Appendix

Appendix

Hydrodynamic Methods of Yield Estimation

Hydrodynamic methods could be used to complement seismic methods of yield estimation

Introduction

The yield of an underground nuclear explosion may be estimated using so-called hydrodynamic methods. These methods make use of the fact that larger explosions create shock waves that expand faster than the shock waves created by smaller explosions. Three steps are involved in making a yield estimate. First, the properties of the geologic media at the test site that may affect the expansion of the shock wave are determined. Second, the expansion of the shockwave caused by the explosion of interest is measured during the hydrodynamic phase, when the ambient medium behaves like a fluid. Finally, the yield of the explosion is estimated by fitting a model of the motion of the shock front to measurements of the motion.

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. Before considering these algorithms and their application to test ban verification, it will be helpful to have in mind how the shock wave produced by an underground nuclear explosion evolves during the hydrodynamic phase and how this evolution is affected by the properties of the ambient medium.

Shock Wave Evolution

The hydrodynamic evolution of the shock wave produced by a large, spherically symmetric explosion underground may be usefully divided into three different intervals. These are listed in table A-1, along with the times after detonation at which they begin for 1 and 150 kiloton (kt) explosions in granite. The characteristics of these intervals follow.

Self-Similar Strong-Shock Interval

At the very earliest times, the energy of the explosion is carried outward by the expanding weapon debris and by radiation. Soon, however,

Table A-1.—Characteristic Times in the Evolution of a Shock Wave Caused by an Underground Nuclear Explosion[a]

Event in the evolution of the shock wave	Time (µs) for a 1 kt explosion	Time (µs) for a 150 kt explosion
Beginning of the Self-Similar Strong Shock Interval[b]	–	-10
Beginning of the Transition Interval[c]	-20	-80
Beginning of the Plastic Wave Interval[d]	-2,000	-10,000

[a]For an idealized spherically-symmetric explosion in granite

[b]Here the shock wave is assumed to become self-similar when it reaches a radius of 1 m (see text) No time is given for a 1 kt explosion because the shock wave caused by such an explosion typically weakens before it has time to become self -similar

[c]Defined as the time when the density just behind the shock front falls to 80 percent of its maximum limiting value

[d]Defined as the time when the speed of the shock wave falls to 120 perCent of the plastic wave speed In reality, granite undergoes a phase transition slightly before the shock speed reaches this value, a complication that has been neglected in this Illustration

SOURCE: F K. Lamb, "Hydrodynamic Methods of Yield Estimation" Report for the US Congress Office of Technology Assessment, Feb 15, 1988

a shock wave forms and begins to move outward. At this time the speed of the shock wave is much greater than the speed of sound in the undisturbed ambient medium, the pressure behind the shock wave is predominantly thermal pressure, and the ratio of the density behind the shock wave to the density in front is close to its limiting value. This is the *strong shock interval*.[1]

If the shock wave envelops a mass of material much greater **than** the mass of the nuclear charge and casing while it is still strong, and if energy transport by radiation can be neglected, the shock wave will become *self-similar*, expanding in a particularly simple way that depends only weakly on the properties of the medium.[2] The time at which

[1]See Ya. B. Zel'dovich and Yu. P. Riazer, *Physics of Shock Waves and High-Temperature Phenomena* (New York, NY: Academic Press, 1967 [English Translation]), ch. XI. As the strength of a shock wave is increased, the ratio of the material density immediately behind it to the material density immediately in front of it generally increases, until a value of the ratio is reached beyond which an increase in the strength of the shock wave produces little or no further increase in the density of the post-shock material. This density ratio is referred to as the limiting density ratio. In typical rocks, pressures behind the shock front of about 10-100 Mbar are needed to produce a density ratio close to the limiting value.

[2]Ibid., ch. I and XII.

the motion becomes self-similar depends in part on the design of the nuclear charge and diagnostic equipment and on the size of the emplacement hole. As the shockwave expands, it weakens and slows, the density behind the shock front drops, and the wave enters a transition interval in which the motion is no longer self-similar. No time is given in table A-1 for the beginning of the self-similar strong-shock interval for a 1 kt explosion because the shock wave produced by such an explosion typically weakens before it has time to become self-similar.

Transition Interval

As the shock wave weakens and slows, it enters a broad transition interval in which the thermal pressure is not much greater than the cold pressure of the medium. The motion of the shockwave changes only gradually and so the time at which the transition interval is said to begin is purely conventional. In this report the shockwave is considered to have entered the transition interval when the density just behind the shock front has fallen to 80 percent of its maximum limiting value. The speed of the shock front is only a few times greater than the relevant sound speed-the speed of the so-called plastic wave—in the medium over much of the transition interval and hence the motion of the shock wave in this interval is more sensitive to the properties of the medium than it is in the strong shock interval.[3]

Plastic-Wave Interval

In the absence of phase transitions and other complications,[4] the shock wave weakens and slows still further, entering an interval in which the pressure behind the shock front is predominantly the cold pressure of the compressed ambient medium and the shock speed is close to the plastic wave speed in the medium. Again, the motion of the shock wave changes only gradually and so the time at which the plastic-wave interval is said to begin is purely conventional. In this report the shock wave is considered to have entered the plastic-wave interval when its speed is less than 120 percent of the plastic wave speed in the medium. In practice, phase transitions and other effects complicate the evolution of the shock wave in this interval for rocks of interest.

