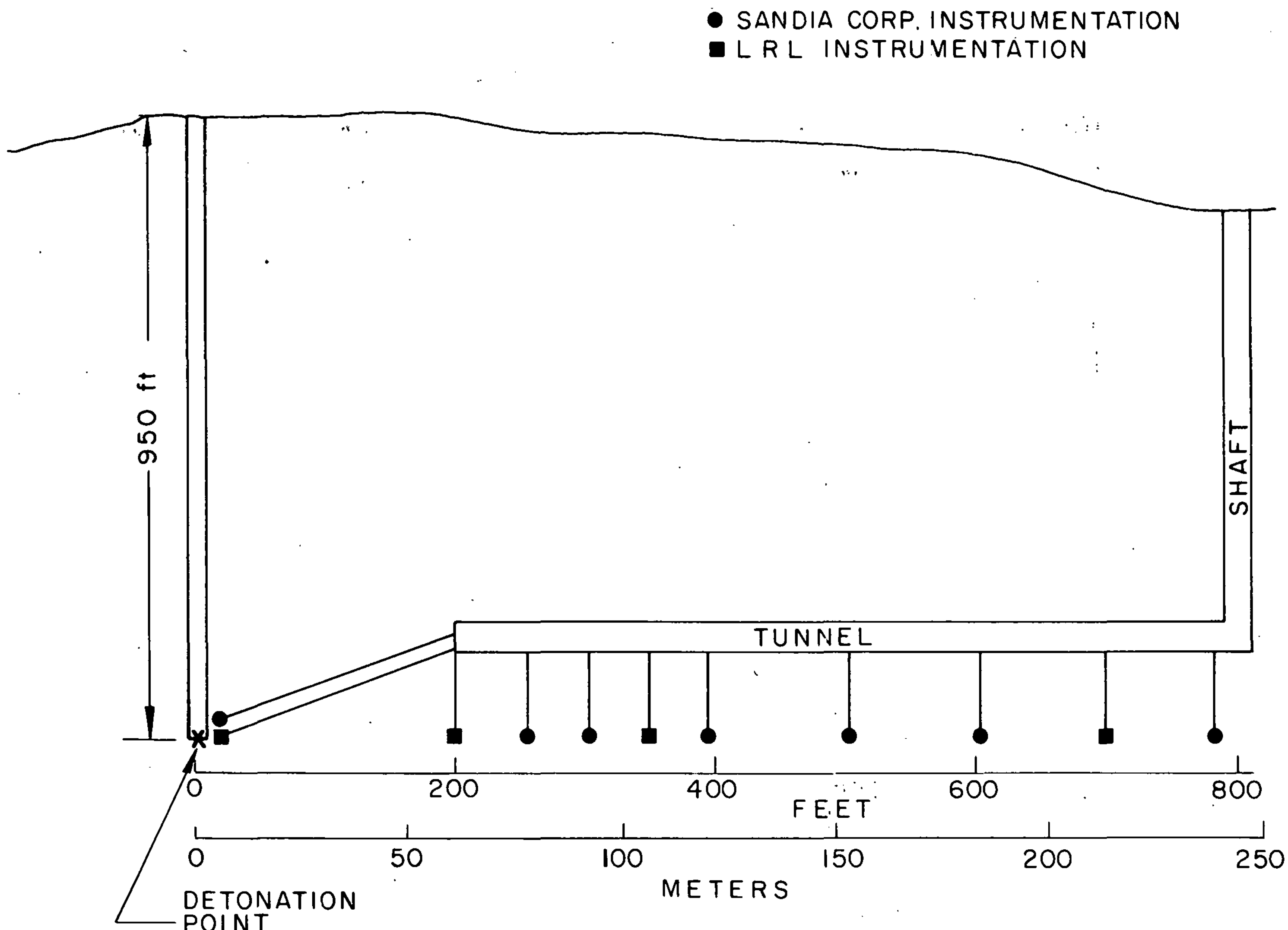

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Fig. 1. Layout of instrumentation of Hardhat event.

