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CHAPTER 5

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ABSTRACT

The yields of nuclear explosions can be estimated using hydrodynamic methods The approach that has been proposed by the United States for nuclear test ban monitoring makes use of the fact that the initial speed of the expanding shock wave produced by an underground explosion increases with the yield Several techniques have been developed in the United States to measure the speed of the shock wave, of which the so-called CORRTEX technique is the most recent and best A variety of algorithms have been used to derive yield estimates from shock wave radius vs time measurements Although more intrusive than seismic methods, current hydrodynamic methods could be used to monitor the Threshold Test Ban and Peaceful Nuclear Explosion treaties, provided that appropriate changes in these treaties are negotiated and that adequate cooperative arrangements are made to assure accuracy Significant engineering, operational, and analysis problems need to be solved before these methods could be used to monitor with confidence a low-threshold test ban The methods are not relevant to a comprehensive test ban

I INTRODUCTION

Hydrodynamic methods have long been used to estimate the yields of nuclear explosions, both in the atmosphere[1] and underground [2] All such methods are based on the fact that the strength of the shock wave produced by an explosion increases with the yield Hydrodynamic methods were introduced as a treaty-monitoring tool in the Protocol of the Peaceful Nuclear Explosions Treaty (PNET) of 1976, which explicitly established such methods as among those that could be used to monitor the yield of any salvo of explosions with a planned aggregate yield greater than 150 kilotons (kt) [3] Hydrodynamic methods have recently become a focus of attention as a result of controversy over monitoring of the Threshold Test Ban Treaty (TTBT)

The TTBT was signed by the United States and the Soviet Union in 1974 and banned underground nuclear tests with yields greater than 150 kt after March 31, 1976.[3] Although neither party has ratified the TTBT, both have separately stated that they will respect the 150 kt limit. From that time to the present, the U.S. government has relied primarily on yield estimates based on teleseismic body wave magnitudes measured outside the Soviet Union to monitor the TTBT limit.[4] According to the U.S. Department of State, this method has an uncertainty of approximately a factor of two at the 95% confidence level for Soviet tests with yields near 150 kt.[5,6] This statement means that 95 times out of 100 the estimated yield of a 150 kt explosion will lie between 75 kt and 300 kt. Put another way, there is only one chance in 40 that a single explosion with a yield of 300 kt would appear to have a most likely yield of 150 kt or less. The probability that two such explosions would appear to be treaty compliant is 1 in 1600, and so on.[7] According to recent studies, the best seismic methods now available are expected to have an uncertainty of a factor of 1.5–1.6 at the 95% confidence level for explosions with yields above 50 kt, if measurements are made only outside the Soviet Union and the Soviet test site is not calibrated, or a factor of 1.3, once the Soviet test site is properly defined and calibrated.[4]

Prior to the Reagan administration, the precision of remote seismic methods was considered adequate. However, the Reagan administration has stated that "the remote seismic techniques we must rely on today to monitor Soviet nuclear tests do not provide yield estimates with the accuracy required for effective verification of compliance."[5] As an alternative to these techniques, the Reagan administration has since 1983 strongly advocated routine use of hydrodynamic methods to monitor the TTBT.[5,6] It believes that it has identified in hydrodynamic yield estimation methods an approach "which will reduce the uncertainty in yield measurement to an acceptable level and will do so without danger of compromising other sensitive information about the nature or performance of the nuclear device whose yield is to be measured."[6]

The present article reviews hydrodynamic yield estimation methods and their application to test ban monitoring. §II provides a brief overview of the development of an underground nuclear explosion and the variety of yield estimation methods currently in use. §III summarizes some relevant material properties of rock and describes the evolution of the shock wave produced by an underground nuclear explosion. In §IV we explain the technique advocated by the Reagan administration to measure the evolution of the shock wave. In §V we describe the algorithms that are currently used to derive yield estimates from these measurements. Technical issues related to the use of hydrodynamic methods to monitor test ban agreements are considered in §VI. In §VII we briefly compare hydrodynamic and seismic yield estimation methods, discuss the current status of U.S.-Soviet test ban negotiations, and mention several public policy issues raised by the U.S. drive to gain Soviet acceptance of hydrodynamic methods for routine monitoring of the TTBT. Our conclusions are summarized in §VIII.

II MONITORING UNDERGROUND NUCLEAR EXPLOSIONS

Currently, about 90% of U S nuclear tests are conducted in vertical shafts at depths of 250–650 m, the remainder are conducted in tunnels [8] In preparing for a test that will be conducted deep underground, the vertical hole that will contain the nuclear charge (the so-called emplacement hole) is first drilled, a process that typically takes 8–10 weeks The charge and diagnostic equipment are then placed in canisters, which can be as much as 15 m in length, and lowered into the emplacement hole Depending on the nature of the test, a variety of diagnostic pipes and cables may lead upward from the canisters to the surface (current U S nuclear weapon tests involve anywhere from ~50 to ~250 diagnostic pipes and cables) After the canisters are in place, the hole is stemmed with sand, gravel, and plugs [9]

In the following two subsections we first describe what happens when a nuclear charge is exploded deep underground and then explain briefly the methods that are used to estimate the yields of such explosions

A Phases of an Underground Explosion

For present purposes the time development of the explosion may be divided into the following three somewhat simplified phases [10,11]

Initial phase—The release of nuclear energy is accompanied by emission of nuclear radiation, fission fragments, and thermal electromagnetic radiation The temperature in the nuclear charge rises steeply, reaching 10^7 K within a microsecond or so At the very earliest times, the energy of the explosion is carried outward by the expanding weapon debris and radiation Soon, however, the vaporized nuclear charge and nearby rock form a bubble of hot gas in which the initial pressure is hundreds of Mbar The enormous pressure in the bubble causes it to expand rapidly, creating a cavity and driving a shock wave into the surrounding rock The final radius R_c of the cavity depends somewhat on the depth of the explosion and the composition of the surrounding rock, as well as the yield For a burst of yield W, a useful appproximate expression is[12]

$$R_c \approx 14\,(W/1\,\mathrm{kt})^{1/3}\ \mathrm{m} \qquad (1)$$

The cavity reaches its final radius in about $90\,(W/1\,\mathrm{kt})^{1/3}$ ms

Hydrodynamic phase—The shock wave initiated by the expansion of the hot gas propagates outward at a speed that is initially much greater than the speed of sound in the surrounding, undisturbed rock At this early time, the stress produced by the shock wave greatly exceeds the critical stress at which the rock becomes plastic, so that to a good approximation the rock can be treated as a fluid This phase is therefore referred to as the "hydrodynamic" phase (In defining the hydrodynamic phase, we emphasize the prefix *hydro* and simply require that the shocked rock behave like a fluid Other authors emphasize instead the root *dynamic* and require not only that the shocked rock behave like a fluid, but also that the speed of the shock wave greatly exceed the speed of sound in the rock, this second usage is common in the Soviet Union) As the shock wave continues to expand, it weakens Eventually, the strength of the rock can no longer be neglected This marks the end of the hydrodynamic phase

Final phase —Even after the compression wave is no longer hydrodynamic, the rarifaction wave that follows is still strong enough to fracture rock Intense fracturing typically occurs out to a radius $\sim 3R_c$ [12] Beyond this point, the degree of fracturing caused by the expanding shock wave drops dramatically until, at $\sim 5R_c$, fracturing essentially stops (Rarifaction waves caused by reflection of the shock wave from the surface or collapse of the roof of the cavity may cause fracturing beyond this radius) The shock wave then continues to expand nearly elastically, eventually evolving into the leading wave of a train of elastic (seismic) waves These waves, which typically carry $\lesssim 5\%$ of the energy of the explosion, propagate through and around the earth and can be observed at points thousands of kilometers from the site of the explosion

B Monitoring Methods

Three different types of methods are commonly used to estimate the yields of nuclear weapon tests These types make use of phenomena that occur during the three phases of the explosion identified above

Radiochemical methods make use of the nuclear reactions that occur during the first phase of the explosion By knowing the relative abundances of various nuclides in the original nuclear device and by determining the relative abundances of fission fragments and fusion products after the explosion, the yield of the explosion can be estimated However, at present there are several barriers to using radiochemical methods to monitor test ban treaties First, the monitoring party must be able to make a variety of measurements at the test site Second, to achieve high precision with this method some knowledge of the design of the nuclear charge may be required Third, in addition to the yield, radiochemical methods can provide other information about the design and performance of nuclear devices, which may be considered sensitive For these reasons, radiochemical methods are not usually considered for treaty monitoring [13]

Hydrodynamic methods make use of the fact that the strength of the shock wave produced by an explosion increases with the yield, other things being equal As a result, the peak particle velocity, pressure, and density are greater at a given radius for explosions of greater yield By comparing measurements of these quantities with a model of the evolution of the shock wave based on knowledge of the nature and structure of the geologic media in which the explosion occured, the yield of the explosion can be estimated In order to use hydrodynamic methods to monitor test ban treaties, the monitoring party must have access to the test site in order to determine the relevant properties of the geologic media there before the test and to measure the evolution of the shock wave during the test To assure high accuracy, constraints on the test geometry are also required Hydrodynamic methods are not part of current TTBT verification provisions

Seismic methods make use of the ground motions caused by the elastic waves that propagate through and around the earth during the third stage of an underground nuclear explosion Some seismic waves (such as body and surface waves) propagate to so-called teleseismic distances ($\geq$2,000 km) from the explosion Yield estimation methods based on these waves can be used with measurements of ground motion made at stations outside the country in which the test occurs Other seismic waves (such as L_g waves) typically propagate only to regional distances ($<$2,000 km) Yield estimation methods based on these latter waves may require data from in-country stations To assure high accuracy, knowledge of the geologic media at the test site and the way in which the earth near the site transmits seismic waves is required As noted earlier, the United States routinely uses seismic data taken at stations outside the Soviet Union to monitor the TTBT In-country monitoring stations and independent access to data on the seismic properties of the test site are not part of the current verification provisions of the TTBT For recent reviews of seismic methods, see refs 4 and 14–18

It has been claimed several times in recent Congressional hearings on TTBT and PNET verification[19–23] that hydrodynamic methods are "direct" whereas seismic methods are not From a scientific point of view there is no such distinction All three methods just described involve (1) production of a signal by the exploding charge, (2) propagation of the signal to locations more or less remote from the detonation point, and (3) detection of the signal by sensors at those locations Important questions are how the size of the signal varies with yield, how well the propagation of the signal is understood, and how accurately and precisely the sensors can measure the signal

It has also been asserted[22] that use of hydrodynamic methods in and of itself eliminates the possibility of systematic error or "bias" Obviously it does not All three methods are subject to both systematic and random errors Relevant questions are the expected sizes of the errors, and whether they are so large as to be of concern