[3]Ibid., pp. 741-744,
[4]Ibid., ch. XII.

Theoretical models and experimental data show that the evolution of the shock wave in all three intervals depends on such properties of the rock as its chemical composition, bulk density, plastic wave speed, and degree of liquid saturation. These properties vary considerably from one rock to another. As a result, the shock wave generally develops differently in different rocks. For example, the characteristic radius at which the shock wave produced by a 150 kt explosion changes from a strong, self-similar wave to a plastic wave[5] varies from about 30 meters in wet tuff to over 60 meters in dry alluvium.

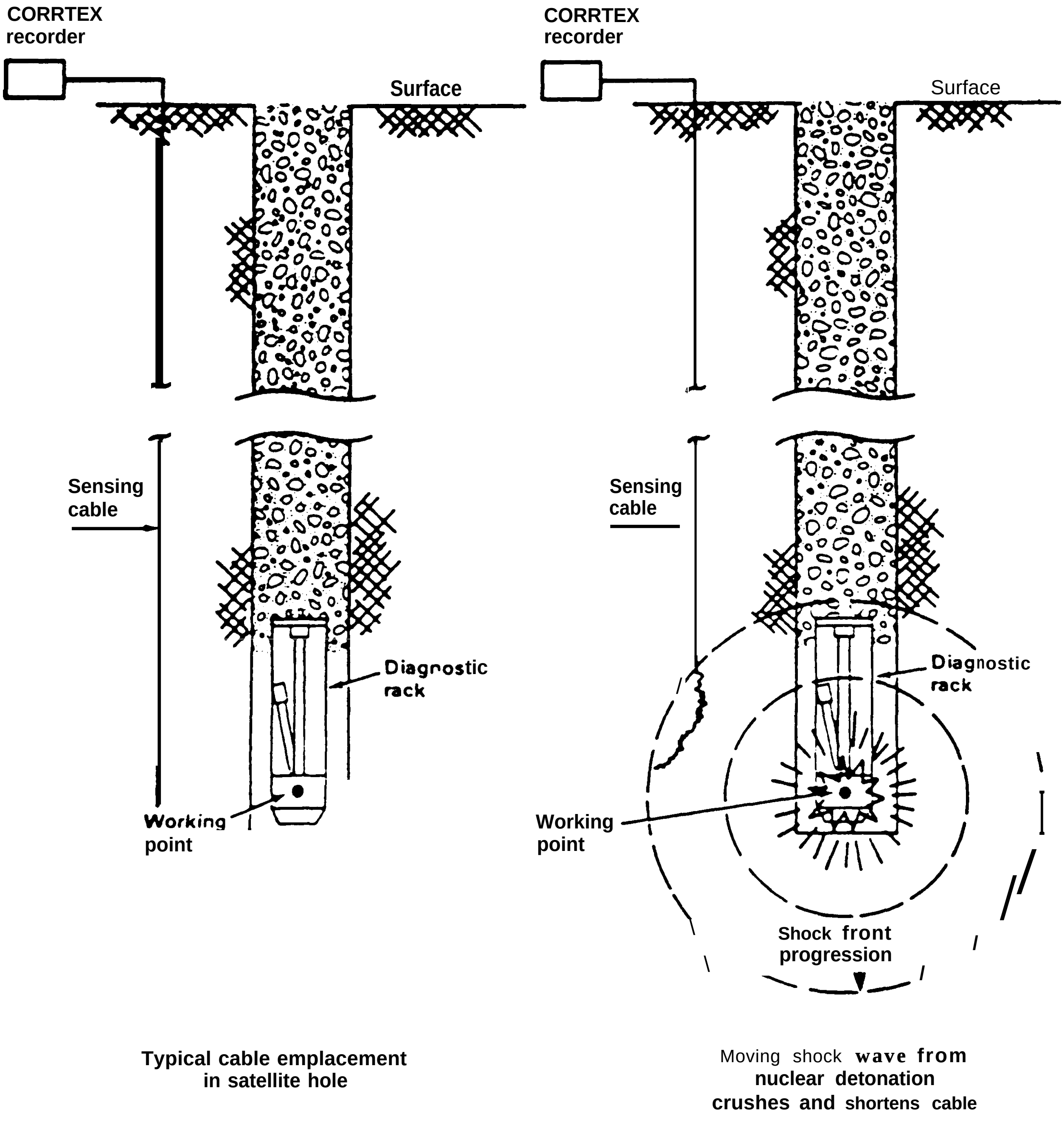
Measuring the Position of the Shock Front

