Chairman of the foundation's board is Gustav O. Lienhard, a retired chairman of the Johnson & Johnson board and president and treasurer of the foundation until Rogers took over as president.

Rogers says he found the members of his board extremely knowledgeable about hospital and medical center operations and also about universities, since most have substantial experience serving on college and university boards. He notes that they bring their corporate backgrounds and university board experience into play as trustees. When Rogers suggested, for example, that the foundation be set up organizationally on the lines of a university administration, the board members made it clear that, based on their observations, "they were not terribly impressed with the suggestion. They took the argument and hit me over the head with it."

Outsiders say the board is likely to be expanded, with new members selected to help with the foundation's broadened program, but that the trustees are, and will likely continue to be, a pragmatic and hardheaded group.

It will no doubt be several years before the Johnson Foundation defines its style and establishes its effectiveness, but, even considering the dimensions of health care problems today, the Johnson Foundation has the resources to do more, metaphorically, then apply a Band-Aid.—JOHN WALSH

RECENT DEATHS

Charles F. Angell, 52; professor of engineering, Wentworth Institute; 15 November.

Edward F. Barta, 82; professor emeritus of pathology, Medical College of Wisconsin; 5 November.

Harry A. Charipper, 71; professor emeritus of biology, New York University; 17 November.

Edwin A. Christ, 54; professor of sociology and anthropology, Westminster College, 15 October.

M. Raymond Collings, 75; former professor of anatomy, Wayne State University; 19 October.

Conrad G. Collins, 64; professor of obstetrics and gynecology, Tulane University; 14 December.

Robert A. Davis, 71; former professor of educational psychology and research, George Peabody College for Teachers; 31 October.

J. W. Egiazaroff, 78; hydroelectric engineer and mathematician, Armenian Academy of Sciences; 10 June.

Emmanuel Fauré-Fremiet, 88; cytologist, electron microscopist, protozoologist and professor emeritus, Collège de France; 6 November.

Irving W. Finberg, 60; professor of engineering, Miami-Dade Junior College; 3 October.

Leonard D. Garren, 43; professor of medicine, University of California, San Diego; 31 October.

RESEARCH NEWS

Nuclear Explosion Seismology: Improvements in Detection

Nuclear explosion seismology has come a long way since 1958 when a committee of experts met in Geneva to consider the best means of detecting violations of a comprehensive test ban treaty. At that time not much was known about seismic signals generated by underground nuclear explosions—only one shot had been detonated. Now several dozen shots have been analyzed in detail, and the original ideas of how to detect and distinguish the seismic signals of explosions from those of earthquakes have been superseded.

Some experts now believe that explosions in hard rock with yields as small as 2 kilotons could be identified on a global scale with no more than a dozen high-quality seismograph stations. But in 1958 there seemed to be little prospect, according to some seismologists, of identifying shots with yields smaller than 50 kilotons at distances greater than 2500 kilometers from the center of the blast. On the basis of these more pessimistic assumptions, 180 stations would have been needed to police the globe.

The negotiations for a comprehensive test ban treaty reached an impasse when the United States and the U.S.S.R. could not agree on the importance of on-site inspections. The United States negotiators felt that on-site inspections were necessary when seismic data could not distinguish the origin of a suspicious signal. The Russians would not acquiesce. Each government has maintained this posture for over a decade.

When the partial test ban treaty was signed in 1963, it covered nuclear tests in the atmosphere, in space, and in the oceans, but there was no agreement on underground explosions because of the differences about on-site inspection. With the improvements in theory and instrumentation during the past decade, some observers now believe that the position of the United States could be changed without any fear of deception. According to Robert Nield, former director of the Stockholm International Peace Research Institute (SIPRI), weapons tests with yields lower than 10 kilotons would be of little advantage to a nuclear country, and any larger underground explosions would surely be identified—either remotely by seismic signals or by spy satellites or locally by old-fashioned espionage.