III SHOCK WAVE EVOLUTION

In hydrodynamic methods of yield estimation, the size of the explosion is estimated by fitting a model of the evolution of the shock wave, which depends parametrically on the yield, to measurements of the motion Shock waves in rock behave differently from shock waves in air primarily because the atoms in rock are close together and interact strongly [24] Therefore, in discussing the application of hydrodynamic methods to underground explosions it will be helpful to have in mind some relevant material properties of rock as well how shock waves produced by underground explosions evolve in rock

A Rock Properties

The strength of a shock wave can be characterized by the peak pressure that it produces Weak shock waves and acoustic waves in rock propagate at a constant speed, the so-called elastic wave speed[25]

$$c_\ell = \left(\frac{K_0 + \frac{4}{3}G_0}{\rho_0}\right)^{1/2} \tag{2}$$

Here K_0 and G_0 are the bulk and shear moduli, respectively, of the rock in its standard state, and ρ_0 is the mass density For granite, $K_0 \approx 360\,\text{kbar}$ and $G_0 \approx 320\,\text{kbar}$,[26] giving $c_\ell \approx 5\,\text{km}\,\text{s}^{-1}$

Shock waves that are strong enough to produce stresses in excess of the critical shear stress p_{crit} cause the rock to lose its firmness and to become plastic (for granite, p_{crit} is about 40 kbar for high strain rates[26]) Such waves are called plastic waves The speed of a plastic wave increases with its strength The weakest such waves propagate at the low-pressure plastic wave speed[25]

$$c_0 = \left(\frac{K_0}{\rho_0}\right)^{1/2}, \tag{3}$$

which is determined by the compressibility of the rock in its standard state Since only the bulk modulus contributes to c_0, it is necessarily less than c_ℓ For solid granite, $c_0 \approx 4\,\text{km}\,\text{s}^{-1}$

In the hydrodynamic regime, conservation of mass, momentum, and energy across the shock front imply[27]

$$\epsilon(p, V) - \epsilon_0(p_0, V_0) = \frac{1}{2}(p_0 + p)(V_0 - V), \tag{4}$$

where ϵ_0 and ϵ, p_0 and p, and V_0 and V are, respectively, the internal energies, pressures, and specific volumes ahead of and just behind the shock front By analogy with the equation relating the initial and final pressures and volumes during adiabatic compression of a fluid, this relation, which is of the form

$$p = H(V, p_0, V_0), \tag{5}$$

is called the *shock adiabat* or *Hugoniot*

Conservation of momentum across the front of a hydrodynamic shock wave implies

$$p = p_0 + \rho_0 D u, \tag{6}$$

where D is the speed of the shock front, measured in the rest frame of the undisturbed rock, u is the particle speed just behind the shock front, and we have assumed that the rock in front of the shock front is at rest Thus, the Hugoniot may be expressed as a relation between D and u, that is

$$D = H(u) \tag{7}$$

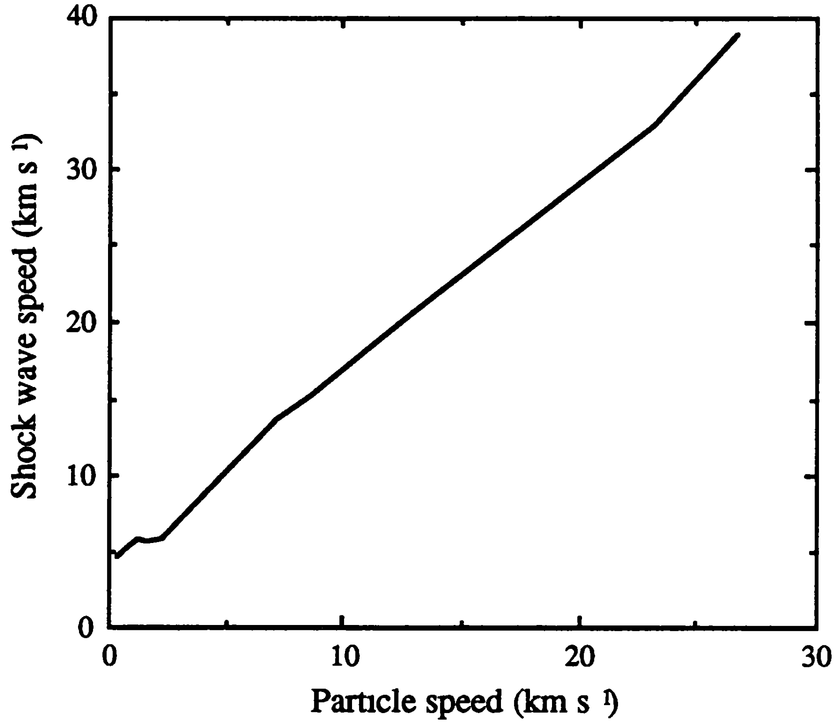

Fig 1 —Relation between shock wave speed D and particle speed u just behind the shock front for granite (ref 29) Note the approximate linearity of the Hugoniot at large u The step in the curve at $u \approx 2\,\mathrm{km\,s^{-1}}$ reflects a phase transition that occurs at about 400 kbar

Figure 1 shows a recent Hugoniot for granite expressed in this way In general, the Hugoniot depends on the chemical composition, porosity, gas-filled porosity, fracture pattern, degree of liquid saturation, and other properties of the rock

For some rocks, the Hugoniot may be adequately represented *in the hydro dynamic regime* by a single linear relation of the form[27 28]

$$D = A + Bu\,, \tag{8}$$

which implies the Hugoniot curve[27]

$$p = \frac{A^2(V_0 - V)}{(B-1)^2 V^2 \left[\frac{B}{B-1} - \frac{V_0}{V}\right]^2} \tag{9}$$

Table 1 lists values of A, B, and ρ_0 for granite and wet tuff that were derived by fitting a Hugoniot of the form (9) to recent high-pressure equations of state for these materials

For Hugoniots of the form (9), the ratio ρ/ρ_0 of the material density imme diately behind the shock front to the material density ahead of the shock front increases with the strength of the shock wave until it reaches a certain value $(\rho/\rho_0)_{\max} = (V_0/V)_{\max} = B/(B-1)$ Once the wave has become this strong,

TABLE 1
Rock Equations of State[a]

Rock	ρ_0 (g cm^{-3})	A (km s^{-1})	B	$R_{t\,1}$ (m)	$R_{t\,150}$ (m)
Granite	2 67	2 80	1 45	3 8	20
Wet tuff	1 95	1 45	1 62	7 0	37

[a]The parameters ρ_0, A, and B are from ref 30 and were obtained by fitting a Mie-Gruneisen equation of state to recent tabulated equations of state for granite (ref 29) and wet tuff (ref 31) at high pressures $R_{t\,1}$ and $R_{t\,150}$ are characteristic shock wave transition radii (see text) for 1 kt and 150 kt explosions

any further increase in its strength does not produce any increase in the ratio ρ/ρ_0 For this reason, the density ratio $(\rho/\rho_0)_{\max}$ is referred to as the limiting density ratio For the granite Hugoniot listed in Table 1, the limiting density ratio is ~3 Peak pressures ~10–100 Mbar are required to achieve density ratios near the limiting value

If a single linear relation adequately describes the Hugoniot at large u and if this relation could be extrapolated to small u, the constant A would correspond to the low-pressure plastic wave speed c_0 However, the large-u relation usually is not valid for small u, and hence A usually does not equal c_0 In granite, for example, A is about 3 km s^{-1} whereas c_0 is about 4 km s^{-1}

Even if the Hugoniot is not linear over the range of u that is of interest, a curve consisting of piece-wise linear segments of the form (8) may serve as a practical approximation to $H(u)$ for many purposes [28]

B Simplified Model

To understand the evolution of shock waves produced by underground nuclear tests, it is helpful to consider first the shock wave that would be produced by release of a large amount of energy in an infinitesimal spherical volume (a so-called point explosion) in homogeneous rock A qualitative understanding of the development of the shock wave produced by such an explosion can be gained from the following relatively simple model Suppose we make the *ansatz* that throughout the motion the particle speed u just behind the shock front is related to the yield W of the explosion by the expression[30 32]

$$u(t) = \left(\frac{3fW}{4\pi R^3 \rho_0}\right)^{1/2}, \tag{10}$$

where R is the radius of the shock front and f is a constant dimensionless factor that describes how the energy of the explosion is partitioned between kinetic energy of bulk motion and internal energy, and how the velocity, density, and internal energy of the shocked material vary with position The factor f is constant for a self-similar shock wave (see below) but is not expected to remain constant as the shock wave evolves [32] Nevertheless, shock wave radius and particle speed data from actual underground nuclear tests as well as computer simulations of such tests indicate that relation (10) with $f \approx 0.5$ is satisfied fairly well for granite and wet tuff until relatively late times [30,32]

Let us now assume, for the sake of illustration, that the Hugoniot of the medium can be adequately represented by a *single* linear relation of the form (8) *over the whole range of* u *that is of interest* Then $c_0 = A$ Therefore, in the following discussion we refer to A as the low-pressure plastic wave speed

Given the *ansatz* (10), the Hugoniot can be rewritten as[32]

$$D \equiv \frac{dR}{dt} = A + B\,u = A\left[\left(\frac{R_t}{R}\right)^{3/2} + 1\right], \tag{11}$$

where

$$R_t \equiv \left(\frac{3fWB^2}{4\pi\rho_0 A^2}\right)^{1/3} \tag{12}$$

is the characteristic transition radius that separates the region where $D \propto R^{-3/2}$ from the region where $D \approx A$ Typical values of R_t for 1 kt and 150 kt explosions in granite and wet tuff are listed in Table 1 for the values of A and B given there In dry alluvium, R_t can sometimes exceed 60 m for a 150 kt explosion

Equation (11) can be integrated to obtain a simple, closed expression for $R(t)$, from which one can calculate $D(t)$, $u(t)$, $p(t)$, and $\rho(t)$ [32,33] This model shows in a qualitative way how the evolution of the shock wave depends on the yield of the explosion and the equation of state of the rock As an example, the peak pressure, peak density, and radius of the shock front at various times are listed in Table 2, for 1 kt and 150 kt explosions in granite The pressure p_0 of the overburden is ~200 bar for a depth of 1 km and hence can be neglected for all depths and times of interest

The motion of the shock front given by equation (11) can be divided into three different intervals

Strong Shock Interval —Initially, the speed of the shock front is much greater than the speed of sound in the undisturbed rock, the pressure behind the shock front is predominantly thermal pressure, and the ratio of the density immediately behind the shock front to the density ahead of the front is close to its limiting value This is the strong shock interval [24]

For a spherically-symmetric point explosion in a homogeneous medium, the motion of the shock wave in the strong shock interval is self-similar [34–36] In such a motion, the distributions with radius of the pressure, density, and particle velocity evolve with time in such a way that only their scales and the radius of the shock front change, while the shapes of the distributions remain unaltered The evolution of such a shock wave is only weakly dependent on the properties of the medium Thus, simple models can be used to estimate the yield if there is an interval of self-similar motion and if data from this interval are available

TABLE 2
Shock Wave Evolution in Granite[a]