Several techniques have been used to measure the position of the shock front as a function of time. During the 1960s and early 1970s, extensive measurements were made using the so-called SLIFER technique.[6] In the mid-1970s an improved technique, called CORRTEX, was developed.[7] This is the technique the Reagan administration has proposed as a new technique to monitor the Threshold Test Ban Treaty (TTBT).[8]

In the CORRTEX technique, an electrical sensing cable is lowered into a vertical hole to a depth greater than the depth at which the nuclear explosion will take place, typically hundreds of meters for explosives with yields near 150 kt. The hole may be the one in which the nuclear explosive is placed (the emplacement hole) or one or more other holes (so-called satellite holes) that have been drilled specifically for this purpose. The latter geometry is shown in figure A-1. If satellite holes are used, they must be drilled at the proper distance(s) from the emplacement hole, typically about ten meters for yields near 150 kt. Then, if the sensing cable is strong enough that it is not crushed by other dis-

[5]See F. K. Lamb, ACDIS WP-2-87-2 (University of Illinois Program in Arms Control, Disarmament, and International Security, Urbana, IL, 1987).
[6]M. Heusinkveld and F. Holzer, *Review of Scientific Instruments, 35, 1105 (1964).* SLIFER is an acronym for "Shorted Location Indication by Frequency of Electrical Resonance."
[7]C.F. Virchow, G.E. Conrad, D.M. Holt, et.al., Review *of Scientific Instruments, 51,642 (1980)* and Los Alamos National Laboratory public information sheet on CORRTEX (April 1986). CORRTEX is an acronym for "Continuous Reflectometry for Radius v. Time Experiments. "
[8]U.S. Department of State, Bureau of Public Affairs, "U.S. Policy Regarding Limitations on Nuclear Testing, ''Special Report No. 150, August 1986; and U.S. Department of State, Bureau of Public Affairs, "Verifying Nuclear Testing Limitations: Possible U.S.-Soviet Cooperation," Special Report No. 152, Aug. 14, 1986.

Figure A-1 .—Use of the CORRTEX Technique



SOURCE: U.S. Department of State, Bureau of Public Affairs, "U.S. Policy Regarding Limitations on Nuclear Testing," Special Report No 150, August 1986 turbances but weak enough that it is crushed by the pressure peak at the shock front, it will be electrically shorted close to the point where the shock front intersects the cable (see figure A-l). As the shock front expands with time, the changing distance from the surface to the shallowest point at which the shock wave intersects the sensing cable is measured at preset time intervals by electrical equipment attached to the cable and located above ground. The CORRTEX technique is much less affected by disturbing early signals from the explosion than were earlier techniques.

The time at which the explosion begins is taken to be the time at which the first signal, produced by the electromagnetic pulse (EMP) from the explosion, arrives at the CORRTEX recorder. If the explosion is spherically symmetric, the length of the unshorted cable decreases rapidly and smoothly with time as the shock front expands away from the center of the explosion and the radius of the shock front at a given time can be calculated using simple geometrical equations. If the explosion is not spherically symmetric, due to the shape of the canister, the design of the nuclear charge, or inhomogeneities in the ambient medium, the interpretation of CORRTEX data is more complicated and could be ambiguous or misleading under the conditions encountered in treaty verification. Problems of this kind can be prevented by cooperative agreements, as discussed below.

An error of 1 meter 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, an accurate survey of the satellite hole is required in order to make an accurate yield estimate. Surveys are currently made with special laser or gyroscopic equipment. In some yield estimation algorithms, the lateral displacement from the center of the explosion can be treated as one of the unknowns in estimating the yield.

Yield Estimation Algorithms

Hydrodynamic methods of yield estimation are evolving as research aimed at gaining a better understanding of underground explosions and improving yield estimation methods continues. At present, four basic types of algorithms are commonly in use. In order to simplify their description, the explosion will be assumed to be spherically symmetric (the complications that can arise if it is not will be addressed later).

Insensitive Interval Scaling

Once measurements of the radius of the shock front as a function of time are in hand, an estimate of the yield of the explosion can be made by comparing the measurements with a model of the motion of the shock front away from the center of the explosion. 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 an additional new method of monitoring compliance with the 150 kt limit of the TTBT.