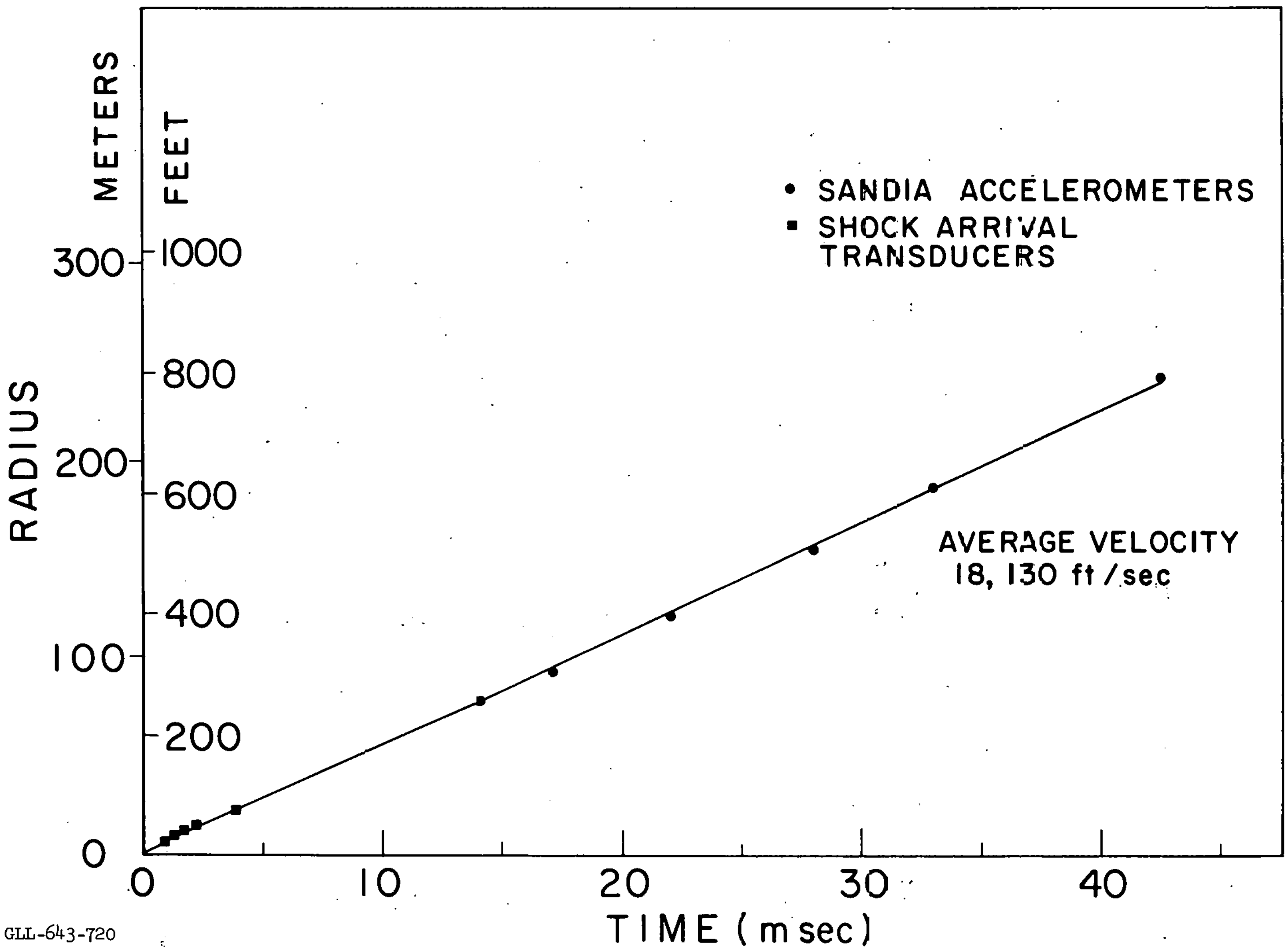

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Fig. 2. Time of arrival data.

peak radial stresses of 4.0 kilobars at 61 meters (200 ft) and 1.2 kilobars at 106.7 meters (350 ft).

THE SOC CODE

Before any meaningful calculation can be attempted, a more or less complete description of the materials involved has to be obtained. The Hugoniot equation of state, the shock energy to vaporize and melt, plastic yield conditions, dynamic strength properties, and elastic properties are all input to a SOC code calculation. Some of these parameters can be determined by rather well developed techniques, but others are not easily determinable and must be estimated on the basis of other related measurements.

Except in the vaporized region, the equation of state is made up of experimental data. At the higher pressure in the liquid and plastic states, the material is represented by the Hugoniot curve relating pressure and volume at the shock front. At the shock front discontinuity, a nonlinear Richtmyer-Von Neuman artificial viscosity (q) is used. The wave front is determined from a maximum in q, which lies at the center of the discontinuity and travels with the wave front velocity. During the unloading, the Hugoniot can be corrected to approximate the unloading isentrope, by using an appropriate Gruneisen Γ. When shock pressures are great enough to vaporize the material on unloading, a transition to the gas equation of state, normalized to the Hugoniot is made irreversibly.

In spherical symmetry, there are two principal stresses, (σ_r) normal and (σ_T) tangent to the wave front. That is, a distinction is made between these and the fluid-like pressure (P), where

$$P = \frac{\sigma_r + 2\sigma_T}{3}.$$

In the liquid state, the material is isotropic and the shear is zero. However, in the elastic-plastic state

$$\sigma_r = P + \frac{4}{3} K, \text{ and } \sigma_T = P - \frac{2}{3} K$$

where K, the so-called stress deviator is expressed by

$$K = \frac{\sigma_T - \sigma_r}{2} .$$

K is calculated differently depending on whether or not the material is crushed.

The plastic yield conditions are expressed in terms of K (Seidl, 1964), where K is equal to or less than the yield stress. For many materials, the yield stress is a function of the strain rate. When knowledge of this behavior is available, different yield conditions can be imposed according to whether the strain rates are high, as occurs at the shock front, or the pressure is slowly rising, or falling off on unloading.

The elastic region of the pressure-density curve is required to agree with sonic velocities in the material. In an isotropic elastic medium, the two characteristic sonic velocities, longitudinal (v_ℓ) and shear (v_s), are related by

$$v_\ell^2 \rho_0 = k + \frac{4}{3} G$$

and

$$v_s^2 \rho = G,$$

where, ρ_0, v_ℓ, and v_s are taken from in-situ measurements. The bulk modulus (k) can also be obtained from hydrostatic measurements. Stephens (1963) has shown that excellent agreement occurs between hydrostatic and dynamic measurements in the elastic region for eight different rock types.