Pressure (kbar)	Density (ρ_{max})	1 kt Explosion Time (μs)	1 kt Explosion Radius (m)	150 kt Explosion Time (μs)	150 kt Explosion Radius (m)
70,000	0 9	4	0 5	20	3
10,000	0 8	10	0 9	80	5
4,000	0 7	40	1 4	200	8
1,500	0 6	90	2	500	11
500	0 5	200	3	1,200	17
150	0 4	600	5	3,000	30

[a]For the model of a spherically-symmetric, point explosion described in the text The Hugoniot (8) was used, with the values of A and B given in Table 1 The phase transition that occurs at ~400 kbar (cf Fig 1) has been neglected The unit of density, ρ_{max}, is the limiting density of granite (see text), which is 9 4 g cm^{-3} for this equation of state

For example, in the evolution given by equation (11), the motion of the shock front radius R during the strong shock interval ($R \ll R_t$) satisfies

$$R(t) \approx W^{1/3}\left(\frac{75fB^2}{16\pi\rho_0}\right)^{1/5}\left(\frac{t}{W^{1/3}}\right)^{2/5} \propto W^{1/3}\left(\frac{t}{W^{1/3}}\right)^{2/5} \qquad (13)$$

Thus, the exponent of time is independent of the properties of the medium Moreover, the evolution is only affected by ρ_0 and B

Unfortunately, in actual underground nuclear tests self-similar motion does not have time to develop, given current testing practices and the yields of interest, as explained below

Transition Interval—As the shock wave expands, it weakens and slows, and the peak pressure and density drop When the shock front reaches a certain radius R_1, the peak density ratio is 0 8 times the limiting value and we say that the shock wave has entered the transition interval (The motion of the shock wave changes only gradually and so the point at which it is said to enter the transition interval is purely conventional Throughout the present article we use the convention that the transition interval begins when the peak density ratio falls to 80% of its limiting value) For an explosion in granite, this occurs when the peak pressure has fallen to ~10,000 kbar (cf Table 2) For a 1 kt explosion in granite R_1 is ~1 m, whereas for a 150 kt explosion R_1 is ~5 m

Over most of the transition interval, the thermal pressure just behind the shock front is not much greater than the cold pressure of the compressed rock, although the speed D of the shock front is still much larger than the low pressure plastic wave speed A In this interval, the motion of the shock wave is more sensitive to the properties of the medium than it is in the strong shock interval, depending on A as well as B and ρ_0 even in the simple model of equation (11) Consequently, more knowledge of the ambient rock is required in order to make accurate yield estimates using data taken in this interval

Plastic Wave Interval—As the shock wave expands and weakens further, the thermal pressure behind the shock front becomes a small fraction of the total pressure and the shock speed D approaches the low-pressure plastic wave speed A At a certain radius R_2 ($\sim R_t$), the shock speed is 1 2 times the low-pressure plastic wave speed and we say that the shock wave has entered the plastic wave interval (Again, the motion of the shock wave changes only gradually and so the point at which it is said to enter the plastic wave interval is purely conventional Throughout the present article we use the convention that the plastic wave interval begins when the shock speed falls to 1 2 times the low-pressure plastic wave speed) For an explosion in granite, this occurs when the peak pressure has fallen to $\sim$150 kbar, corresponding to a peak density ratio $\sim$0 4 times the maximum (cf Table 2) For a 1 kt explosion in granite R_2 is $\sim$5 m, whereas for a 150 kt explosion R_2 is $\sim$30 m

For the model given by equation (11), the plastic wave interval corresponds to $R \geq 3\,R_t$ In this regime

$$R \approx \text{const} \; + A\,t\,, \tag{14}$$

where the constant is determined by the motion in the strong shock and transition intervals

The evolution of the shock wave in the plastic wave interval is sensitive to the equation of state and the constitutive relations describing the rock For actual rocks, the evolution in this interval is complex, as described below Hence relatively detailed modeling is required in order to obtain accurate yield estimates from data taken in this interval

C Other Effects

The evolution of the shock wave produced by an actual underground nuclear test is more complex than the evolution just described, for several reasons First, the actual shock wave is not produced by a spherically-symmetric point explosion The emplacement holes currently used in U S tests have radii R_e as large as 1 5 m[10] and emplacement holes with larger radii are planned for the future Moreover, the nuclear charge and diagnostic canisters may be many meters in length As a result, the source of the shock wave is vapor and radiation filling a volume with a dimension of meters Moreover, the explosion is usually not spherically symmetric, causing the expanding shock wave to be aspherical initially The energy flows produced by explosions in tunnels may be even more complex

The motion of the shock wave cannot become self-similar until the shock wave has enveloped a mass of material much greater than the mass of the nuclear charge and casing, and energy transport by radiation is negligible The radius R_0 at which this occurs is necessarily much greater than the radius R_e of the emplacement hole and depends on the design of the nuclear charge and surrounding diagnostic equipment Unless there is a range of radii satisfying $R_0 \ll R \ll R_1$, the shock wave will not have time to become self-similar before entering the transition interval The data in Table 2 show that no such range exists in granite for current emplacement practices, even for explosions as large as 150 kt Thus, the simplicity of estimating yields from an interval of self-similar motion cannot be realized, given current testing practices and the yields of interest

Other complications arise from the complexity of the motion in the transition and plastic wave intervals in actual rocks As the shock wave expands and weakens, one or more phase transitions may occur We have already noted that granite undergoes a phase transition when the peak pressure falls to ~400 kbar At a somewhat lower peak pressure (~200 kbar in granite), the shock speed becomes less than the elastic wave speed c_ℓ At this point the shock wave splits into an elastic wave followed by a plastic wave [25 37] The initial pressure jump in the elastic wave is p_{crit}, which is ≈ 40 kbar for granite [26] Since $c_0 < c_\ell$, the weakening plastic wave cannot overtake the elastic wave and the two-wave structure is stable As a result, the plastic wave propagates through rock that has already been compressed and accelerated to a velocity ~1–10 m s^{-1} by the elastic wave (Since c_0 is several km s^{-1}, for most purposes the acceleration of the medium by the elastic wave may be neglected and the plastic wave may be taken to propagate with a speed c_0 relative to the undisturbed ambient medium, as was done in eq [6]) Finally, when the peak pressure in the plastic wave is no longer much greater than the critical shear stress p_{crit}, the shear strength of the rock can no longer be neglected In granite, for example, p_{crit} is ≈ 40 kbar, and the hydrodynamic approximation therefore begins to fail when the peak pressure falls below ~150 kbar

In addition to these complications that occur in a homogeneous medium, theoretical models and experimental data show that the evolution of shock waves in actual geologic media can be affected by voids, layering, and other geologic structures that may vary from one test site to another

IV MEASURING SHOCK WAVE EVOLUTION

A variety of sensors have been used at different times in the United States to measure the evolution of shock waves produced by underground nuclear explosions These include strain gauges, particle velocity gauges, accelerometers, and pressure sensors [26] In the United States, recent efforts to develop instrumentation for test ban monitoring have focused on radius vs time (RVT) techniques, which measure the radius of the shock front as a function of time

A Using Sensing Cables

One RVT measuring technique that has been used in the United States since the early 1960s is based on the fact that the pressure peak near the front

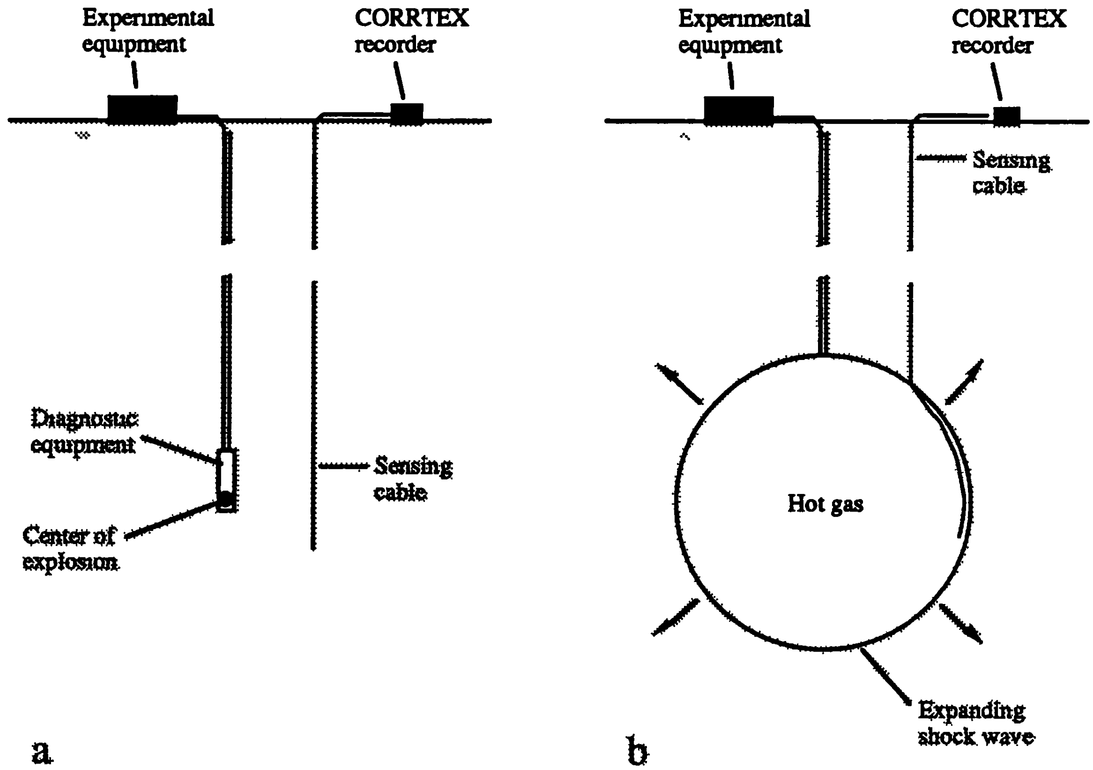

Fig 2—Schematic drawings illustrating (a) placement of the shock front sensing cable in a satellite hole and (b) progressive shortening of the cable by the expanding shock wave produced by a nuclear explosion

of the shock wave can crush an electrical cable In this approach, a coaxial sensing cable is lowered into the emplacement hole before it is backfilled or into one or more other holes (so-called satellite holes) that have been drilled nearby specifically for this purpose The satellite-hole geometry is shown in Figure 2a If the sensing cable is strong enough that it is not crushed by the elastic precursor or other unwanted signals but weak enough that it *is* crushed by the pressure peak in the hydrodynamic shock wave, the cable will be electrically shorted or its impedance substantially changed near the point where the hydrodynamic shock front intersects it As the shock wave expands with time, the length of cable from the measuring equipment to the shallowest point at which it has been crushed is measured by electrical equipment attached to the cable and located above ground, as shown in Figure 2b If the time at which the explosion began and the path of the cable relative to the center of the explosion are known and if the explosion is spherically symmetric, the radius of the shock front as a function of the time since the beginning of the explosion can be calculated from a record of the changing length of the cable