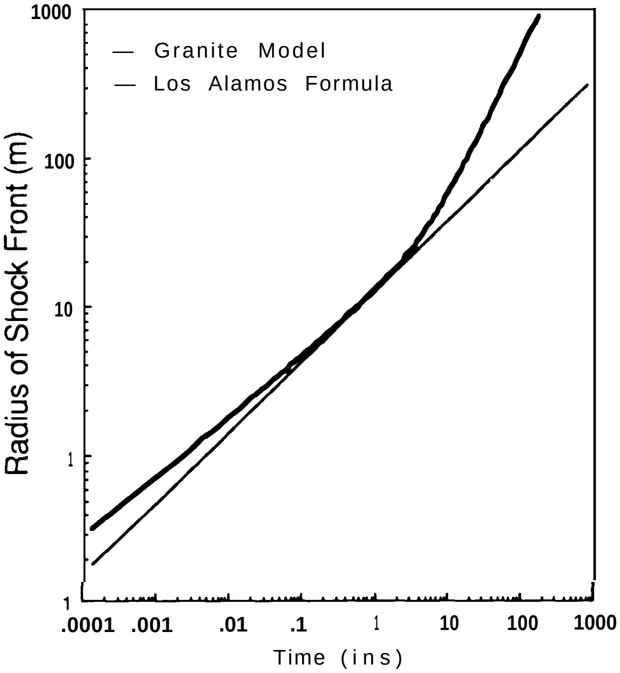
Insensitive interval scaling is based on the assumption that the radius of the shock wave for an explosion of given yield is independent of the medium during a certain interval in time and radius called here the insensitive *interval*. Indeed, studies indicate that for the collection of rocks within U.S. test experience (mostly silicates), rock properties are correlated in such a way that there is a time during the transition interval when the radius of the shock front produced by an explosion of given yield varies relatively little from one rock to another.[9]

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 shock radius versus time data in this interval.[10] The Los Alamos Formula is a power law that approximates the actual radius versus time curve during the insensitive interval. This is illustrated by figure A-2, 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.

[9]The rocks for which the United States had good data or models are the dry alluvium, partially saturated tuff, saturated tuff, granite, basalt, and rhyolite at the test sites used, almost all of which are at the Nevada Test Site. At present, the reason for the correlation of rock properties that gives rise to the insensitive interval is not well understood from a fundamental physical point of view. Moreover, it is known that the radius of the shock wave in this interval is very different for other very different kinds of rocks. Thus, the existence of an insensitive interval must be established by test experience or modeling, and is only assured for certain geologic media.

[10]The Los Alamos Formula for the shock radius in meters is $R(t) = \alpha \cdot W^{1/3}(t/W^{1/3})^{\beta}$, 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 β are constants. Different values of a and β have been used by different individuals and groups and have changed with time. The values of a and β used here are 6.29 and 0.475 (see M. Heusinkveld, *Journal of Geophysical Research, 87, 1891, 1982).*

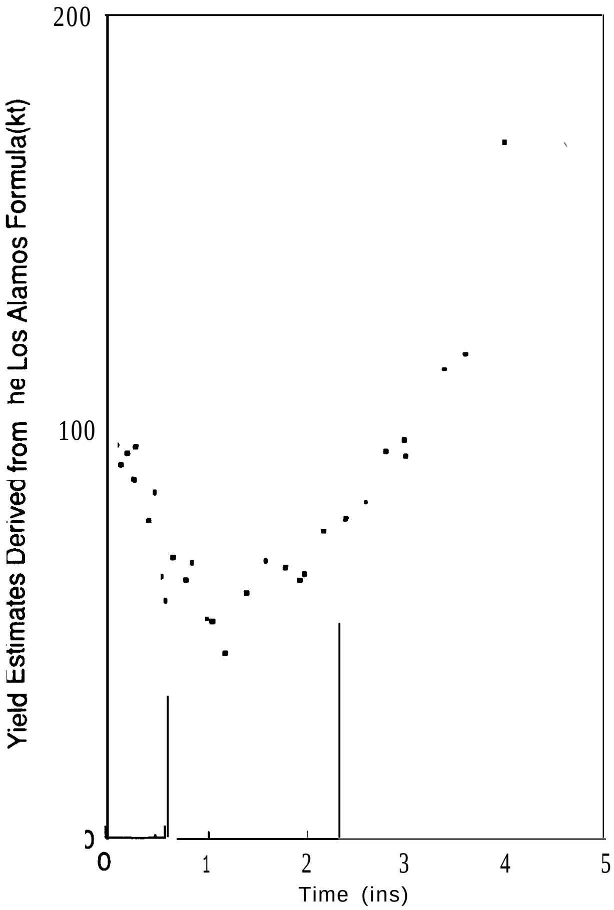
Figure A-2.—Comparison of the Los Alamos Formula With a Semi= Analytical Model of the Shock Wave in Granite Caused by a Spherically asymmetric Point Explosion With a Yield of 62 Kilotons



SOURCE: F.K. Lamb, "Hydrodynamic Methods of Yield Estimation," Report for the US. Congress, Office of Technology Assessment, Feb. 15, 1988.