Dynamic strength properties of the rock are less easily determinable. The bulk tensile strength of most rock masses are zero, or at most very small, because of the highly fractured state in which they are usually found. Dynamic compressive strength of rocks are not as easily obtained, and in most cases must be estimated, perhaps, something like twice or three times static measurements. In the case where the material has open cracks, the compressive stress that can be supported without crushing the material is always less than when cracks are closed and also depend on the strain rate. If the material does crush, then it is assumed that a type of Coulomb friction exists, somewhat like the resistance to shear for loose sand.

At the start of a calculation, the material is divided into two or more regions, a central gas region into which the energy from the explosion is put as internal energy of the gas, and the regions outside in which the material is initially plastic-elastic. The regions are divided into equal thickness zones to the outside. This is the ground surface in a vertical calculation, or extends somewhat beyond the region of interest in the horizontal case. After the shock wave has passed and the energy from the explosion distributed, the material state of each zone may have changed to expand the vaporized region or form melted, crushed, or cracked regions according to the peak stresses that developed in each region.

THE CALCULATION

The main purpose of making calculations is to develop a capability for predicting the phenomena from underground nuclear explosions on the surrounding media. These predictions are useful in a number of ways. Certain engineering criteria regarding such things as stemming and placement of surface installations can be established. Possible damage to existing underground structure from shock effects can be determined. Shock wave propagation is also important in crater formation from buried charges. The reliability of the calculations depends not only on the code, but also on the knowledge of the geology of the media, and the properties of the materials involved.

For the Hardhat event, predictions were made based on a 5-kiloton nuclear explosion, 950 feet below the surface in granite (Seidl,

1962) using the best available data at that time. These predictions were useful in determining instrument placement, and for range and time settings of the measuring equipment. Since then, more data on the properties of granite have become available, and with the measurements to compare with results, adjustments of some of the input parameters for granite used in the original calculation were made to cause better agreement.

In determining the dynamic equation of state of a material, measurements are made in the Laboratory by subjecting representative samples of the material to strong shocks generated by high explosives. Lombard (1961) has compiled data of shock velocity (U_s) and particle velocity (U_p) on a number of rock types, amongst which is granite. From these measurements the so-called Rankine-Hugoniot conditions can be obtained:

$$P - P_0 = \rho_0 U_s U_P,$$

$$\rho/\rho_0 - 1 = \frac{U_p}{U_s - U_p},$$

$$E - E_0 = \frac{P - P_0}{2} (1/\rho_0 - 1/\rho)$$

where P is pressure, E specific internal energy, and ρ the instantaneous density. The subscripts refer to initial values. Figure 3 is a plot of the data for granite. The scatter at the lower pressures is due to several causes. An elastic precursor of about 40 kilobars has been measured for granite (Grine, 1960). This means that a two-wave structure exists to about 320 kilobars; above which the shock velocity is greater than the dilatational sonic velocity. A number of polymorphic transitions of the mineral constituents of granite below 320 kilobars further complicate the interpretation of the measurements.

In the elastic region, the equation of state of granite is defined by the bulk modulus and the shear modulus. Figure 4 is a plot of the gran-

