One millionth of a second sufficed for the underground nuclear explosion to release ten times more energy than the Hiroshima bomb. The shock wave spread spherically outward from a cavity of vaporized rock, obliterating electronic cables in two nearby drill holes and launching rocks into the air above the shot point. A cluster of observers four kilometers away was jolted by the expanding wavefront, which continued to spread deep into the Earth. In Ann Arbor, special seismographic equipment recorded small vibrations as the wave passed by 760 seconds later. In many ways, this explosion on September 14, 1988, located at the Shagan River test site in Kazakhstan, U.S.S.R., was not different from the hundreds of previous underground nuclear explosions set off by the superpowers in the last 32 years, but in other ways this event has changed the course of history. This article describes the complex interplay between science and policy underlying this historic event.

Why was the September 14, 1988, explosion so unusual? First, one of the drill holes near the device, called a satellite hole, was actually drilled by United States engineers using a special U.S. drill rig that was flown into the top secret Soviet test site by seven flights of huge C-5A transport planes. The electronic cables in the hole were installed by the U.S. in order to estimate the yield of the explosion by the hydrodynamic procedure called CORTEX, which is based on the fact that the speed of the initial shock wave is proportional to the yield of the explosion. Never before had it been possible to directly measure the yield of a Soviet nuclear explosion by instruments at their test site. Over fifty of the local observers of the test were U.S. scientists, engineers, and diplomats, the first American nuclear experts ever allowed to witness a Soviet nuclear test. Finally, the seismic recordings made in Ann Arbor and four other designated locations were immediately copied and sent to the Soviet Union as part of a data exchange. A previous test of a U.S. nuclear device on August 17, 1988, at our own Nevada Test Site was conducted under similar conditions, with on-site Soviet hydrodynamic equipment and observers, as well as reciprocal seismic data exchange.

These unprecedented activities, truly remarkable, given the long history of secrecy and suspicion surrounding the nuclear testing programs in the U.S. and Soviet Union, were the result of the Joint Verification Experiment (JVE) of 1988, which involved a pioneering cooperation between the two superpowers to develop verification techniques for monitoring nuclear test ban treaties.

What has been the outcome of the JVE? Basically, it has provided a critical calibration of the Soviet test site, using the officially preferred CORTEX procedure. Knowledge of the yield of the September 14 explosion allows remote seismological yield estimation procedures to be conducted with much greater precision and confidence than previously possible. In turn, this verification of seismological methods has undermined the contention by the Reagan administration that the Soviet Union has systematically violated previous nuclear testing treaties and provides confidence in our technical ability to monitor yield limitation treaties. Thus, former objections to ratification of earlier treaties or negotiation of new,
more restrictive testing treaties are greatly diminished. However, the favorable political climate that allowed the JVE to take place may be imperilled by a rigid insistence by the current U.S. administration on extensive use of additional CORTEX monitoring. Unlike remote seismic methods, CORTEX is highly intrusive and expensive, requiring active foreign presence on the respective test sites. The JVE has swept aside many of the criticisms of seismic monitoring methods, which are much more acceptable to the Soviets (they have always been content to adopt seismic monitoring of U.S. tests). Seismic methods are also the only means for monitoring clandestine tests. While additional calibration with the CORTEX method will improve the reliability of seismological monitoring, the two procedures should be viewed as complementary rather than interchangeable. An appreciation of the scientific and political issues surrounding nuclear testing policy requires a consideration of the history of nuclear testing negotiations.

The Joint Verification Experiment has its roots in the tumultuous history of official nuclear testing negotiations between the U.S. and U.S.S.R., but its immediate catalyst was, in part, direct interaction between seismologists in the two countries. What do seismologists have to do with this? Well, seismology, the study of how elastic waves propagate in the Earth, assumed a central role in monitoring nuclear testing with the signing of the 1963 Limited Test Ban Treaty (LTBT), which banned atmospheric, oceanic, and deep space testing by the signatories. This drove all nuclear testing by the superpowers underground, where relatively few tests had been conducted since the first underground explosion in 1957. The seismic waves generated by an underground explosion propagate throughout the Earth and can be detected by ground motion monitoring instruments called seismometers. The seismic recordings provide the basis for detecting and locating an event, distinguishing an explosion signal from a natural earthquake signal, and estimating the energy release, or yield, of the explosion.

\[ N_E = \log \left( \frac{D}{R} \right) + b \]

Top: Recording of the short period P wave from the September 14, 1988, Soviet underground explosion made at station AAM, in Ann Arbor. The seismic magnitude is determined from the amplitude of the ground motion, after correction for instrument response. This station gives \( m_B = 6.2 \), while the global average of 113 stations gives \( m_B = 6.1 \). Typically, seismic yield estimates are made as shown at the bottom, by using an \( m_B \) yield calibration curve determined for events with known yields. This requires knowledge of any magnitude bias. The JVE provides a reliable \( m_B \) known yield point to set the baseline of the calibration curve.