In practice, the Los Alamos Formula is usually first fit to a broad interval of radius versus 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 radius versus time curve at both early and late times, the sequence of yield estimates typically forms a U-shaped curve. This is illustrated in figure A-3, 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. If the assumptions on which the algorithm is based are satisfied, the yield estimates near the bottom of the curve approximate the actual yield of the explosion, In the usual form of the algorithm, only the radius versus time 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. The length of the algorithmic interval and the time at which it occurs are both proportional to $W^{1/3}$, where W is the yield of the explosion (see table A-2). The algorith-

Figure A-3.—Application of the Los Alamos Formula to an Explosion in Granite



SOURCE: F.K. Lamb, "Hydrodynamic Methods of Yield Estimation," Report for the U.S. Congress, Off Ice of Technology Assessment, Feb. 15, 1988.

mic interval is indicted in figure A-3 by the two vertical bars at the bottom of the figure. In this example, the assumptions of the algorithm are satisfied and the average of the yield estimates that lie within the algorithmic interval is very close

Table A-2.—Algorithmic Intervals for Various Yields[a]

Time	Time interval (ins)	Radius interval (m)
1	0.1-0.5	2-4.5
10: : : : : : : : : : : : : : : :	0.2-1.1	4.5-1o
50.	0.4-1.8	8-17
100.	0.5-2.7	10-21
150.	0.5-2.6	11-24

[a]The time intervals used by various individuals and groups varies. Throughout this report the algorithmic interval Is taken to be from $0.1W^{1/3}$ milliseconds to $0.5W^{1/3}$ milliseconds after the beginning of the explosion, where W is in kilotons,

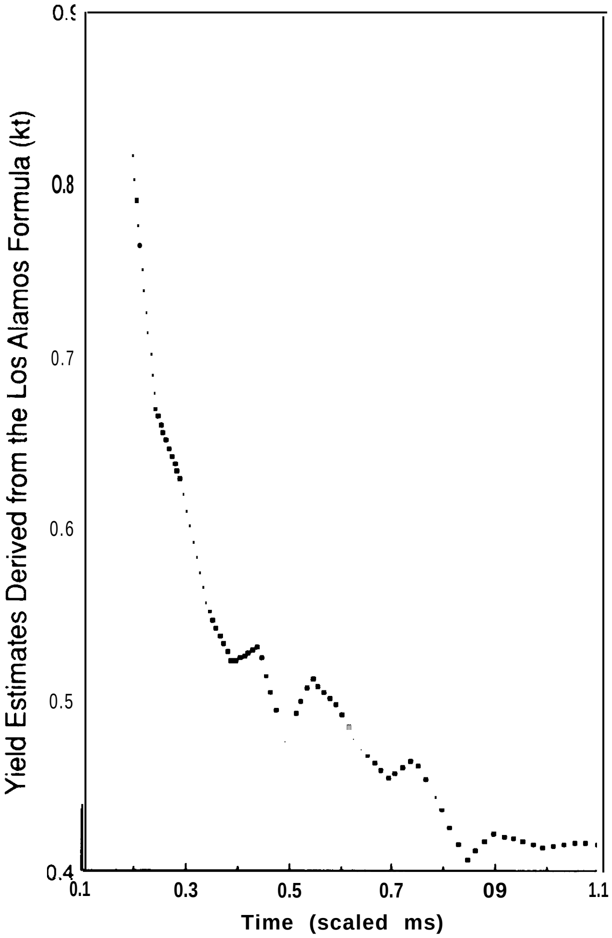
SOURCE: F.K. Lamb "Hydrodynamic Methods of Yield Estimation" Report for the U.S. Congress, Office of Technology Assessment, Feb. 15, 1988.

to the announced yield of 62 kt. Studies indicate that yield estimates made using this algorithm have a precision of about a factor of 1.2 at the 95 percent confidence level for spherically-symmetric explosions with yields greater than 50 kt conducted at the Nevada Test Site (NTS). Estimates of the accuracy of the algorithm made by comparing results with the usually more accurate radiochemical method are similar. According to official statements, the insensitive interval algorithm is expected to be accurate to within a factor of 1.3 at Soviet test sites for explosions with yields greater than 50 kt in media within U.S. test experience." Some scientists believe that the uncertainty would be somewhat larger.

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 A-4, which shows the yield estimates obtained by fitting the Los Alamos Formula to good-quality SLIFER data from atypical low-yield explosion in alluvium. In this example the radius and time data have been scaled using the actual yield so that the derived yield should be 1 kt. However, the yield estimates given by the Los Alamos Formula are systematically low, ranging from 30 to 82 percent of the actual yield, and do not forma U-shaped curve. The average of the yield estimates that lie within the algorithmic interval is about 60 percent of the actual yield. The overall appearance of the yield versus time curve shows that the assumptions of the algorithm are not satisfied.

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.[12] As explained earlier, radius versus time data in the algorithmic interval would indeed be relatively independent of the medium if this were so, and would follow a power-law curve similar to the Los Alamos Formula. However, the shock wave is not strong during the algorithmic interval, be*cause* in this interval the shock speed is only a few times the speed of sound and the post-shock pressure is much less than the pressure required to achieve the maximum limiting density. Indeed, the exponent of time usually used in the Los Alamos Formula is significantly greater than the value appropriate for a strong shock wave. The Los Alamos Formula is, as noted earlier, an empirical relation, which was obtained by fitting a power-law expression to data from a collection of explosions in a variety of different rocks and approximates actual radius versus time curves over a portion of the transition interval.