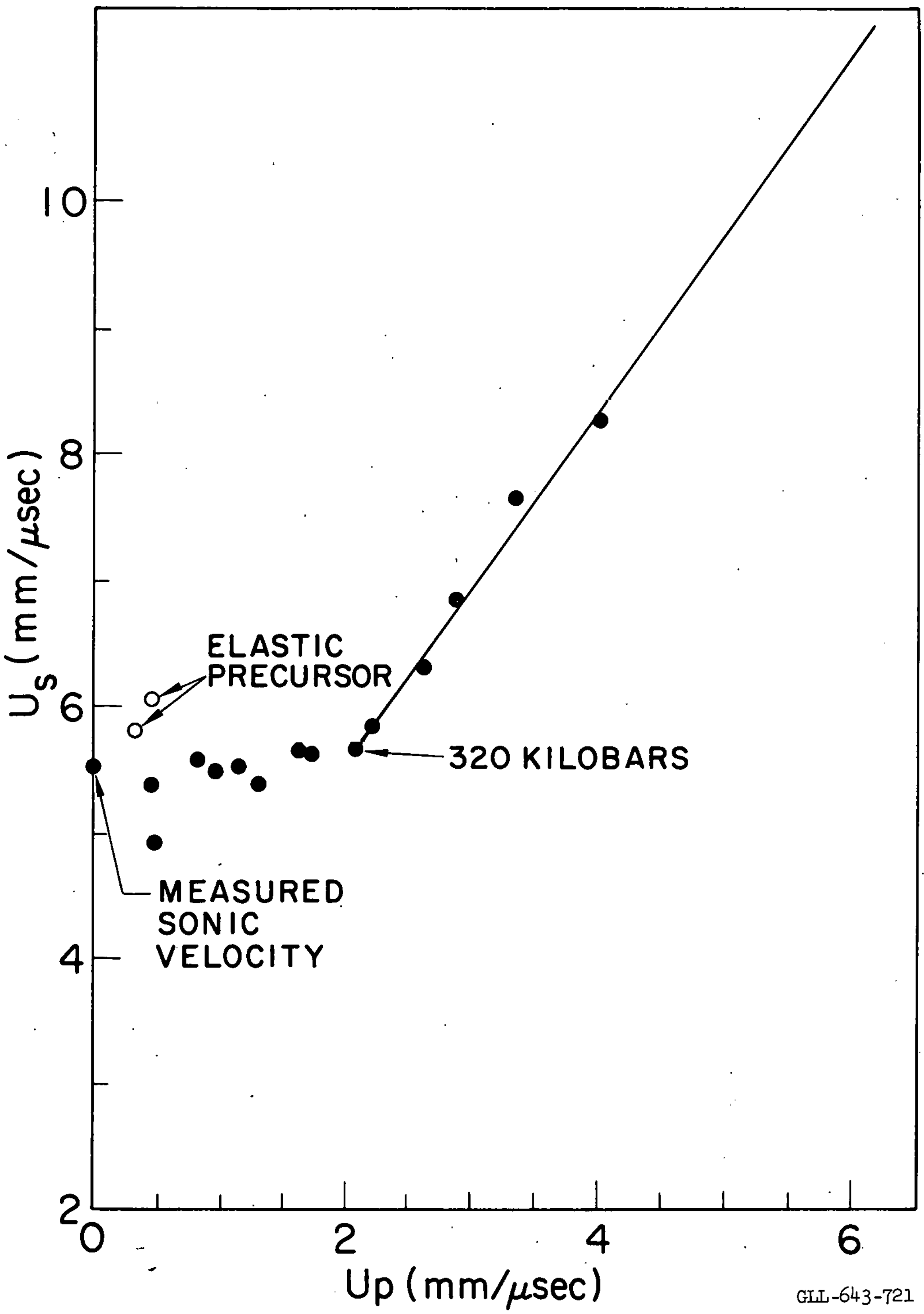

Fig. 3. Hugoniot measurements for granite.

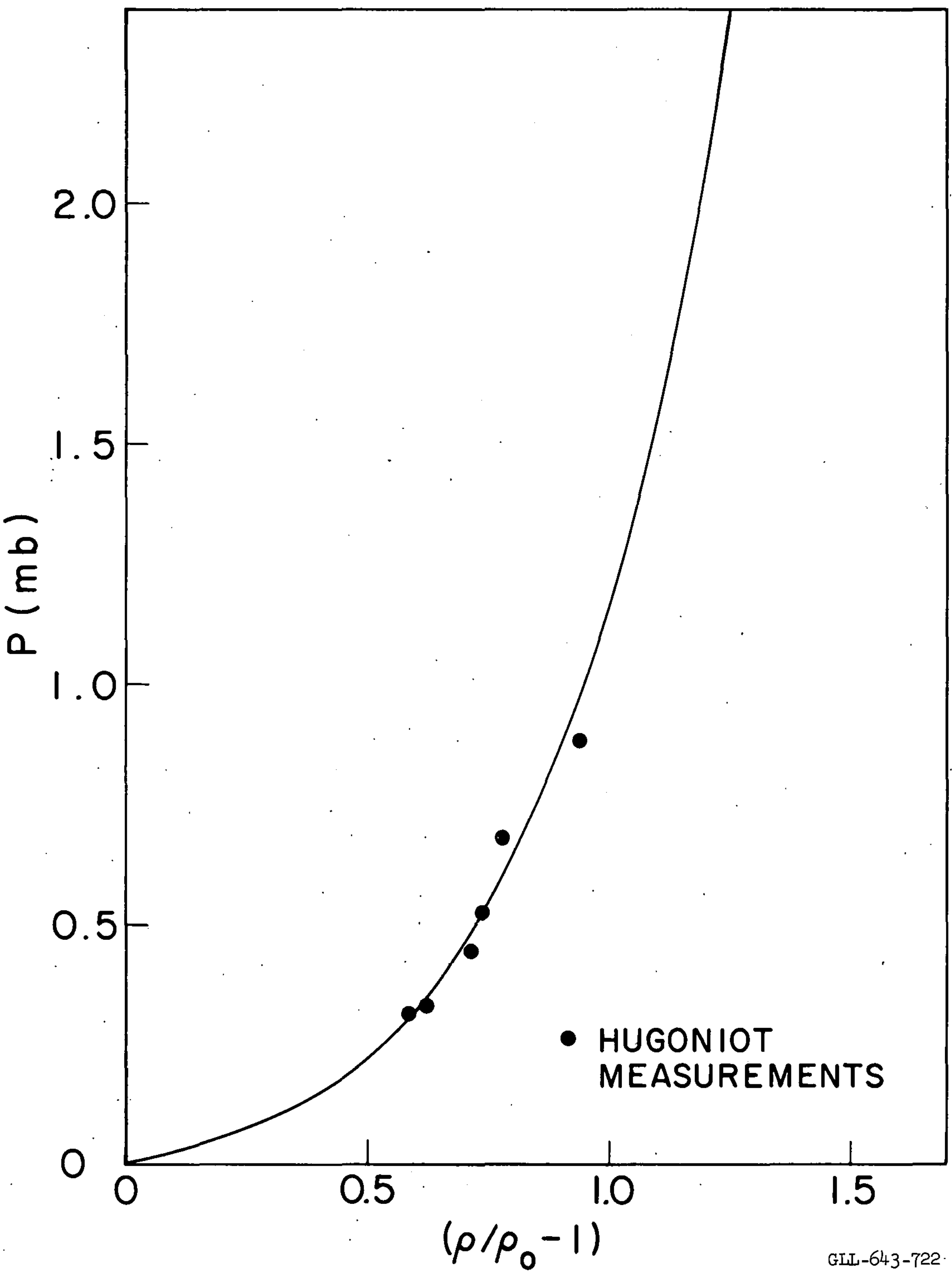

Fig. 4. Shock Hugoniot for granite.