There are four basic elastic waves of use in the problem of identifying underground explosions—two kinds of body waves and two corresponding surface waves. On a conventional seismograph the first signal is usually due to a fast-moving body wave known as a P wave—for primary. The P waves are acoustic waves; the displacement of the particles in the ground is along the waves' direction of travel. The P waves provide the signals used to determine the direction of the first motion from an earthquake.

The other type of body waves are shear waves; they are called S waves—for secondary. The velocity of S waves is lower than that for P waves, and the direction of the ground motion is perpendicular to the direction of travel. A liquid material cannot maintain S waves because it has no restoring force. Explosions should produce weak S waves because all of the energy initially goes into compressional motion. On the other hand, earthquakes often generate sizable S waves, as would be expected if the sliding or shear hypothesis for the mechanism of earthquakes is correct. The S waves are a good diagnostic agent; but unfortunately the characteristic frequencies of explosion S waves lie in the peak of the microseismic noise band; so that they are difficult to record.

Of the two types of surface waves, Rayleigh waves are very useful for nuclear explosion seismology. They travel near the earth's surface although they are not confined to the crust. They undulate along the surface causing the ground particles to execute retrograde elliptical motion. Rayleigh waves were first described by J. W. S. Rayleigh in 1887. The other kind of surface wave was predicted by the English mathematician A. E. H. Love. Love waves cause sideways motion along the surface. So far they have not been of much use in detecting small explosions because the horizontal-component seismometers required to detect them are relatively susceptible to low-frequency noise sources.

First Motion Criterion

Originally seismologists thought that explosions and earthquakes could be distinguished by the depth of the source and by the direction of the first ground motion. In the simplest models, earthquakes are assumed to occur when large stresses build up in a huge column of rock, so that the rock fractures and faults. Then two rock masses slide past each other, moving in opposite directions along the fault line. If a coordinate system is superimposed on the fault, with one axis along the fault direction and the other at right angles, the first motion of the ground will be different in adjacent quadrants. During the earthquake, extra rock mass will move into two of the quadrants and will move out of the other two quadrants. In those quadrants receiving extra mass, the first motion is compressional and the vertical displacement of the ground is outward. In the other two quadrants the first motion is inward.

Explosions occur at a point, and the rock is displaced outward in all directions. Thus, if the direction of the first motion is determined in a large number of stations located at various angles from a seismic event, it should be possible to determine its source.

The depth of a seismic event can be determined by the time lag between waves that travel directly from the source to the station and those that travel upward initially and reflect off the interface with the atmosphere. All events that occur below a given depth must be earthquakes, as there is a limit to the depth at which engineers could detonate a bomb.

Unfortunately the first motion and the depth of focus have drawbacks as criteria for detecting explosion. The most serious problem is that signals from smaller explosions suffer interference from the natural seismic background noise. These background tremors, or microseisms, are caused locally by wind, traffic, industrial activity, and other such events. Remote contributions to the microseisms are from motion in the atmosphere and in the sea. In the worst circumstances, the noise can completely obscure the signal on the seismograph or it can even cause the direction of the first motion to be misread—for example, giving a compression when the real motion is a rarefaction.

Changes in the near-surface structure of the earth along the propagation path fundamentally changes the character of a seismic wave recorded at distances of less than 3000 km. The least distorted signals occur at "teleseismic" distances from the seismic event. This region lies between 3000 and 10,000 km from the source. At these greater distances the travel time of the signals in the complex structure of the upper layers of the earth are minimized, and the signal is less disturbed. Yet the signal still must compete with the ground motion resulting from microseisms, movement which is seldom less than 1 nanometer in the frequency range of 1 to 10 cycles per second. Seismic events with magnitude less than 4 on the Richter scale displace the ground by less than 1 nm in the teleseismic window. This magnitude roughly corresponds to an explosion of 2 kilotons in granite or of 6 kilotons in tuff—a less compact rock. These values are close to the theoretical limit of detection. The record of the first motion of the ground is well below this threshold.