Figure A-4.—Application of the Los Alamos Formula to a Low-Yield Explosion in Alluvium



SOURCE: F.K. Lamb, "Hydrodynamic Methods of Yield Estimation," Report for the US. Congress, Office of Technology Assessment, Feb. 15, 1988.

Similar Explosion Scaling

If a given explosion occurs in the same medium as a previous explosion at a different site, and if radius versus time data and the yield are available for the previous explosion, then the yield of the given explosion can be estimated by similar explo*sion scaling*. The reason is that for explosions in the same medium, the radius versus time curve depends only on the yield of the explosion, and this

[11]U.S. Department of State, op. cit., footnote 8.

[12]For example, "The accuracy of the method is believed to be relatively, but not wholly, independent of the geologic medium, provided the satellite hole measurements are made in the 'strong shock' region . . . " (Ibid.) This misconception may have arisen from the fact that the interval formerly used to estimate the yields of nuclear explosions in the atmosphere using hydrodynamic methods *is* within the strong shock region.

dependence is known and is simple.[13] Hence, an estimate of the yield of the given explosion can be made by comparing the two sets of radius versus time data. This algorithm can make use of 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. Similar explosion scaling has been proposed as a supplement to insensitive interval scaling for TTBT verification.

Semi-Analytical Modeling

Semi-analytical modeling is another approach that is useful for studying the evolution of shock waves in geologic media and for estimating yields. 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 measurements of the shock wave motion with time.[14] Semi-analytical algorithms can in principle make use of more of the data than can the insensitive interval algorithm and can also be used to estimate the uncertainty in the yield caused by uncertainties in the properties of the ambient medium.

Numerical Modeling

If a treatment that includes the details of the equation of state and other properties of the ambient medium is required, or if the explosion is asymmetric, modeling of the motion of the shock front using numerical hydrocodes may be necessary.[15] In principle, such simulations can Provide radius versus time 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 data from later phases of the shock wave evolution. In practice, the yield estimates obtained using such a procedure are fairly sensitive to the equation of state of the ambient medium, which is known with sufficient accuracy for only a few geologic media. If adequate equation of state data are lacking, numerical modeling may not be warranted.

In summary, the shockwave produced by an underground nuclear explosion propagates differently in different media and different geological structures. As a result, knowledge of the ambient medium and local geological structures is required in order to make accurate yield estimates using hydrodynamic methods. Several different yield-estimation algorithms have been developed. These algorithms, like those based on seismic methods, involve some complexity and require sophistication to understand and apply correctly. Some key terms that have been introduced in this discussion are listed and explained in table A-3.

Application to Monitoring Treaties

Assuring Accuracy

Ambient Medium.-The physical properties and geologic structure of the ambient medium enter directly into yield estimates based on hydrodynamic methods. Incorrect assumptions about the average properties of the ambient medium may bias the yield estimate, decreasing its accuracy, while small-scale variations will cause scatter in the radius versus time data, decreasing the precision of the yield estimate. Thus, it is important to gather information about the types of rock present at the test site and their properties, including their chemical composition, bulk density, and degree of liquid saturation, as well as the speed of sound in the ambient medium and any specific features of the local geologic structure that could affect the yield estimate. Availability of the required data would need to be assured by appropriate cooperative measures.

Some information about the geologic medium at the test site could 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 frag-

“See H. L. Brode, *Annual Review of Nuclear Science,* 18, 153-202 (1968).

“For an early semi-analytical model, see M. Heusinkveld, *Report UCRL-52648* (Lawrence Livermore National Laboratory, Livermore, CA, 1979). For improved semi-analytical models, see F. K. Lamb, *ACDIS WP-87-2-1* (University of Illinois Program in Arms Control, Disarmament, and International Security, Urbana, IL, February 1987); W. C. Moss, *Rep. UCRL-96430 Rev. 1* (Lawrence Livermore National Laboratory, Livermore, CA, July 1987); and R. A. Axford and D. D. Helm, *Proc. NEDC* (Los Alamos, October 1987).

15 For a discussion of numerical models currently in use see F. K. Lamb, “Monitoring Yields of Underground Nuclear Tests, ” *Threshold Test Ban Treaty and Peaceful Nuclear Explosions Treaty, Hearings Before the Committee on Foreign Relations, United States Senate* (Washington, DC: U.S. Government Printing Office, 1987), pp. 359-370.