ite Hugoniot, which is put into the SOC code as a linearly interpolated P vs μ table, where $\mu = \rho/\rho_0 - 1$. In-situ seismic measurements of the dilatational and shear velocities in granite are 5440 meters/sec (17,850 ft/sec) and 3050 meters/second (10,000 ft/sec), respectively (United Electrodynamics, 1962). The average measured wave front velocity of 5526 meters/sec (18,310 ft/sec) is in good agreement with the in-situ seismic velocities. Derived from the seismic measurements, the bulk modulus and shear modulus used in the calculation were 0.361 and 0.315 megabar, respectively. This corresponds to a wave front velocity of 5380 meters/sec (17,646 ft/sec) in the elastic region. Since the wave front velocity is greater at pressures above about 320 kilobars, the average velocity is somewhat higher, so as to give good agreement with the shock wave time of arrival measurements.

The dynamic properties of granite were estimated and adjusted to obtain good agreement between measurement and calculation. The bulk tensile strength was assumed to be zero, that is, radial or tangential cracking would occur depending on which of the principal stresses became tensile. Birch (1942) reports static measurements of compressive strength for granite of 10 kilobars for confined tests and 1.5 kilobars for unconfined tests. The dynamic compressive strengths were assumed to be about twice the values from static tests; 20 kilobars, when cracks are closed and material confined, and 3 kilobars with open cracks.

The dynamic yield stress was made to be consistent with a 40-kilobar elastic precursor during loading, when pressures are rising rapidly and strain rates are high, and the yield stress for slowly rising pressure pulses was adjusted to 5 kilobars, where good agreement was obtained with peak pressure measurements below this pressure.

Because the Gruneisen Γ for many pure rock mineral substances ranges between 0.5 and 1.5, a Γ of 1.0 was used for granite. Since the calculation was concerned primarily with material behavior near the shock front, a small error in the unloading isentrope should have little effect there. Vaporization occurred behind the shock front when the internal energy exceeded 0.584×10^{12} ergs per original cc. Melting occurred when the internal energy was greater than 0.093×10^{12} ergs per original cc. These values are equivalent to a shock vaporization pressure of 2.14 megabars and a shock melting pressure of 456 kilobars, if the Gruneisen Γ was 0, and the Hugoniot becomes the unloading isentrope. With Γ being set equal to 1, these pressures are slightly higher.

The calculation was made in two steps. First a fine-zoned case was run to more precisely determine the fall-off of peak pressure with distance in the region above 100 kilobars, and the limit of vaporization. The 5 kilotons were distributed uniformly as internal energy of a sphere of iron gas, with an average density and volume equal to that of the device canister. The second case used coarser zoning to cover the region below 100 kilobars, where the pressure was falling off less rapidly. It assumed that the initial density of the gas was approximately equal to the total mass of material vaporized, divided by the volume of the vaporized region. In both cases, the average initial bulk density of granite was 2.67 g/cm^3.

The peak shock pressure as a function of distance from the detonation center is shown in Fig. 5, along with limits of vaporization, melting, crushing and cracking. Peak pressure falls off as $r^{-1.94}$ in the region below approximately 1 megabar for a 5-kiloton detonation in granite.

Pressure history measurements (Heusinkveld <u>et al.</u>, 1962) at 60.96 meters (200 ft) and 106.6 meters (350 ft) are plotted in Fig. 6. Superimposed on these plots are the calculated pressure histories for the nearest zone position. At most, the curves are displaced 0.3 msec in time. The oscillatory shape at the calculated curves is due to the mathematical method the code uses. The true pulse shape should be more like the envelope formed by the peaks. The large discrepancy in arrival time between the calculated and observed pressure pulse at 350 ft is attributed to an error in instrument position determination, since this is the only one of many measurements that does not fall on the shock time of arrival curve.