Recognizing the emerging importance of seismology and our then primitive understanding of seismic wave propagation through the Earth, the Kennedy and Johnson administrations undertook a major expansion of University and private sector research in seismology and upgraded the world-wide network of seismometers, including the station in Ann Arbor operated by the Seismological Observatory in the Department of Geological Sciences.

Disagreements over on-site inspection restrictions and deployment of seismometers in the Soviet Union prevented the LTBT from specifying yield limitations for underground explosions. Explosions as large as 4,000 kilotons (kt) [1 kt = energy in 1000 tons of TNT; the Hiroshima weapon was 13 kt] were tested during the next 11 years, with seismology playing the major role in the respective U.S. and Soviet monitoring programs. Then, in 1974, during the last few months of the Nixon administration, the Threshold Test Ban Treaty (TTBT) was signed at the Moscow Summit. This treaty, which has not yet been ratified by Congress, restricts the yields of underground tests to 150 kt, as of March 1976. The TTBT imposed a new mandate on the monitoring community: verify compliance with the yield limitation. While several decades of seismological research had greatly enhanced seismological detection and identification of underground tests, there was less confidence in seismic yield estimation capabilities in the 1970s, which precluded Congressional ratification of the treaty.

Despite the concerns about our monitoring capabilities, the Carter administration had a commitment to achieve a Comprehensive Test Ban Treaty (CTBT), which would terminate all nuclear testing by the superpowers. Enforcement was to be based on deployment of seismometers in the U.S. and U.S.S.R., along with on-site inspection, both being issues that had been unpalatable to the security-conscious Soviets ever since the LTBT negotiations during the Kennedy administration. The Carter administration negotiations actually made substantive progress, but abruptly broke off with developments in Afghanistan and failure of the SALT II talks. The official policy during the first term of the Reagan administration was to not resume the CTBT talks and to assert that the Soviet nuclear testing activities since 1976 constitute a "likely violation" of the 1974 TTBT. The latter stance was based in large part on the official
yield estimates derived from seismological and other national technical means, such as satellite surveillance and military intelligence.

During these political developments, intense seismological research was greatly improving our understanding of the Earth and its effects on seismic waves from underground explosions. Seismic yield estimates are based on the amplitudes of seismic waves, which are proportional to the energy released by the explosion. The amplitudes must be corrected for propagation and recording instrument effects, and then they are used to compute logarithmic "magnitudes," analogous to the Richter magnitudes used for comparing the size of local earthquakes [an excellent reference is the Office of Technology Assessment report "Seismic Verification of Nuclear Testing Treaties," GPO Stock No. 052-003-01108-5].

It became increasingly clear that the same yield explosion at the Soviet and U.S. test sites would not result in the same magnitudes based on distant P waves (acoustic waves that propagate through the Earth). This is because of the high temperatures in the earth below the Nevada Test Site, which soften the rock and reduce the seismic wave amplitudes by a factor of about two, relative to the colder regions under the major Soviet sites. This phenomenon causes a "magnitude bias," which must be determined so that corrections can be applied to the magnitude, allowing a reliable yield estimate to be made. The magnitude bias can be estimated by comparing various magnitude scales, based on different types of seismic waves that have varying sensitivity to the temperature differences, but the most reliable procedure is to have "calibration," in which a device with a "reliably known" (i.e., directly measured) yield is detonated at the foreign site and the corresponding seismic magnitude measured.

During the early 1980s a vigorous debate developed between several prominent seismologists and the Department of Defense personnel responsible for official yield estimation for Soviet explosions. The seismologists contended that the official magnitude-yield relation did not incorporate a large enough value for the magnitude bias, thereby leading to an erroneous conclusion that the Soviets were systematically violating the TTBT. In the eyes of the administration, the reliability of the seismological procedures was tarnished by the successive downward revisions of the seismic yield estimates accompanying recognition of (and increasing estimated size of) the magnitude bias. The statistical confidence interval for seismic yield estimates, which had long been cited as a "factor of two," was discredited, given overall factor of 2 to 3 reductions in the yield estimates with time. This unfortunate situation arose because the science was advancing, with unanticipated information coming to light, at the same time as it was being called upon to serve in a policymaking role. Thus, the Reagan administration placed greater reliance on hydrodynamic means of yield estimation, with a nominal uncertainty factor of 1.3, despite the fact that the CORTEX methods are highly intrusive (an expensive drill hold at the foreign test site is required) and useless for preventing clandestine testing.

Suddenly, in 1986, the contentious domestic and international situation changed dramatically. Private negotiations between the Natural Resources Defense Council (NRDC) of Washington, D.C., and the Soviet Academy of Science led to non-governmental U.S. seismologists deploying modern seismic equipment at three locations within 150 km of the Kazakhstan test site, while reciprocal Soviet instruments were deployed in Nevada. This agreement, criticized by a representative of the U.S. administration as "an absurd private excursion," was achieved during the unilateral Soviet moratorium on nuclear testing, which lasted from August 6, 1985, to December 31, 1986. In a period of ongoing internal reform and glasnost, the Soviet Union had unexpectedly eliminated the long-standing obstruction in the official test monitoring negotiations regarding in-country deployment of seismic equipment by U.S. personnel. The main players on both sides were seismologists interested in overcoming this obstacle in the monitoring negotiations.