As a concrete example, suppose the sensing cable is placed in a vertical satellite hole displaced laterally a distance d from the emplacement point Then if the length L_0 of the sensing cable from the surface to the point where the cable

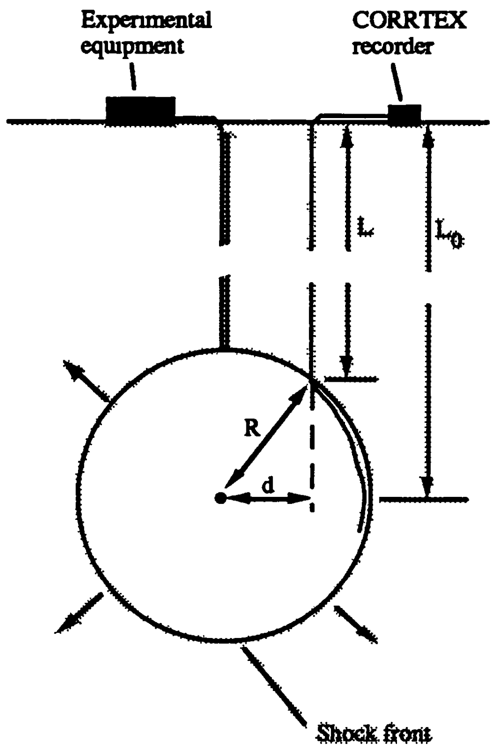

Fig 3 —Schematic drawing illustrating how the radius R of the shock wave at time t is related to the lateral displacement d of the sensing cable from the center of the explosion, the length L_0 of the sensing cable from the surface to the point where the cable is first crushed, and the length L of the cable

is first crushed is known, measurements of $L(t)$ can be converted into estimates of the radius R of the shock front as a function of time t using the Pythagorean relation

$$R(t) = \left[d^2 + \left(L_0 - L(t)\right)^2\right]^{1/2} \tag{15}$$

The geometrical meaning of the quantities appearing in equation (15) is shown in Figure 3 In practice the sensing cable usually is not perfectly vertical and more complicated calculations must be performed to convert $L(t)$ to $R(t)$

As discussed in §V, an error of 1 m in the measured distance of the crushing point from the center of the explosion will cause an error of about 50 kt in the yield estimate, for yields near 150 kt Thus, accurate surveys of the emplacement and satellite holes and an accurate knowledge of the path of the sensing cable within the satellite hole are required in order to make an accurate yield estimate If the cable wanders within the hole and this is not taken into account, the length of the cable crushed by the shock wave will be greater than the linear distance traveled by the shock front, causing the the speed of the shock wave and therefore the yield of the explosion to be overestimated In the United States, hole surveys are currently made with special laser or gyroscopic equipment In some yield estimation algorithms, the lateral displacement of the satellite hole from the center of the explosion can be treated as one of the unknowns in estimating the yield

If the explosion is not spherically symmetric, due to the effect of the canister, the design of the test geometry, or inhomogeneities in the ambient medium, interpretation of the sensing cable data becomes more complicated and could be ambiguous or misleading under the conditions likely to be encountered in treaty monitoring Potential problems of this kind could be addressed by cooperative agreements, as discussed in §VI

Sensing cables with a variety of crushing strengths, ranging from as little as 30 bar to as much as 30 kbar, have been used[38] However, even the latter cable can be crushed by the elastic precursor in granite Thus, once the shock wave has split, the length of cable to the crushing point may reflect the position of the elastic shock front rather than that of the hydrodynamic shock front which follows[39,40] If so, the sensing cable cannot provide data about the motion of the hydrodynamic shock wave[26] Worse, if the motion is misinterpreted as that of the hydrodynamic wave, the estimated yield of the explosion will be erroneously high As a result, interpretation of data in this interval requires great care

The Reagan administration has strongly advocated adoption of the satellite-hole geometry for monitoring the TTBT using hydrodynamic methods In order to collect ground shock data in the hydrodynamic region from explosions with yields near 150 kt, the satellite hole must be slightly deeper than the emplacement hole, which is typically ~650 m deep for such explosions, and the deepest portion of the satellite hole must be no further than ~30 m from the center of the explosion In order to use the particular hydrodynamic yield estimation algorithm advocated by the administration (insensitive-interval scaling, see §V), the sensing cable must cover the algorithmic interval, which is a more demanding criterion and requires that the bottom of the satellite hole be no more than ~10 m from the center of the explosion, for yields near 150 kt

In order to apply hydrodynamic methods to monitoring a 10 kt low-threshold test ban, the bottom of the satellite hole would have to be well within ~10 m of the emplacement point, which is typically ~250 m deep for charges with yields near 10 kt In order to apply insensitive interval scaling, the satellite hole would have to be within ~4 m of the center of the explosion

Use of the satellite hole geometry requires sophisticated drilling capabilities in order to make sure that the satellite hole maintains the proper separation from the emplacement hole[41] In addition, conversion of cable length to shock wave radius is more complicated if the cable is in a satellite hole than if it is in the emplacement hole On the other hand, the satellite-hole geometry reduces the intrusiveness of the method and eliminates the disturbing effects of jetting within diagnostic pipes and other phenomena that can crush or short the sensing cable ahead of the hydrodynamic ground shock In the discussion that follows, we shall assume that the sensing cable is in a satellite hole, unless otherwise stated

B. Measuring the Position of the Crushing Point

During the 1960s and 1970s, the position of the crushing point was measured in the United States using a technique called SLIFER (which is an acronym for Shorted Location Indicator by Frequency of Electrical Resonance).[26,42] In this approach, the cable is used as the inductive element of a resonant oscillator. As the cable is progressively crushed, the frequency of the oscillator changes. By knowing the propagation velocity of electromagnetic signals in the cable and the frequencies of the oscillator that correspond to $L = 0$ and $L = L_0$, one can convert measurements of the change in oscillator frequency during the explosion to estimates of the change in the length of the cable.

In the late 1970s, an improved approach to measuring the length of sensing cables, called CORRTEX, was developed (CORRTEX is an acronym for Continuous Reflectometry for Radius versus Time Experiments).[39,40,43,44] In this approach, a sequence of electrical pulses is sent down the cable. At the crushing point, these pulses are reflected back up the cable to recording equipment. By knowing the speed at which the pulses propagate down and up the cable, the round trip travel time of each pulse can be converted into an estimate of the length of the cable at the time the pulse was reflected.

Current (CORRTEX III) equipment can store up to 4,000 data points. Pulse separations from $10\,\mu s$ to $90\,\mu s$ can be selected, giving a record of the changing cable length that is 40 ms to 360 ms in length. The pulses typically propagate down and up the sensing cable at about $2 \times 10^5\,\mathrm{km\,s^{-1}}$. A typical uncertainty in the round-trip travel time during a nuclear explosion is 500 ps, corresponding to an uncertainty of about 10 cm in the measured length of the cable or about 5 cm in the distance to the crushing point. The cable length measurements can be checked by creating fiducial loops in the cable at predetermined points, which will create downward jumps in the cable length as the crushing point passes over them. Using these jumps, the cable length data can be adjusted for systematic errors. The time at which the explosion begins is estimated by recording the time at which the electromagnetic pulse (EMP) from the explosion arrives at the CORRTEX recorder. The CORRTEX technique is less affected by disturbing signals produced by the explosion than were earlier techniques and is the technique that has been advocated by the Reagan administration for monitoring the TTBT.

RVT techniques are also used to estimate the yields of underground nuclear tests in the Soviet Union. The Soviets use two different sensing techniques, called Mis (or Miz) and Contactor.[45,46] The current Soviet approach reportedly uses a sensing system with switches that are sequentially destroyed by the shock front.[47]

V. YIELD ESTIMATION ALGORITHMS

Once measurements of the length of the sensing cable have been converted to estimates of the radius of the shock front as a function of time, the yield of the explosion is estimated by applying some algorithm, by which we mean a particular procedure for comparing the RVT data with a particular model of the motion of the shock front Because hydrodynamic methods of yield estimation are evolving as research aimed at increasing our understanding of underground explosions and improving yield estimation methods continues, the description of yield estimation algorithms in the present section is necessarily a status report

Although the algorithms used by different individuals or groups can (and usually do) differ in detail, most of the algorithms currently in use are of four basic types insensitive interval scaling, similar explosion scaling, semi-analytical modeling, and numerical modeling These are the algorithms that are discussed here In order to simplify matters, we will assume at first that the explosion is spherically symmetric and that the ambient geologic medium is homogeneous Some of the complications that can arise if the explosion is aspherical or the medium is inhomogeneous are described at the end of this section

A Insensitive Interval Scaling

The simplest algorithm currently in use is insensitive interval scaling This is the algorithm that the Reagan administration has proposed to use in analyzing CORRTEX data as a new routine method of monitoring Soviet compliance with the TTBT

Insensitive interval scaling assumes that the radius of the shock wave produced by an explosion of given yield does not depend on the rock in which the explosion occurs during a certain interval in time and radius called the "insensitive interval" This assumption is based on empirical evidence that the radius of the shock front *is* relatively insensitive to the medium during a certain interval in time and radius toward the end of the transition interval, for the particular geologic media for which the United States has good experimental data or theoretical models These media include the dry alluvium, partially saturated tuff, saturated tuff, granite, basalt, and rhyolite at the nuclear test sites the U S has used These media are mostly silicates and almost all are located at the Nevada Test Site The radius of the shock front appears to depend only weakly on the medium despite the fact that phase transitions and shock wave splitting occur in some of these media during the insensitive interval The radius of the shock front in one medium approaches and then deviates from that in another gradually, so that the insensitive interval is not sharply defined

Although the reason for the existence of an insensitive interval for this collection of media is currently not well understood from a fundamental physical point of view, it appears to stem from a particular correlation among the relevant properties of these media It *is* known that the relevant properties of other geologic media are *not* correlated in this way, so that the radius of the shock front in these media during the "insensitive interval" is very different from the radius of the shock front in the silicates cited above Thus, the existence of an insensitive interval must be established by test experience or modeling, and is only assured for certain geologic media

In using insensitive interval scaling, the shock wave sensing cable must be placed close enough to the center of the explosion that it samples the insensitive interval Yield estimates are then derived by fitting a simple empirical formula, called the Los Alamos Formula, to the RVT data in this interval [48] If the radius R of the shock front is expressed in meters, this formula is

$$R(t) = a\,W^{1/3}(t/W^{1/3})^b\,, \tag{16}$$

where W is the yield of the explosion in kilotons, t is the elapsed time since the beginning of the explosion in milliseconds, and a and b are constants According to the assumption on which the algorithm is based, the values of a and b do not depend on the medium (because of this, eq [16] has sometimes been referred to as the Los Alamos "universal formula") The values of the constants a and b are typically determined by fitting equation (16) to a selected interval of RVT data from a collection of nuclear explosions Different individuals and groups have found different values of a and b at various times Even the values used by a single group have changed with time by amounts that have caused estimated yields to change by tens of percent The values of a and b used here are 6 29 and 0 475 [48]