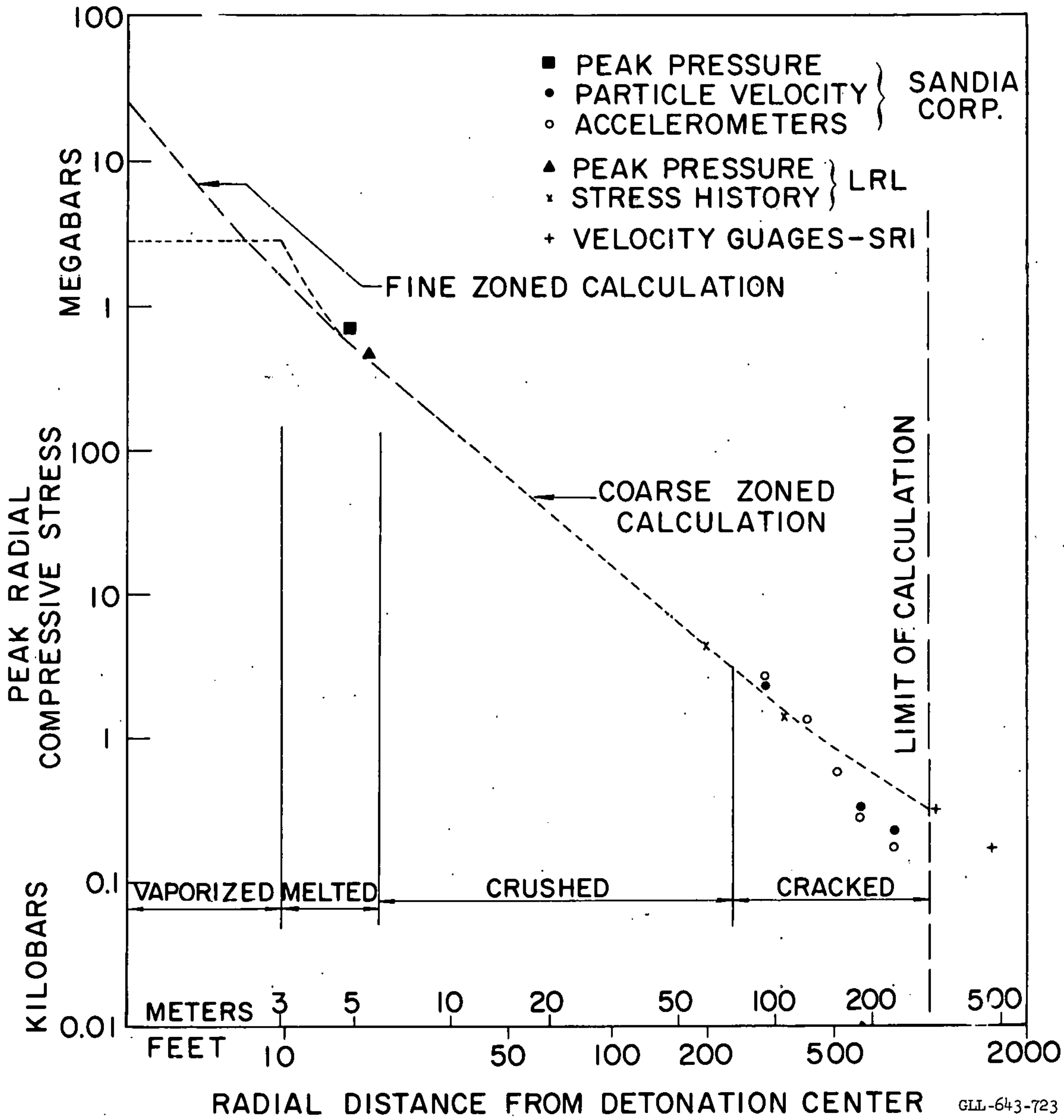

Fig. 5. Hardhat event, peak radial stress vs radius.