At frequencies lower than 1 cycle per second the seismic background reaches a maximum between 0.25 and 0.125 cycle per second. The problem of "seeing" small signals through this noise has not yet been solved, though it is likely that these signals carry useful information about the source function. However, the noise drops off for lower frequencies, and seismologists have focused considerable interest on seismic waves with periods greater than about 15 seconds (frequencies lower than 0.06 cycle per second). Waves with these periods travel along the surface of the earth from the source to the detector, and, for now, provide the most promising means of distinguishing earthquakes from explosions. In view of the amount of energy they convert into waves that pass through the earth's interior (body waves), earthquakes generate considerably larger surface waves than explosions do. With improvements in long-period detectors, some seismologists are looking to waves with 40-second periods—the earth noise in this range of frequencies seems to reach a minimum—for further improvements in discrimination thresholds.

New Detection Criteria

It became apparent in the mid-1960's that the ratio of the body-wave magnitude to the surface-wave magnitude is a powerful technique for distinguishing seismic events. The experimental data that supported the theoretical analyses were obtained from some of the 120 continuously recording stations of the World-Wide Network of Standard Seismograph Stations. This network was financed by the United States after the 1958 Geneva meeting as a major contribution to the program for improving seismology in the interests of a comprehensive test ban treaty. One of the first analyses by the United Kingdom Atomic Energy Authority was reported by H. Thirlaway in a 1968 SIPRI paper (*1*). It showed that the value of ratio $m_b : M_s$—where m_b is the body-wave magnitude and M_s is the surface-wave magnitude—can be used to distinguish earthquakes from explosions when m_b is greater than 4.75. This value of m_b corresponds to an explosion of about 12 kilotons in hard rock.

The usefulness of the $m_b : M_s$ criterion is that it identifies explosions. Both the first motion and the depth of focus identify earthquakes only; the residue of events needs to be identified by nonseismological means, such as on-site inspection. In contrast, the ratio of the magnitude of the body wave to the surface wave eliminates, in principle, the need for on-site inspection.

In the most recent report of the Seismic Study Group of SIPRI (*2*), D. Davies of M.I.T. mentions that there seems to be no breakdown in the $m_b : M_s$ discriminant down to m_b of 4.0. However, the instruments now deployed cannot identify explosions down to this magnitude. According to the SIPRI group, it is now possible to identify all explosions with yields of 20 or more kilotons from known test sites in hard rock. The SIPRI group believes that new developments in instrumentation can lower the threshold to 10 kilotons in hard rock within 2 years and that improvements in discrimination criteria may ultimately allow seismologists to exploit differences in earthquakes and explosions with yields as low as 2 kilotons in hard rock. Reaching the lower thresholds, however, would also require large investments in new equipment.

The major improvement in seismology over the past decade has been the deployment of seismographic arrays. And in the past year there have been substantial advances in long-period instruments. The biggest limitation however is ground noise. A small number of arrays located in carefully selected low-noise zones could set the detection threshold at 1 or 2 kilotons in hard rock.

The first large arrays were built at Pole Mountain, Wyoming, at Eskdalemuir, Scotland, and at Yellowknife, Canada. In the simplest form, an array consists of two straight lines of seismograph stations that intersect at right angles. At Eskdalemuir each line has 11 stations, separated from each other by about 1 km. Because there is a small time delay between the signals at each station when a seismic event occurs, it is possible to "beam" the array in order to separate signals generated in different locations and to roughly determine the direction of the event. Furthermore, when the signals from all of the stations are combined, the random ground motion from microseisms is diminished relative to the true signal. The Large Aperture Seismic Array in Montana covers 200 km and contains 525 seismometers. New long-period arrays are in operation in Sweden, India, Alaska, and Norway.