The Los Alamos Formula is a simple power law that approximates the actual RVT curve during the insensitive interval This is illustrated in Figure 4, which compares the Formula with a model of the evolution of the shock wave produced in granite by a spherically-symmetric point explosion with a yield of 62 kt In practice, the Los Alamos Formula is usually first fit to a broad interval of radius vs time data that is thought to include the insensitive interval The result is a sequence of yield estimates Due to the departure of the Formula from the actual RVT curve at both early and late times, the sequence of yield estimates typically forms a U-shaped curve This is illustrated in Figure 5, which shows the sequence of yield estimates obtained by applying the Formula to the relatively high-quality SLIFER data from the *Piledriver* explosion in granite (yield estimation using CORRTEX data cannot be illustrated here because at present all CORRTEX data remain classified) If the assumptions on which the algorithm is based are satisfied, the yield estimates near the bottom of the curve should approximate the actual yield of the explosion

In the usual form of the algorithm, only the RVT data that fall within a certain predetermined interval chosen on the basis of previous experience (the so-called *algorithmic interval*) are actually used to make the final yield estimate Because both the location and the extent of the algorithmic interval depend on the yield W of the explosion (both are proportional to $W^{1/3}$), an iterative procedure must be followed in estimating the yield of an explosion whose yield is initially unknown Table 3 lists the algorithmic interval for several yields

The sensitivity of an individual yield estimate to an error in the inferred location of the shock front depends on the position of the data point within the algorithmic interval and the yield of the explosion For example, the sensitivity

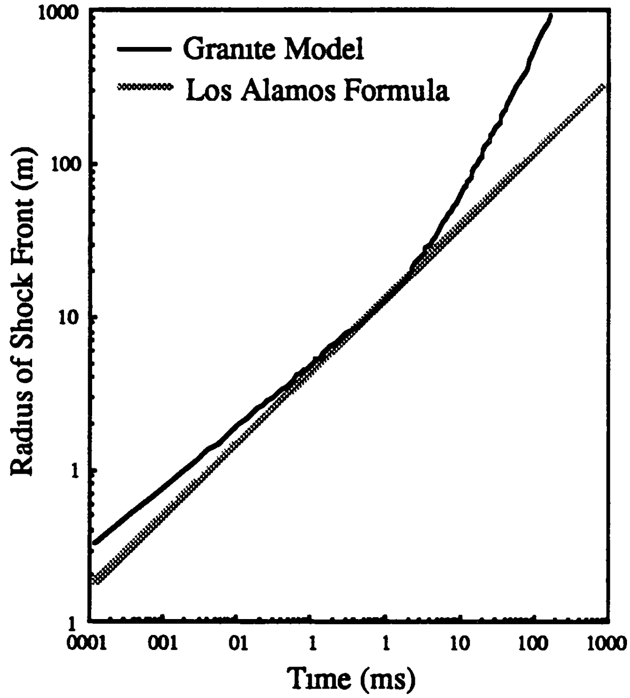

Fig 4 —Comparison of the Los Alamos Formula with a model of the evolution of a shock wave in granite produced by a spherically-symmetric point explosion with a yield of 62 kt, showing the agreement during the transition interval and the departure of the Formula from the model at earlier and later times The effect of the phase transition at 400 kbar has been included in the model

varies from 13 kt m^{-1} at the beginning of the interval to 7 4 kt m^{-1} at the end of the interval, for a 10 kt explosion, and from 77 kt m^{-1} to 18 kt m^{-1}, for a 150 kt explosion

The algorithmic interval for a yield of 62 kt is indicated in Figure 5 by the two vertical bars at the bottom of the figure In this example the assumptions on which the algorithm is based appear to be satisfied and the average of the yield estimates that lie within the algorithmic interval is very close to the announced yield of 62 kt

The insensitive interval algorithm does not work as well if the assumptions on which it is based are not satisfied This is illustrated in Figure 6, which shows the yield estimates obtained by fitting the Los Alamos Formula to good quality SLIFER data from a typical low yield explosion in alluvium In this example the RVT data have been scaled in the manner described below in the subsection on similar explosion scaling, so that the derived yield should be 1 kt (the actual yield is classified) The yield estimates given by the Los Alamos Formula are systematically low, ranging from 30% to 82% of the actual yield, and do not form a U-shaped curve The average of the yield estimates that lie within the algorithmic interval is about 60% of the actual yield The overall appearance of the yield vs time curve shows that the assumptions of the algorithm are not satisfied

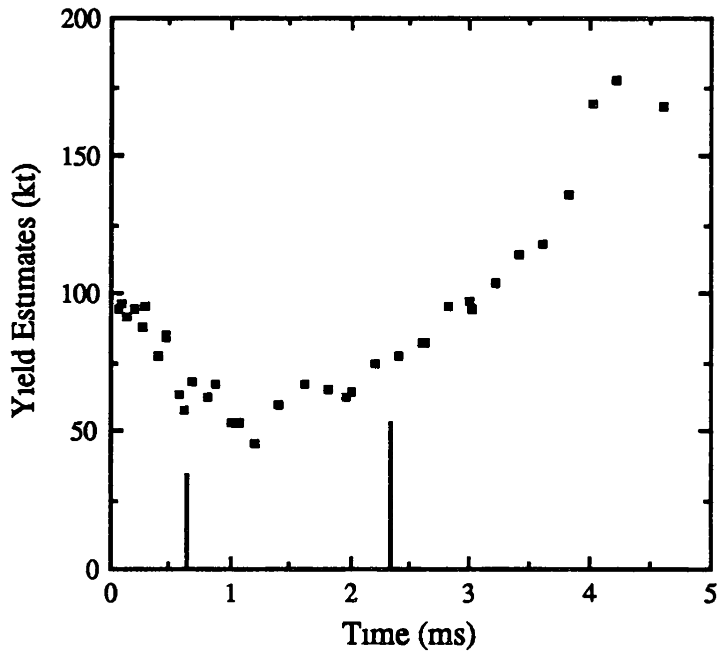

Fig 5 —Yield estimates derived by applying the Los Alamos Formula to SLIFER data from the *Piledriver* explosion in granite, which had a nominal yield of 62 kt The so-called algorithmic time interval is the interval between the two vertical bars The average of the yield estimates within the algorithmic interval is in good agreement with the nominal yield Note the departure of the yield estimates from 50–70 kt at earlier and later times, which is caused by the deviation of the Formula from the actual radius vs time behavior of the shock wave outside the algorithmic interval (cf Fig 4)

TABLE 3
Algorithmic Intervals[a]

Yield (kt)	Time Interval (ms)	Radius Interval (m)
1	0 10 — 0 5	2 1 — 4 5
10	0 21 — 1 1	4 5 — 9 7
50	0 37 — 1 8	7 7 — 17
100	0 46 — 2 3	9 8 — 21
150	0 53 — 2 7	11 — 24

[a]The intervals used by various individuals and groups vary Throughout this article the algorithmic interval is taken to be from $0\,1\,W^{1/3}$ ms to $0\,5\,W^{1/3}$ ms after the beginning of the explosion, where W is the yield of the explosion in kilotons

A common misconception has been that the algorithmic interval lies within the strong shock region and that the relative insensitivity of yield estimates to the properties of the medium stems from this [49] This misconception apparently

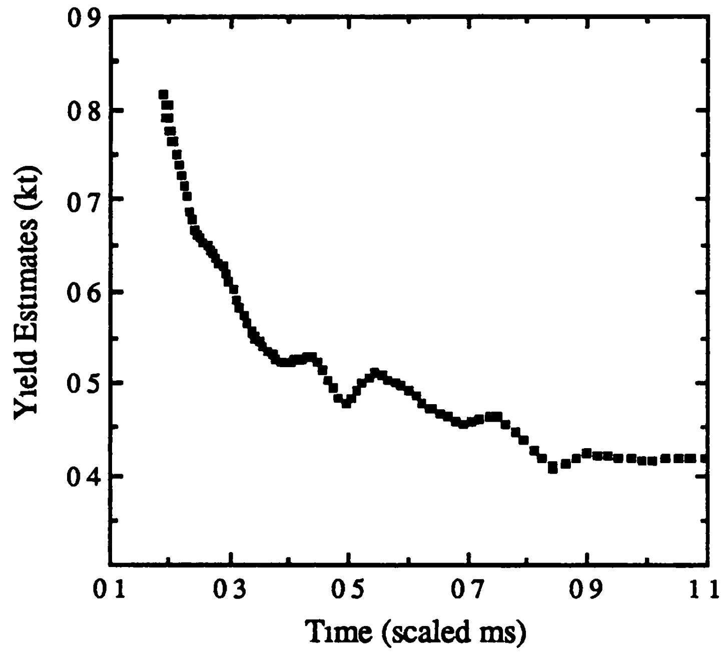

Fig 6 —Yield estimates derived by applying the Los Alamos Formula to SLIFER data from a low-yield explosion in alluvium (note that the vertical axis is offset from zero) The data have been scaled so that the estimated yield should be 1 kt Difficulties in applying the insensitive interval algorithm to low-yield explosions in alluvium are not uncommon

has arisen at least in part because the interval formerly used to estimate the yields of nuclear explosions in the atmosphere using hydrodynamic methods *is* within the strong shock region As explained earlier, the relative insensitivity of the radius of the shock front to the medium in the algorithmic interval would be explained if the algorithmic interval were within the strong shock region and if the motion were self-similar The formula for the radius of the shock front would then be a power-law function of time like the Los Alamos Formula, except that the exponent of t would be 0 4 However, in reality the shock wave motion is not self-similar during the algorithmic interval, for current test geometries and the yields permitted by the TTBT In fact, the shock wave is not even strong during this interval, since the shock speed is only a few times the low-pressure plastic wave speed while the peak pressure is much less than the pressure required to achieve the limiting density ratio Indeed, the exponent of time usually used in the Los Alamos Formula, 0 475, is significantly greater than the exponent 0 4 characteristic of a strong, self-similar shock wave The power-law Los Alamos Formula is not a theoretical result like the power-law formula for the radius of a strong, self similar shock wave Rather, it is an approximate, empirical relation, which was obtained by fitting a simple power law expression to a selected interval of RVT data from a collection of nuclear explosions in several different media

B. Similar Explosion Scaling

As long as the final state of the shocked rock is independent of the rate of compression and explosions take place in the same medium, the RVT curve depends only on the yield of the explosion.[11] If $R = f(t)$ is the RVT curve for an explosion with a yield of 1 kt, then the curve for a yield of W kt is

$$R = W^{1/3} f(t/W^{1/3}) \tag{17}$$

The model given by equation (11), for example, scales with yield in this way. Thus, if the shock wave motion is measured for a given explosion of unknown yield that takes place in the same medium as a previous explosion, and if both RVT data and the yield are available for the previous explosion, the yield of the given explosion can be estimated by comparing the two sets of RVT data. This algorithm is called similar explosion scaling.