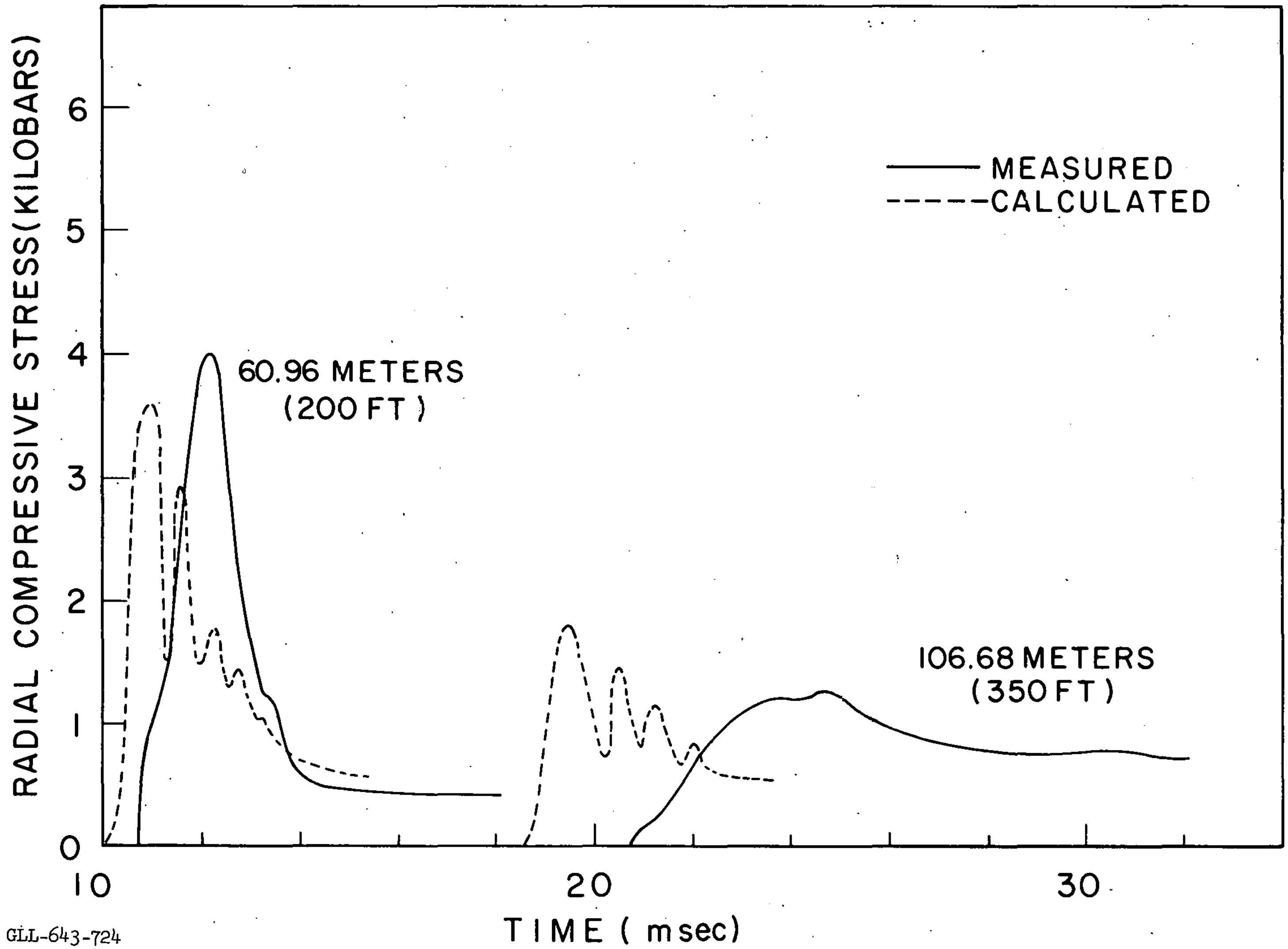

Fig. 6. Pressure history measurements.

The peak particle velocity vs radius is plotted in Fig. 7. The measurements shown were obtained by integration of the acceleration-time data, and by direct observation of velocity gauge signals. Sandia data seem to indicate the velocity to be falling off faster than that calculated. However, measurements by Stanford Research Institute at 457 meters (1500 ft) agree better with the calculation.

The Hardhat tunnel collapsed completely out to a radius of 137 meters (450 ft). Additional collapse occurred to 155 meters (510 ft), but this was associated with a weak fault zone (Lombard and Cauthen, 1964). The peak radial stress is about 1.3 kilobars at this radius. The calculated pulse shape is shown in Fig. 8.

DISCUSSION OF RESULTS

The agreement between calculation and measurements for the Hardhat event has demonstrated the capability for predicting with considerable accuracy the close-in effects of the shock wave from an underground nuclear explosion. The differences that are noted are due to uncertainties in the measurements of the phenomena, in measurements of the material parameters, and the fact that a spherical model was assumed.

Measurements of material properties upon which the input parameters are based are made on selected samples or in areas that are similar to the detonation region, but are not necessarily representative. Often there are large variations in the structural geology for a given type of material within one area. The properties of the materials upon which the calculation is based must exhibit an average behavior of the medium.

The code uses a spherical model, whereas in reality the geometry of the device room in an underground nuclear explosion is rarely spherical. Also, the detonation is not truly a point source, and a small displacement of the detonation center can mean a rather large discrepancy in peak pressure within the first few meters.