Table A-3.–Glossary of Hydrodynamic Yield Estimation Terms

Term/Explanation
Strong Shock Interval: The interval in radius and time during which the speed of the shock wave is much greater than the speed of sound in the unshocked medium
Transition Interval: The interval in radius and time outside the strong shock interval in which the speed of the shock wave approaches the speed of sound in the unshocked medium
Plastic Wave Interval: The interval in radius and time outside the transition region in which the speed of the weakening shock wave is approximately the plastic wave speed
SLIFER Technique: A technique for measuring the position of the shock wave 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 site of the explosion
CORRTEX Technique: A technique for measuring the position of the shock wave 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 site of 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 wave as a function of time during the algorithmic interval
Los Alamos Formula: The empirical formula used in the insensitive interval scaling algorithm to make yield estimates by fitting to shock radius versus time data
Algorithmic Interval: The special time interval used in insensitive interval scaling during which the radius of the shock wave is relatively insensitive to the ambient medium; usually assumed to be 0,1-0.5 scaled milliseconds after the beginning of the explosion
Similar Explosion Scaling: A yield estimation algorithm in which data obtained from a previous explosion in the same medium are scaled to fit measurements of the position of the expanding shock produced by the explosion under consideration

SOURCE: F.K. Lamb "Hydrodynamic Methods of Yield Estimation" Report for the US. Congress, Office of Technology Assessment, Feb. 15, 1988,

ments from the wall of the emplacement 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 Peaceful Nuclear Explosions Treaty (PNET), which explicitly established the hydrodynamic method as one of the monitoring methods that could be used for large salvos and specified verification measures like these.[16]

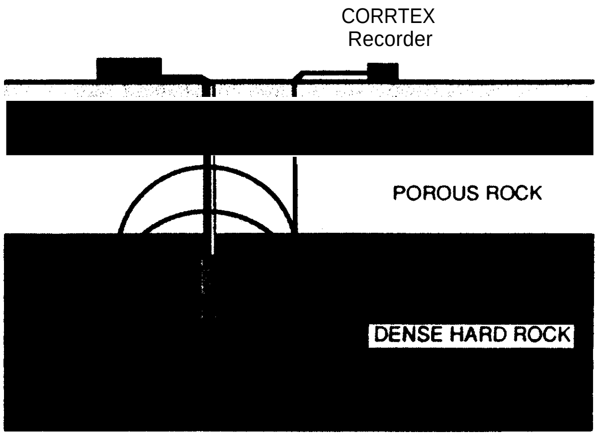
Test Geometry.–CORRTEX data must be taken very close to the center of the explosion in order to cover the insensitive interval (see table A-2). As a result, yield estimates can be affected by the arrangement of the nuclear charge and the canister or canisters containing it and the diagnostic equipment.[17] In particular, any properties of the experimental set-up or the surrounding geologic media that cause the shock front to be distorted at the radii of interest could affect the accuracy of the yield estimate. The reason is that a CORRTEX sensing cable measures only the depth of the shallowest point where a pressure wave first crushes it, at a single lateral displacement from the explosion. Thus, unambiguous interpretation of the data may become difficult or impossible if the explosion is not spherically symmetric.

For example, 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 it before the ground shock arrives, the CORRTEX data will describe that flow of energy and not the motion of the ground shock. Alternatively, the motion of the ground shock itself could be sufficiently distorted that interpretation of the shock position data becomes ambiguous or misleading. As another example, a large canister or double explosion could short the CORRTEX cable in such away that only part of the total yield is sensed over most of the interval sampled by the CORRTEX cable, as shown in figure A-5. The physical size of

[16] *Arms Control and Disarmament Agreements* (U.S. Arms Control and Disarmament Agency, Washington, DC, 1982).

[17] The importance of these disturbing effects is less for high-yield than for low-yield explosions.

Figure A-5.—Effect of Nuclear Test Design on Shock Wave Radius Measurements Using CORRTEX Equipment



SOURCE: F.K. Lamb, "Hydrodynamic Methods of Yield Estimation," Report for the U.S. Congress, Office of Technology Assessment, Feb. 15, 1988.

canisters and diagnostic lines-of-sight tend to pose more of a problem for nuclear directed-energy weapons than for traditional nuclear weapons.[18]

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 is not necessarily the case when monitoring the nuclear tests of another party. Cooperative agreements to make possible optimal placement of sensing cables and to exclude nuclear test geometries that would significantly disturb the yield estimate would therefore be required.[19]

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 filling of the nuclear charge emplacement hole with certain types of materials. Such agreements could also provide for observation of the emplacement of the nuclear charge and the stemming of the emplacement 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, drafts, or other cavities, additional measures, such as placement of several sensing cables around the weapon 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.[20]

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. In assessing whether hydrodynamic methods should be used beyond this period, the disadvantages of the test restrictions must be weighed against the potential contribution to treaty monitoring made by these methods.

In summary, the accuracy that could be achieved using hydrodynamic methods to estimate the yields of underground nuclear explosions depends on the amount of information that can be gathered about the medium in which the explosion occurs, and the nature and extent of cooperative arrangements that can be negotiated to optimize the placement of sensing cables and to limit disturbing effects.

Hydrodynamic methods for estimating the yields have not yet been studied as thoroughly or as widely as the seismic methods currently in use, although they have been examined more thoroughly than some seismic methods that have been proposed for the future. Tests and simulations to identify troublesome configurations have been carried out, but only a few explosions have been monitored with the CORRTEX sensing cable in a satellite hole.[21] Given the possibility that hydrodynamic yield estimation 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 reduce further the chances of confusion, ambiguity, spoofing, or data denial would be very useful.