Similar explosion scaling can utilize data outside the insensitive interval and works well if the ambient media at the two explosion sites are sufficiently similar. However, in practice it has sometimes proved difficult to ascertain whether the relevant properties of the media are similar enough to give the desired accuracy. As a result, application of this algorithm has sometimes led to unexpected errors in the estimated yield.

If hydrodynamic yield estimation is adopted for TTBT verification, similar explosion scaling would presumably be used where possible to check the results of insensitive interval scaling.

C. Semi-Analytical Modeling

Another approach that is useful for studying the evolution of shock waves in geologic media and for estimating yields is semi-analytical modeling.[30,32,50–52] In this approach both the properties of the ambient medium and the motion of the shock front are treated in a simplified way that nevertheless includes the most important effects. The result is a relatively simple, semi-analytical expression for the radius of the shock front as a function of time. If the required properties of the ambient medium are known and inserted in this expression, the yield of an explosion can be estimated by fitting the expression to RVT data.

Semi-analytical algorithms can make use of data over a more extensive interval than the interval used in the insensitive interval algorithm. For example, application of equation (10) to particle velocity data taken 8 m from an explosion with a nominal yield of 10.4 kt gave an estimated yield of 10.3 kt.[53] Even data taken at a radius of 13.5 m, well outside the algorithmic interval, gave a yield of 7.9 kt. Semi-analytical models can also be used to estimate the uncertainty in the yield caused by uncertainties in the properties of the ambient medium.

D. Numerical Modeling

If a treatment that includes the details of the equation of state and other properties of the ambient medium is required, if it is desired to utilize RVT data in the region where the shock wave has split, or if the explosion is not spherically symmetric, modeling of the motion of the shock front using numerical codes may be necessary [54] In principle, such simulations can provide RVT curves that extend over much of the shock wave evolution, making it possible to base yield estimates not only on data from the transition interval but also on data from later phases of the shock wave evolution In these later phases, the shock wave is no longer hydrodynamic, so yield estimation methods that make use of such data are not hydrodynamic methods Yield estimates made using data from later phases are fairly sensitive to the equation of state and constitutive relations that characterize the ambient rock Since these are accurately known only for a few rocks, accurate yield estimates are possible using late-time data only for explosions in a few geologic media

E Complications

In order to use hydrodynamic methods, RVT data must be taken within meters of the center of the explosion (cf Tables 2 and 3) At such small distances, the arrangement of the nuclear charge and the canister or canisters containing it and the diagnostic equipment can introduce asymmetries in the expansion of the shock wave that will affect the yield estimate

- A long canister can produce a shock wave that is initially cylindrical and hence crushes the sensing cable in such a way that only part of the total yield is sensed over most of the interval sampled, as shown schematically in Figure 7a The physical size of canisters and diagnostic lines-of-sight tend to pose more of a problem for tests of nuclear directed-energy weapons than for tests of traditional nuclear weapons [55]
- Explosions of nuclear charges in tunnels may be accompanied by complicated (and unanticipated) energy flows and complex shock wave patterns If significant energy reaches the sensing cable ahead of the ground shock and shorts or destroys it before the ground shock arrives, the CORRTEX data will describe that flow of energy and not the motion of the ground shock Moreover, the ground shock itself may become sufficiently distorted that the RVT data are confusing or misleading

In complicated geometries, disturbing effects like these are difficult to analyze and correct for using data from a single sensing cable, since it senses only the depth of the shallowest point where a pressure wave first crushes it, at a single azimuth and lateral displacement from the explosion As a result, unambiguous interpretation of the data may become difficult or impossible The disturbing effect of a canister and emplacement hole of given size is less for higher-yield than for lower-yield explosions, since the hydrodynamic region extends further from the canister and emplacement hole for a higher yield explosion In addition, higher-yield charges are not usually exploded in tunnels

In addition to the potential disturbing effects of the nuclear test design, any errors in characterizing the surrounding geologic media will introduce errors

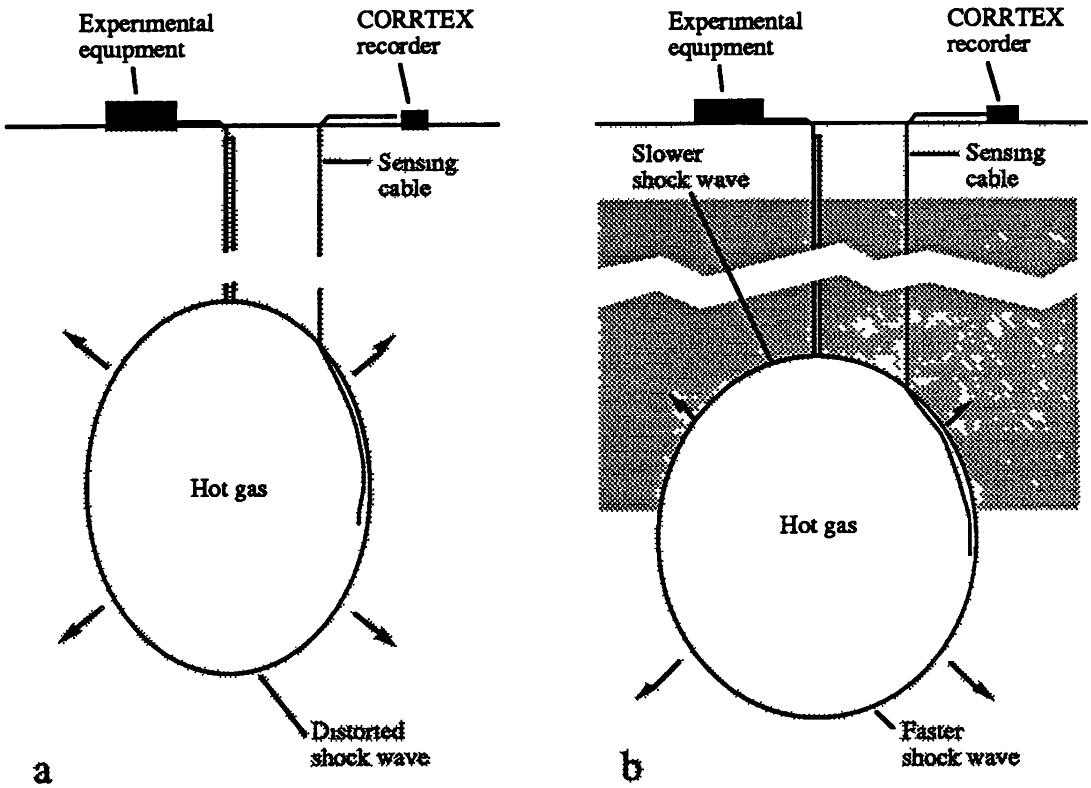

Fig 7—Schematic drawings illustrating disturbance of hydrodynamic yield estimates by (a) a nuclear test design that produces a cylindrical shock wave during the algorithmic interval and (b) slowing and weakening of the upward traveling portion of the shock wave when it encounters a much denser geologic stratum

in yield estimates derived using hydrodynamic methods Incorrect assumptions about the average properties of the rock surrounding the emplacement hole may bias the yield estimate, decreasing its accuracy, while small-scale variations in the rock will cause scatter in the RVT record, decreasing the precision of the yield estimate In addition, geologic structures like that shown in Figure 7b can affect the yield estimate At the Nevada Test Site, for example, the alluvial deposits are weakly consolidated erosion products of the surounding mountains with physical properties that vary widely Layers of gravel, the residues of ancient stream beds, are often encountered in drilled holes While most RVT records follow the expected behavior, an occasional event will produce an RVT record whose irregular behavior defies simple explanation Such behavior has been attributed to spatial variations in the ambient medium [26]

F Summary of Yield Estimation

Shock waves produced by an underground nuclear explosion propagate differently in different media and different geologic structures As a result, knowledge of the rock and geologic structure within $\sim 10\,(W/1\,\mathrm{kt})^{1/3}$ meters of the center of the explosion is required in order to make accurate yield estimates using hydrodynamic methods The evolution of the shock wave can also be affected by the test geometry Knowledge of the test geometry and/or limitations on the aspects that could disturb the RVT data are therefore required in order to make accurate yield estimates Several different yield estimation algorithms have been developed Like the algorithms used to estimate yields from seismic data, these algorithms involve some complexity and require sophistication to understand and apply correctly

Hydrodynamic yield estimation methods have not yet been studied as thoroughly or as widely as seismic methods Although approximately 100 tests have been carried out with the CORRTEX sensing cable in the emplacement hole, only a few have been carried out with the cable in a satellite hole[5,6] (in addition, SLIFER data from sensing cables in satellite holes are available for several tens of earlier explosions) Moreover, no systematic and comprehensive review of the scientific evidence concerning the accuracy and precision of U S hydrodynamic yield estimation methods has yet been carried out The U S Department of State has asserted that the methods are accurate to within 15% (at the 95% confidence level) of radiochemical yield estimates for tests with yields greater than 50 kt in the geologic media in which tests have been conducted at the Nevada Test Site [5,6] According to these same reports, the algorithm is expected to have an uncertainty of a factor of 1 3 at the 95% confidence level if used in a treaty-monitoring context at the Soviet test sites near Shagan River to monitor explosions with yields greater than 50 kt [5,6] However, some scientists familiar with the methods believe that the uncertainty could be somewhat larger [4]

Some key terms that have been introduced in this discussion are listed and explained in Table 4

VI APPLICATION TO MONITORING TEST BAN TREATIES

A Assuring Accuracy

Ambient medium—As explained in §III and §V, the physical properties and geologic structure of the media around the emplacement point affect the evolution of the shock wave produced by an underground nuclear explosion Thus, it is important in test ban monitoring to gather information about the types of rock present at the test site and their properties, including their chemical composition, bulk density, porosity, gas-filled porosity, and degree of liquid saturation, as well as the speed of sound in the rock and any specific features of the local geologic structure that could affect the yield estimate Such data are easily gathered by the party conducting the explosion Availability of the required data to the monitoring party could be assured by appropriate negotiated cooperative measures

Some information about the geologic medium at the test site can be obtained by examining the contents of the hole drilled for the CORRTEX sensing cable Verification could be improved by cooperative arrangements that would also allow observation of the construction of the emplacement hole, removal and examination of rock core or rock fragments from the wall of the emplacement