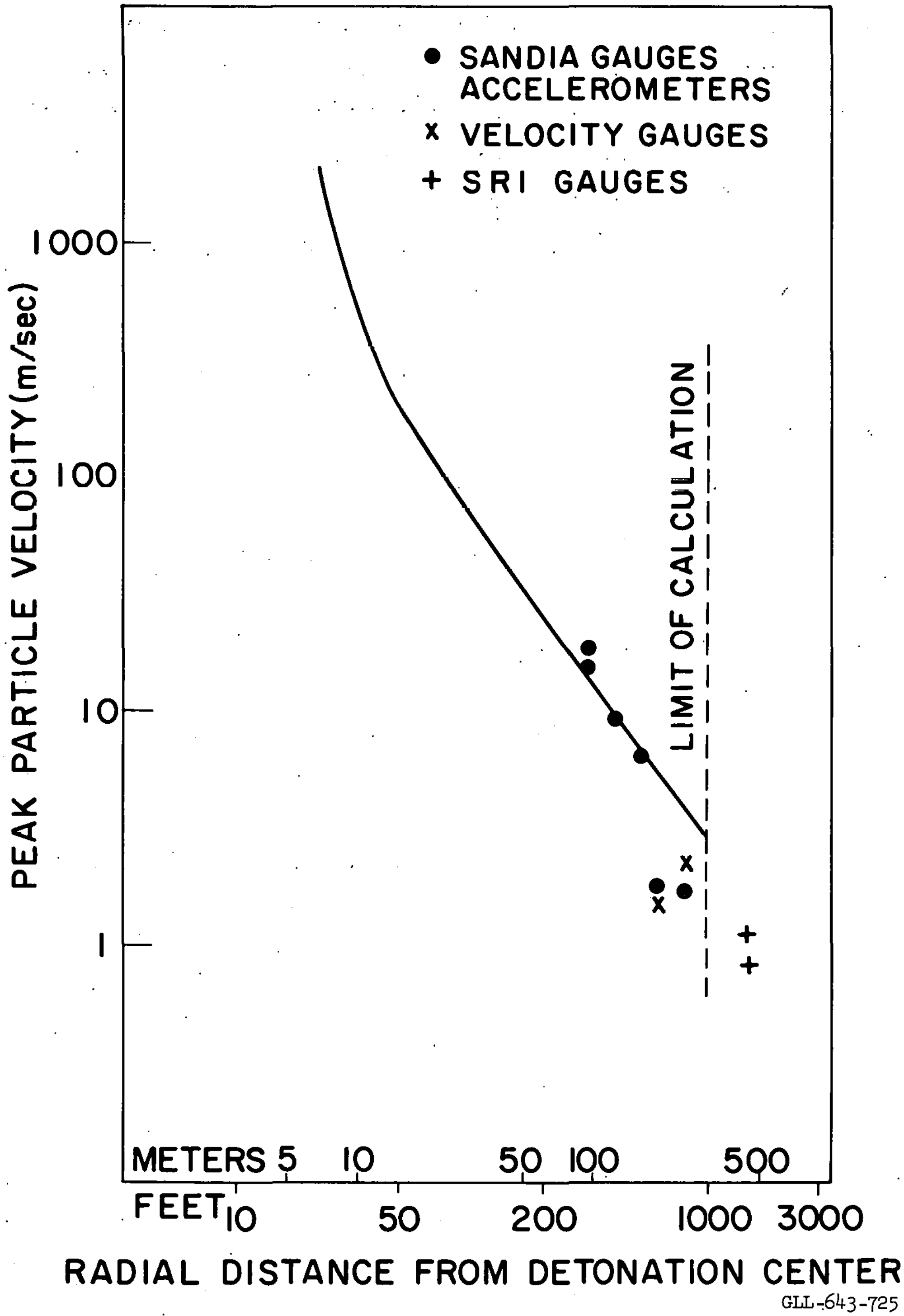

Fig. 7. Peak particle velocity vs radius.

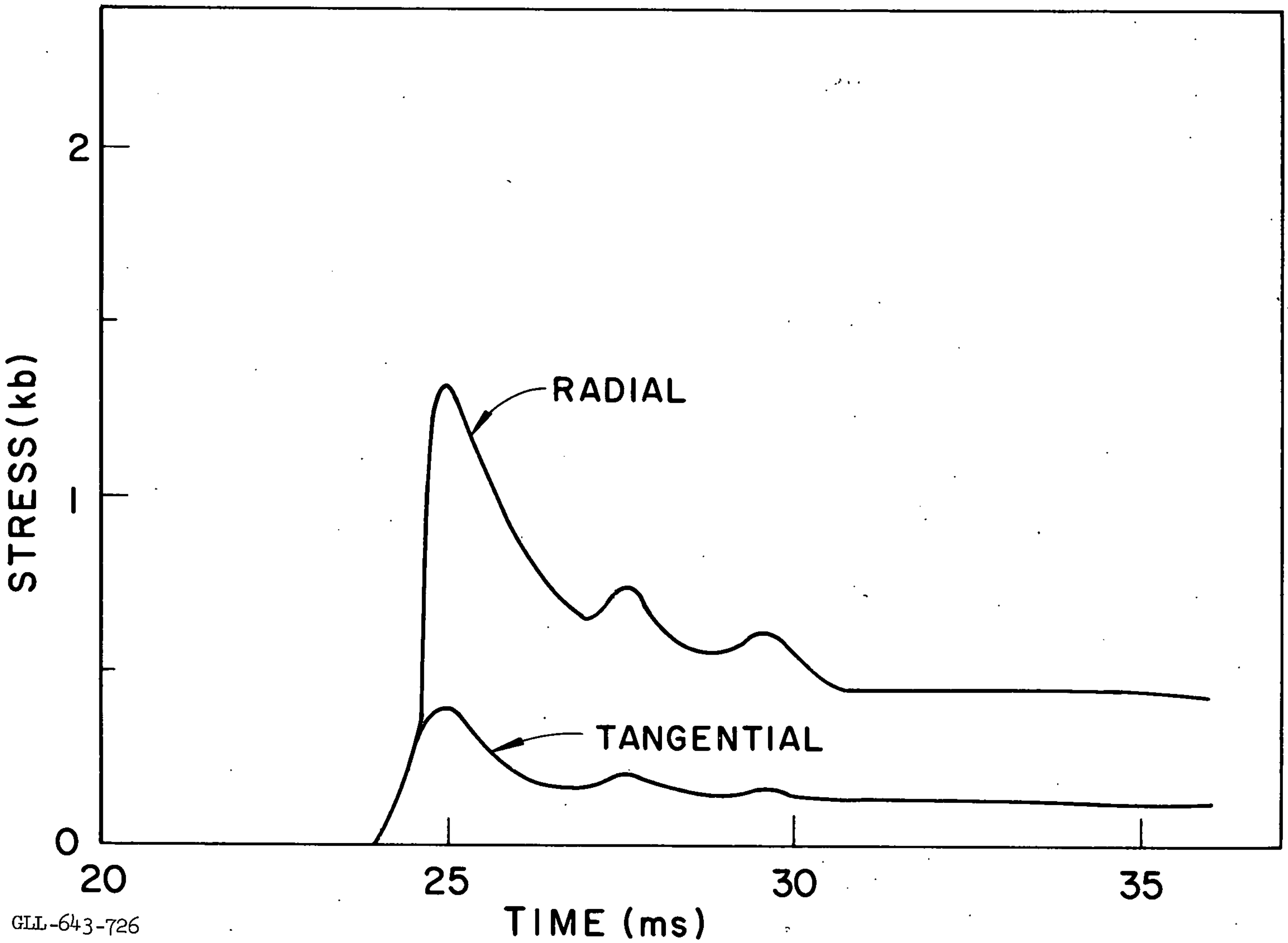

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Fig. 8. Calculated pressure vs time at tunnel collapse (155 meters).

The device yield itself is based on measurements, and each measurement has an uncertainty. The uncertainty can be due to a number of sources, such as time and position resolution or instrument design and calibration. Some measurements are obviously in error and are discarded because of disagreement with other reliable values.

In the Plowshare group, a major effort is being made to better understand the phenomenology of underground nuclear detonations by code development, obtaining better input parameters to these codes, and improved measurement techniques.

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