Minimizing Intrusion

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

1. Personnel from the monitoring country would be present at the test site of the testing country for perhaps 10 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.[22]
2. 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.[23]

[18] See Sylvester R. Foley, Jr., Assistant Secretary for Defense Programs, Department of Energy, letter to Edward J. Markey, Congressman from Massachusetts, Mar. 23, 1987.

[19] S. S. Hecker, *Threshold Test Ban Treaty and Peaceful Nuclear Explosions Treaty, Hearings Before the Committee on Foreign Relations, United States Senate* (Washington, DC: U.S. Government Printing Office, 1987), pp. 50-61 and 226-235; M. D. Nordyke, *Ibid.*, 67-71 and 278-285; Foley, ibid

[20] Op. cit., footnote 16.

[21] Op. cit., footnote 8. Approximately 100 tests have been carried out with the CORRTEX cable in the emplacement hole, and SLIFER data from satellite holes are available for several tens of earlier explosions.

[22] R.E. Batzel, Threshold *Test Ban . . .*, op. cit., footnote 19, PP. 48-50 and 210-225, and Foley, op. cit., footnote 18.

[23] Batzel, ibid.

3. 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.

Intrusiveness could be minimized by careful attention to monitoring procedures and equipment. For example, the electrical equipment required 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 NTS be similarly designed. The security problems posed by opportunities to observe test preparations are more severe for nuclear directed energy weapon tests, since they tend to have more and larger complex diagnostic systems and canister arrangements which, if fully revealed to the Soviets, might disclose sensitive information. The United States has determined that the Soviet personnel and activities that would be required at NTS 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.[24]

Specific Applications

Threshold Test Ban Treaty.–As noted earlier, hydrodynamic yield estimation has 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. To reduce the cost and intrusiveness of such verification, it could be restricted to tests with expected yields greater than some threshold that is an appreciable fraction of 150 kt. Hydrodynamic measurement of the yields of one or more nuclear explosions at each country's test site or sites has also been suggested as a method of calibrating seismic yield estimation methods.[25]

From the point of view of the United States, possible advantages of being able to use hydrodynamic yield estimation methods at Soviet test sites include the additional information on yields that this would provide, establishment of the principle of on-site inspection at nuclear test sites, and the possibility of collecting data on the ambient media and geologic structures at Soviet test sites. Obviously, the larger the number of explosions and the greater the number of test sites monitored, the more information that would be obtained. Possible disadvantages for the United States include the potential difficulty of negotiating routine use of hydrodynamic methods at Soviet test sites, which could impede progress in limiting nuclear testing, and the operational security problems at NTS caused by the presence of Soviet monitoring personnel there.

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.[26] 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 principal 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. -Underground nuclear explosions as small as 1 kt produce shock waves that evolve in the same way as those produced by explosions of larger yield. However, such explosions can and usually are set off at shallow depths and can be set off in alluvium. As a result, the motion of the ground can be markedly different from that on which standard hydrodynamic yield estimation methods are based, causing a substantial error in the yield estimate (see figure A-4). There can also be significant variations in the motion of the ground shock 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 yield of such a small explosion. For one thing, the sensing cable must be placed very close to the nuclear charge (see table A-3). Drilling a satellite hole within 3 meters of the emplacement hole to the depths of typical nuclear device emplacement, as would be required in order to use hydrodynamic

[24] Foley, op. cit., footnote 18.

[25] It has been suggested that the nuclear calibration charges to be detonated at the test sites could be provided by the monitoring country. If they were, a hydrodynamic estimate of the yield might not be needed, since, as explained inch. 7, the yields of certain types of nuclear charges are accurately reproducible. Knowledge of the surrounding medium and geologic structure would still be needed to provide assurance that the coupling of the explosion to seismic waves was understood. However, some way would have to be found to provide assurance that no sensitive information about the design of the nuclear weapons of either country would be revealed.

[26] *Arms* . . . , op. cit., footnote 16.

methods to estimate the size of an explosion with a yield near 1 kt, would be challenging, to say the least. The need for such close placement would necessitate further restrictions on the maximum size and orientation of the canister used to contain the nuclear charge and diagnostic instrumentation. Such restrictions might be deemed an unacceptable interference with test programs. However, use of small canisters with numerous diagnostic lines-of-sight to the detonation point could disturb the CORRTEX measurements. Because the shock wave radii to be measured are much smaller at low yields, survey errors become much more important.

Possible solutions to these problems 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.–As their name implies, hydrodynamic yield estimation methods have been developed to measure the sizes of underground nuclear explosions. They are a potentially valuable component of a cooperative program to monitor limits on yields, but are neither intended nor able to detect, identify, or measure the yields of unannounced or clandestine nuclear tests. Thus, they are not applicable to monitoring a comprehensive test ban.

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