TABLE 4
Glossary of Hydrodynamic Yield Estimation Terms

Term	Explanation
Algorithmic interval	The interval, in time usually 0 1–0 5 scaled ms after the beginning of the explosion, from which data is selected in applying insensitve interval scaling
CORRTEX technique	A technique for measuring the position of the shock front expanding away from an underground explosion by determining the round-trip travel time of electrical pulses sent down a sensing cable placed in a hole in the ground near the explosion
Insensitive interval scaling	A yield estimation algorithm in which the Los Alamos Formula is fit to measurements of the position of the expanding shock front as a function of time during the algorithmic interval
Los Alamos Formula	The empirical formula used in insensitive interval scaling to make yield estimates by fitting to shock front radius vs time data
Plastic wave interval	The interval in radius and time in which the speed of the weakening hydrodynamic shock wave is less than 1 2 times the low-pressure plastic wave speed
Similar explosion scaling	A yield estimation algorithm in which shock front radius data are compared with similar data from a previous explosion in the same medium
SLIFER technique	A technique for measuring the position of the shock front expanding away from an underground explosion by determining the resonant frequency of an electrical circuit that includes a sensing cable placed in a hole in the ground near the explosion
Strong shock interval	The interval in radius and time in which the density just behind the shock front is close to its limiting value
Transition interval	The interval in radius and time in which the density just behind the shock front is less than 80% of its limiting value but the speed of the hydrodynamic shock wave is still greater than 1 2 times the low-pressure plastic wave speed

hole, examination of any logs or drill core from existing exploratory holes, removal and examination of rock core or rock fragments from the walls of existing exploratory holes, and if necessary, construction of new exploratory holes

There is precedent for such cooperative arrangements in the Protocol to the Peaceful Nuclear Explosions Treaty (PNET), which explicitly established that hydrodynamic methods could be used to monitor the yield of any explosion with a planned aggregate yield greater than 150 kt and which specified verification measures like those described here [3]

Test geometry —As explained in §V, the arrangement of the nuclear charge and the canister or canisters containing it and the diagnostic equipment can introduce asymmetries in the expansion of the shock wave which disturb the yield estimate In using hydrodynamic methods to estimate the yields of one's own tests, the design and placement of the nuclear charge and related equipment are known and can be taken into account This information may not be available when monitoring the nuclear tests of another party Cooperative agreements to ensure satisfactory placement of the sensing cable and to exclude nuclear test geometries that would significantly disturb the yield estimate are therefore required [55–58]

Such agreements could, for example, limit the length of the canister containing the nuclear charge and the cross-sectional dimensions of the emplacement hole, and mandate stemming of the emplacement hole with certain types of materials Such agreements could also provide for observation of the emplacement of the nuclear charge and the backfilling of the emplacment hole, confirmation of the depth of emplacement, and limitations on the placement of cables or other equipment that might interfere with the CORRTEX measurement For test geometries that include ancillary shafts, drifts, or other cavities, additional measures, such as placement of several sensing cables around the nuclear charge emplacement point, may be required to assure an accurate yield estimate For tunnel shots, sensing cables could be placed in the tunnel walls or in a special hole drilled toward the tunnel from above Again, there is precedent for such cooperative measures in the PNET [3]

The restrictions on the size of canisters and diagnostic lines-of-sight that would be required even with the sensing cable placed in a satellite hole would cause some interference with the U S nuclear testing program at NTS However, these restrictions have been examined in detail by the U S nuclear weapon design laboratories and the Department of Energy, and have been found to be manageable for the weapon tests that are planned for the next several years [55 58] For the more distant future, the disadvantages of the required restrictions on testing must be weighed against the potential contributions to treaty monitoring that could be made by hydrodynamic methods

In summary, the accuracy that could be achieved using hydrodynamic methods to monitor test ban treaties depends on the amount of information about the ambient medium that can be gathered by the monitoring party and the nature and extent of cooperative arrangements to limit disturbing effects Some tests and simulations to identify troublesome configurations have been carried out, but such configurations have not been thoroughly explored Given the possibility that hydrodynamic yield estimation methods may have to be used to monitor treaty compliance in an adversarial atmosphere, the possibility of deliberate efforts to introduce error or ambiguity, and the tendency for worst-case interpretations to prevail, additional research to improve understanding of the accuracy and precision of these methods and to reduce further the chances of confusion, ambiguity, spoofing, or data denial is very important

B Minimizing Intrusion

Hydrodynamic yield estimation methods are more intrusive than seismic methods for several reasons

- Drilling of the emplacement and satellite holes and emplacement of the nuclear charge and diagnostic equipment typically take 8–10 weeks In order to monitor these operations, personnel from the monitoring country would have to be present at the test site of the testing country for ten weeks or so before as well as during each test, and would therefore have an opportunity to observe test preparations The presence of these personnel would pose some operational security problems [55 58 59]
- The exterior of the canister or canisters containing the nuclear charge and diagnostic equipment must be examined to verify that the restrictions necessary for the yield estimate to be valid are satisfied For tests of nuclear directed-energy weapons, this examination could reveal sensitive design information unless special procedures are followed [58]
- Sensing cables and electrical equipment will tend to pick up the electromagnetic pulse (EMP) generated by the explosion A detailed analysis of the EMP would reveal sensitive information about the design and performance of the nuclear device being tested [60]

Intrusiveness can be minimized by careful attention to monitoring procedures and equipment For example, the electrical recording equipment can be designed to avoid measuring sensitive information about the nuclear devices being tested CORRTEX equipment has been designed in this way, and the United States could insist that any Soviet equipment used at the Nevada Test Site be similarly designed Placement of the recording equipment in Faraday cages and other measures could be mandated in order to minimize the chance that sensitive information concerning the test could be picked up by the monitoring party

The security problems posed by opportunities to observe test preparations are more severe for nuclear directed energy weapon tests, since they tend to have larger and more complex diagnostic systems and canister arrangements which, if fully revealed to the Soviets, might disclose sensitive information [55 58] The United States has determined that the Soviet personnel and activities that would be required at the Nevada Test Site to monitor U S tests would be acceptable both from a security standpoint and from the standpoint of their effect on the U S test program Detailed operational plans have been developed to accommodate such visits without adverse impact on operations [55]

C Specific Applications

Threshold Test Ban Treaty—As noted earlier, hydrodynamic yield estimation methods have been proposed by the Reagan administration as a new routine measure for monitoring the sizes of nuclear tests, in order to verify compliance with the 150 kt limit of the TTBT These methods can be used only if appropriate changes in the TTBT are negotiated In addition, adequate cooperative arrangements would need to be made in order to assure the accuracy of the resulting yield estimates To reduce the cost and intrusiveness of verification, use of hydrodynamic methods could be restricted to tests with planned yields greater than some threshold that is an appreciable fraction of 150 kt As an alternative to routine use, hydrodynamic methods could be used to help calibrate seismic yield estimation methods by measuring the yields of one or more nuclear calibration explosions at test sites,[57 61] provided that the medium in which the explosion takes place is within U S test experience and the necessary procedures are followed to assure the accuracy of the hyrdrodynamic yield estimate

Peaceful Nuclear Explosions Treaty—As it stands, the PNET does not provide for use of hydrodynamic yield estimation except for salvos in which the planned aggregate yield is greater than 150 kt [3] Thus, if the TTBT is modified to allow hydrodynamic yield estimation for all weapon tests with planned yields above a certain value, the purpose of the modification could in principle be circumvented by carrying out weapon tests as "peaceful" nuclear explosions of "planned yield" less than or equal to 150 kt, unless the PNET is also modified to close this loophole

Low Threshold Test Ban Treaty—Tamped underground nuclear explosions as small as a few kilotons produce shock waves that evolve in the same way as those produced by explosions of larger yield However, because the algorithmic interval for such explosions is much closer to the nuclear charge and diagnostic canisters than the algorithmic interval for tests with much larger yields, the disturbing effect of the canisters is generally more serious for such explosions Moreover, low yield tests can be and often are set off at shallow depths in softer material, such as alluvium, or in tunnels As a result, the propagation of the shock wave can differ markedly from the models on which standard hydrodynamic yield estimation methods are based, causing confusion or error in the yield estimate There can also be significant variations in the motion of the shock wave from explosion to explosion under these conditions

In addition, serious practical, operational, and engineering problems arise in trying to use hydrodynamic methods to estimate the yields of explosions with yields of a few kilotons For one thing, the sensing cable must be placed very close to the nuclear charge Drilling a satellite hole within 2–5 meters of the emplacement hole to the depth at which the nuclear charge is placed (typically $\sim$250 m even for low-yield explosions in vertical shafts), which would be required in order to use hydrodynamic methods to monitor explosions with yields in the 1–10 kt range, is at or beyond the capabilities of current drilling techniques.[41] The need for such close placement would also necessitate more stringent restrictions on the maximum sizes and orientations of the nuclear charge and the diagnostic canisters. Such restrictions might be deemed an unacceptable interference with test programs. The alternative of using small canisters with numerous diagnostic lines-of-sight to the detonation point could disturb the shock wave and introduce errors in the yield measurements. Finally, because the shock wave radii to be measured are much smaller at low yields, survey errors become much more important.

It is possible that some of these difficulties could be circumvented by developing models and algorithms that would allow routine use of RVT data at radii beyond the hydrodynamic interval, as discussed in §V. Others could be alleviated by conducting tests with simple geometries to define and calibrate test sites so that insensitive interval scaling could be accurately applied. However, these and other potential solutions to the problems that would be encountered in monitoring low-yield tests using hydrodynamic methods have not yet been carefully and thoroughly studied. Thus, at the present time hydrodynamic yield estimation methods could not be used with confidence to monitor compliance with threshold test bans in which the threshold is less than several tens of kilotons.

Comprehensive Test Ban Treaty.—Hydrodynamic methods can only be used with shock wave data taken within meters of the center of the explosion. Moreover, their use requires advance notification of tests, extensive preparations in advance at the test site, and the presence of monitoring personnel during the test. Hydrodynamic methods were not intended and clearly are not able to detect or identify unannounced, remote, or clandestine nuclear tests. As a result, they cannot contribute to monitoring a comprehensive test ban.

VII. DISCUSSION

Hydrodynamic methods could be a potentially valuable component of a cooperative program to improve monitoring of the TTBT and PNET. Hydrodynamic yield estimates are more affected than seismic estimates by local features that disturb the evolution of the shock wave, such as canisters or local geologic structures. For explosions larger than ~10 kt, seismic yield estimates are less affected by local features but are affected by how the shock wave evolves into seismic waves. Thus, yield estimates based on hydrodynamic methods would complement yield estimates based on seismic methods.

Apparently, a systematic and comprehensive review of the scientific evidence concerning the accuracy and precision of hydrodynamic yield estimation methods has not yet been conducted in the United States. Nor has the United States any experience as yet in applying these methods at Soviet test sites. As noted in §V, the U.S. Department of State has asserted that yield estimates based on CORRTEX data analyzed using the insensitive interval algorithm are expected to have an uncertainty of a factor of 1.3 at the 95% confidence level, for explosions larger than 50 kt at the Soviet test sites near Shagan River. If achieved, such an uncertainty would be slightly smaller than the uncertainty of a factor of 1.5–1.6 that according to recent studies[4] could probably be achieved using the best current seismic methods, if the test site is not calibrated and measurements are made only outside the Soviet Union.