At the same time as the National Resources Defense Council initiative,

Explanation of magnitude bias. For explosions of the same yield in the same rock type at the two test sites, the seismic magnitude will be 0.3-0.4 magnitude units lower for the U.S. explosion because the P waves are attenuated (diminished in amplitude) by propagating through the hotter rock beneath the U.S. test site.
repeated contacts between official U.S. and Soviet representatives were reopening the possibility of developing further limitations on nuclear testing, and resolving the question of possible Soviet violation of the 1974 TTB T. On September 17, 1987, a joint statement by the two countries proposed that verification experiments be conducted to validate the monitoring capabilities required for ratification of the TTB T. By the time of the December 1987 Washington Summit, the plans included the first ever mutual, on-site determinations using hydrodynamic methods. The NRDC activity had apparently broken the long-standing resistance to in-country personnel and equipment deployments near the test site, or at least served as a useful precedent. The final version of the JVE was signed at the Moscow Summit on May 31, 1988, only a few months prior to the actual tests.

An additional provision of the JVE agreement provided for exchange of yield information, seismic records, and geological data for five earlier tests by each nation. The 1974 TTB T had stipulated a similar exchange for two events each, but this had never taken place. Five seismic stations with long operating histories, including the station in Ann Arbor, were selected for the historic data exchange, along with exchange of recordings of the two JVE tests.

Following the precedent set by the NRDC deployment in 1988, five more state-of-the-art seismic stations were deployed in the Soviet Union by the 61-University consortium Incorporated Research Institutions for Seismology (IRIS), of which the University of Michigan is a member. This deployment was formally supported by the administration, and ongoing plans by IRIS and the U.S. Geological Survey involve expanding the number of U.S. seismic stations to more than 10 in the next two years. The data collected by this network will not only provide means for nuclear test monitoring to very low (10

kt) yield thresholds, but will also greatly increase our understanding of earthquake activity in the Soviet Union, such as the recent devastating Armenian event.

The Joint Verification Experiment has provided a reliable calibration of the magnitude-yield relation for the primary Soviet test site. This allows us to confidently assign the correct magnitude bias to events in the same test site with yields near the Threshold Test Ban Treaty limit. Preliminary disclosure of the Soviet JVE yield estimates in the New York Times (Oct. 30, 1988) indicate that the validated magnitude bias is in fact almost identical to that advocated by the seismologists during the acrimonious debates in the early 1980s. This strongly supports the seismologists' contention that Soviet testing was not in violation of the 1974 TTB T, thereby opening the door for Congressional ratification of that treaty. The heightened confidence in the seismic yield estimation capabilities, coupled with the presence of numerous U.S. seismic systems in the Soviet Union, eliminates several of the technical obstacles to pursuing test bans with lower yield thresholds, and perhaps eventually a Comprehensive Test Ban Treaty.

Negotiations subsequent to the JVE have focussed on use of CORRTEX for the larger explosions at either test site, involving a tremendously expensive and intrusive process (the JVE CORRTEX experiments cost $28 million, and subsequent tests will cost $10 million each). From a scientific point of view, the JVE constituted a multi-million dollar test of the seismological hypothesis of "magnitude bias," which was fully confirmed. While the seismological yield estimation procedures would significantly benefit from additional calibration events, the accuracy of seismological techniques is rapidly converging on a factor of 1.3 uncertainty achieved by CORRTEX. Seismology will continue to provide the only means for monitoring off-site or clandestine testing, and is relatively inexpensive. Indeed, the administration's preference for CORRTEX was strongly tested by the Nevada explosion component of the JVE. In that case, the seismic methods gave a yield estimate close to the predicted yield of 145 kt, but CORRTEX reportedly gave an estimate above 150 kt, embarrassingly in apparent violation of the 1974 treaty, unless allowance is made for the factor of 1.3 uncertainty.

After nearly 30 years of negotiations, the Soviets abruptly swept aside their objections to the major U.S. requirements for most nuclear testing treaties involving in-country seismic equipment, on-site verification, and data exchange. This coincided with the more publicized progress on eliminating intermediate range weapons provided for by the INF treaty. Undoubtedly the complex political developments in the U.S.S.R. created a more responsive policy toward nuclear testing negotiations. It seems very unlikely that the Soviets ever would have agreed to the JVE had they actively violated the 1974 TTB T, and there was certainly some political mileage to be gained by having compliance confirmed.

The issues of whether additional testing restrictions are beneficial or harmful to national security are complex and technical, but thanks to the efforts of the seismologists and Geneva negotiators, a first generation of the necessary technical means for verifying existing and future test ban treaties is largely in place. Rigid insistence on exclusive monitoring using CORRTEX is likely to slow progress in any negotiations; given the outcome of the JVE, the administration should reappraise the potential for accurate yield estimation and monitoring with seismic methods.

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