For small explosions the surface waves often get lost in the noise; and some U.S. experts, such as Stephen Lukasik, director of the Defense Department's Advanced Research Projects Agency (which has been responsible for the detection program), believe that an identification method based on a lack of surface waves may not be acceptable as a diagnostic tool. Other schemes have been tried, and one based on the frequencies of the body waves may prove to be worthwhile. In a small sample, W. H. Bakun and L. Johnson, University of California, Berkeley, were able to distinguish between earthquakes and explosions down to m_b equal to 3.2 (*3*). Davies believes that these short-period frequencies may be more important as diagnostic tools than has been appreciated.

As the m_b value is pushed lower and lower, the seismologist will face an increasing number of natural earthquakes from which they will need to weed out the possible explosion. At m_b equal to 4.0 there are more than 10,000 events per year, and sometimes this number is doubled. Some of these events can be discounted as explosions because they occur under the oceans or are located so deep in the earth that they could not be explosions.

Regional Differences

An important discovery in the past year is the underlying significance of "regionalization." Namely, an explosion detonated in one location may generate a signal in a particular station that differs in amplitude and in form from the signal produced by an equivalent explosion detonated in the same kind of rock located elsewhere (*4*). As the complicated structure of the earth is carefully mapped and interpreted, it may become possible to predict the characteristics of a signal from an as-yet-untried test site. Body wave amplitudes, for example, vary with azimuth if the waves pass through island arcs, such as the Aleutian Islands. In these regions the lithosphere is supposed to be thrust down into the mantle and supposedly causes focusing. Surface waves are relatively unaffected except at margins between continents and oceans. Some of the energy is either focused, defocused, or scattered. Under these conditions, magnitudes of both body waves and surface waves can vary by as much as 1 unit from station to station.

The problems of intercontinental propagation were considered in detail in the 1971 Canadian Working Paper for the U.N. Conference of the Committee on Disarmament. According to the Canadians' calculations, the discrimination threshold for single stations located on the same continent as the explosion is about 7 kilotons. For arrays located across an ocean, the threshold is only 18 kilotons. However, arrays relatively near the blast may reach a discrimination threshold of 2 kilotons.

The seismic magnitude of an explosion depends on the nature of the surrounding rock as well as on the yield and the tectonic environment. In unconsolidated rock, such as alluvium, the signals are about ten times less than for an equivalent explosion in consolidated rocks. Exploding the bomb in a cavity will reduce the signal even further. These methods of foiling detection have been considered by many experts and cause concern for their respective governments. Other deceptions include waiting in readiness for a large earthquake to conceal the signal from the explosions, and firing several explosions in a line in order to mimic an earthquake. However, none of these deceits is foolproof.

Decoupling a 100-kiloton bomb requires a cavity of about 200 meters in diameter and the removal of 8 million tons of earth. Besides being expensive, this activity is susceptible to detection by espionage. The thickest known layers of alluvium are about 500 meters thick, and hence restrict the maximum yield to about 20 kilotons. Above this yield either detectable craters would be formed or detectable radioactive gas would leak to the atmosphere. Work now in progress may indicate ways to unscramble the signals from the other two means of concealment. Furthermore, in both of those methods the concentrated and prolonged activity near the test site may lead to detection by conventional intelligence.

The intense expansion and standardization of seismograph stations in the past decade already seems to have cleared many of the technical obstacles to a comprehensive test ban treaty. However, it is unlikely that the system can ever be improved so that the accuracy of detection is 100 percent. If we are to have complete cessation of nuclear testing, the initiative will have to come from the politicians now that the capability to detect all but the smallest explosions is in view.

—GERALD WICK

References

1. H. Thirlaway, *Seismic Methods for Monitoring Underground Explosions* (SIPRI, 1968).
2. D. Davies, *Seismic Methods for Monitoring Underground Explosions* (SIPRI, progress report, 1971).
3. W. H. Bakun and L. Johnson, *Geophys. J.* **22**, 139 (1971).
4. A. Douglas, P. D. Marshall, D. J. Corbishley, *Nature Phys. Sci.* **233**, 50 (1971).