Hydrodynamic methods could also be used to help calibrate seismic methods. According to the results of a recent study, application of the best current seismic methods to measurements made outside the Soviet Union is expected give yield estimates that have an uncertainty of a factor of 1.3 at the 95% confidence level, the same precision reportedly expected for hydrodynamic methods, once the Soviet test site is properly defined and calibrated.[4]

In its first years, the Reagan administration declined to resume the U.S.-Soviet negotiations on a CTBT that had been adjourned in 1980. However, in the summer of 1986 both parties agreed to begin new, low level talks on nuclear testing.[60,62] The Soviet Union reportedly pressed for resumption of negotiations on a CTBT and emphasized seismic verification methods whereas the United States sought an agreement allowing use of hydrodynamic methods as an additional verification measure for the TTBT and PNET.[62] Then, in April 1987, the Soviet Union suggested experiments at the U.S. and Soviet test sites as a way to advance the negotiations and to compare verification methods.[63–65] As a result of further discussions[66,67] the United States and the Soviet Union announced on September 17, 1987, that they had agreed to renew full-scale negotiations on nuclear testing limitations.[68,69] Formal negotiations began in November 1987 in Geneva.

The parties agreed as a first step to negotiate verification measures for the TTBT and PNET. In these negotiations, the sides agreed to make no changes in the treaties themselves but to negotiate a new protocol to each treaty, which would specify verification provisions.[69] Once these two treaties have been ratified, the parties have agreed to begin negotiations on ways to implement a step-by-step program to further limit nuclear tests.[69]

At the Washington Summit in December 1987, President Reagan and General Secretary Gorbachev agreed to conduct a joint verification experiment (JVE) at each other's nuclear test sites.[69] In this experiment, one nuclear charge with a yield near the 150 kt limit will be exploded at the Nevada Test Site, another will be exploded at the Soviet test site near Semipalatinsk. The purpose of the experiment is to compare the verification techniques advocated by the two sides in the Geneva negotiations.

In preparation for the JVE, 20 nuclear testing experts from each side visited the other side's nuclear testing site in January 1988 to familiarize themselves with how each side conducts tests and to provide a basis for the design and conduct of the JVE.[69,70] The second round of the current U.S.-Soviet test ban negotiations began in February 1988, and remained in continuous session until June 30, 1988.[47] In March, drilling of the necessary holes began.[69]

An agreement on the conduct of the JVE was signed on May 31, 1988, as part of the Moscow Summit [71] The agreement, which with its annex totals 105 single-spaced pages, specifies that each party will have the opportunity to estimate the yield of each of the JVE explosions using both hydrodynamic methods (with sensing cables in both the emplacement hole and a satellite hole) and teleseismic methods (using recordings made at five designated seismic stations of each side) [69,71] Each party will also have the opportunity to make yield estimates using its national seismic network To assist the teleseismic measurements, on June 28, 1988, each side shared with the other data on five of its high-yield underground tests conducted after January 1, 1978, but before January 1, 1988, recorded at its five designated seismic stations located at teleseismic distances from its nuclear test site Associated geological and geophysical information and estimates of the yields of the five events were also exchanged [69]

Originally, the Soviet Union had suggested that each side furnish the nuclear charge to be exploded at the other side's test site, so that the monitoring side would be able to compare the yields estimated using both seismic and hydrodynamic methods with a yield estimate based on knowledge of the design of the nuclear charge [64–66] However, the JVE is actually being carried out with a U S nuclear charge at the U S test site and a Soviet nuclear charge at the Soviet test site [71] As a result, the monitoring party will not have available an estimate of the yield of the explosion that is independent of both seismic and hydrodynamic methods In order to solve this calibration problem, the sides have agreed to accept the hydrodynamic yield estimate derived from the data taken with the sensing cable in the emplacement hole as the yield of the explosion for the purposes of the experiment

The JVE test at the Nevada Test Site, code-named *Kearsarge*, was completed as scheduled on August 17, 1988 The Soviet Union reportedly gathered hydrodynamic data on the explosion using sensing cables in the emplacement and satellite holes, regional seismic data from the seismic stations that have been installed nearby as part of the NRDC Soviet Academy cooperative verification project,[72,73] and teleseismic data from its own national seismic network [46,72] The Soviets will also be able to use data from a variety of seismographic stations in the United States that routinely publish such data The United States reportedly gathered hydrodynamic data on *Kearsarge* and will also be able to use data from its national seismic network as well as published data Data on this explosion were exchanged in Geneva on August 30, 1988, at the start of the third session of the current round of negotiations

According to press reports following *Kearsarge*,[74] the nuclear charge was expected to have a yield of about 140 kt However, one U S hydrodynamic measurement reportedly gave a yield estimate slightly more than 150 kt while the other gave a yield estimate slightly more than 160 kt In contrast, data from the U S seismic network reportedly confirmed expectations that the yield of the explosion would be about 140 kt If the yield of the explosion *was* 140 kt and if the uncertainty of the hydrodynamic yield estimation algorithm used by the United States is a factor of 1.15 at the 95% confidence level at the Nevada Test Site, as asserted by the U.S. Department of State,[5,6] then the probability that a single yield estimate would be larger than 160 kt is only about one in 40, while the joint probability that one yield estimate would be more than 150 kt *and* the other more than 160 kt is about one in 300. As a result of this outcome, the U.S. Department of Energy has reportedly decided to make a radiochemical yield estimate in order to better assess the yield of *Kearsarge*.

As this is being written, preparations for the explosion at the Semipalatinsk Test Site, which is currently scheduled for September 14, 1988, are in progress. Because of its strong advocacy of hydrodynamic methods, the United States has chosen not to gather regional seismic data on this explosion but will gather hydrodynamic data using CORRTEX sensing cables in the emplacment and satellite holes.[75] The United States will also have available teleseismic data from its national seismic network. Regional seismic data on the test at Semipalatinsk may be recorded by seismic stations that have been installed nearby as part of the NRDC-Soviet Academy cooperative verification project. If they are, these data would presumably also be available to the U.S. government. Thus, the JVE will provide the United States with a variety of information with which to improve its seismic estimates of the yields of past as well as future nuclear tests at Semipalatinsk.

The U.S. drive to negotiate hydrodynamic monitoring of the TTBT and PNET raises several important issues concerning the interaction of technology and public policy. From a purely scientific point of view, gathering of additional data on U.S. and Soviet test yields and achievement of better precision in estimating yields are advances. However, the principal purpose of TTBT and PNET monitoring is presumably to increase the security of the United States and the Soviet Union, rather than to advance scientific studies.

From a security perspective, the purpose of requiring a precision of a factor of 1.3 at the 95% confidence level for monitoring the 150 kt limit of the TTBT appears unclear. Such a precision means that there is only one chance in four that a single explosion with a yield of 164 kt would appear to be in compliance with the TTBT. The administration has not explained why such a high precision is needed, nor has it explained why current seismic methods, which according to recent studies could achieve a similar precision using measurements made only outside the Soviet Union, are still considered inadequate. Was the requirement for such high precision established after a careful review of the purposes of the TTBT and PNET and the costs and benefits of requiring various levels of precision? Or was it adopted simply because it was the highest precision that was thought to be achievable with hydrodynamic methods at the time the policy advocating such methods was adopted?

In assessing whether this degree of precision is necesssary, one must bear in mind the fact that if tests producing yields of 150 kt are performed, then approximately half of unbiased yield estimates will be above 150 kt (just as approximately half will be below 150 kt), no matter how precise the estimates

Moreover, both parties to the TTBT recognized at the time it was signed that the yield of a nuclear test cannot always be predicted accurately in advance, so that even if the planned yield is 150 kt, some variation from this value may occur [3]

Whatever the justification for requiring a precision of a factor of 1 3 at the 95% confidence level in monitoring the 150 kt limits of the TTBT and PNET, the considerations that enter an assessment of the precision that would be optimal in monitoring possible future lower-threshold test ban agreements are different, and depend on the threshold chosen For some choices of threshold, an uncertainty much greater than a factor of 1 3 might be adequate However, the emphasis on achieving a precision of a factor of 1 3 at 150 kt could establish this precision in the public mind as a requirement that must also be met in monitoring any future limitations on nuclear testing Such a development could impede progress toward achieving such limitations

Similarly, the emphasis on hydrodynamic monitoring of the TTBT and PNET might also establish this verification technology as a requred part of any low-threshold test ban agreement Given the difficulties that would have to be overcome to apply these methods with confidence to monitoring low yield tests, such a requirement could become an additional impediment to achieving a low threshold test ban

The current test ban negotiations and the Joint Verification Experiment have led to increased openness about the U S and Soviet nuclear testing programs and increased cooperation between the national security establishments of the United States and the Soviet Union According to participants, both sides have approached the JVE as a useful joint venture, in which it has been possible to make enquiries, receive answers, and resolve concerns [69] In addition to these benefits, the JVE will also provide useful data on the seismic properties of the U S and Soviet test sites that may help both parties to resolve past concerns over compliance and to advance toward ratification of the TTBT and PNET

VIII CONCLUSIONS

Hydrodynamic methods were developed primarily as a tool to estimate the sizes of explosions in the U S and Soviet nuclear test programs and are inherently more intrusive than seismic methods From a scientific point of view hydrodynamic methods are no more "direct" than seismic methods Nor are hydrodynamic methods necessarily free of systematic error The use of hydro dynamic methods at Soviet test sites would give estimates of the yields of Soviet tests larger than 50 kt that are slightly more precise than could be achieved using the best currently available seismic methods, if (1) the cooperative arrangements needed to assure the accuracy of hydrodynamic methods are successfully negotiated and followed, (2) U S hydrodynamic methods applied at Soviet test sites prove to be as precise as expected by the U S Department of State, (3) the Soviet test sites are not calibrated for seismic measurements, and (4) seismic data are collected only outside the Soviet Union On the other hand, the precision of the best available remote seismic methods is expected to be comparable to the precision that could be achieved using hydrodynamic methods if the Soviet test sites are appropriately defined and calibrated Significant engineering, operational, and analysis problems need to be solved before hydrodynamic methods could be used to monitor with confidence a low-threshold test ban The methods are not relevant to a comprehensive test ban

Possible advantages of an agreement allowing use of hydrodynamic yield estimation methods for monitoring the TTBT and PNET include the increased openness about nuclear testing programs to which this would lead and the ongoing cooperation between the national security establishments of the United States and the Soviet Union that would occur, as well as the additional deterrence against cheating and the additional assurance of compliance that use of these methods would provide Such an agreement would also establish the principle of on-site inspection at nuclear test sites, would make available more accurate data on the yield distribution of large nuclear tests, and might indirectly limit nuclear testing in the future

Possible disadvantages of seeking an agreement allowing routine use of hydrodynamic methods for test ban monitoring include the potential difficulty of successfully negotiating such use, the restrictions that such use would impose on nuclear test designs, which could adversely affect nuclear testing programs in the future, and the operational security problems at test sites that would be created by the continuous presence there of dozens of monitoring personnel from the other country Adoption of hydrodynamic yield estimation methods for routine test ban monitoring might also create an impediment to further progress in limiting nuclear testing Many of the possible advantages of hydrodynamic methods could be gained and many of the possible disadavantages of routine use avoided by an agreement allowing limited use of such methods, such as for calibration of seismic methods

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