

SOURCE PHYSICS EXPERIMENTS AT THE NEVADA TEST SITE

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ABSTRACT

The U. S. capability to monitor foreign underground nuclear test activities relies heavily on measurement of explosion phenomena, including characteristic seismic, infrasound, radionuclide, and acoustic signals. Despite recent advances in each of these fields, empirical, rather than physics-based, approaches are used to predict and explain observations. Seismologists rely on prior knowledge of the variations of teleseismic and regional seismic parameters such as p- and s-wave arrivals from simple one-dimensional models for the teleseismic case to somewhat more complicated enhanced two-dimensional models for the regional case. Likewise, radionuclide experts rely on empirical results from a handful of limited experiments to determine the radiological source terms present at the surface after an underground test. To make the next step in the advancement of the science of monitoring we need to transform these fields to enable predictive, physics-based modeling and analysis.

The Nevada Test Site Source Physics Experiments (N-SPE) provide a unique opportunity to gather precise data from well-designed experiments to improve physics-based modeling capability. In the seismic experiments, data collection will include time domain reflectometry to measure explosive performance and yield, free-field accelerometers, extensive seismic arrays, and infrasound and acoustic measurements. The improved modeling capability that we will develop using this data should enable important advances in our ability to monitor worldwide for nuclear testing. The first of a series of source physics experiments will be conducted in the granite of Climax Stock at the NTS, near the locations of the HARD HAT and PILE DRIVER nuclear tests. This site not only provides a fairly homogeneous and well-documented geology, but also an opportunity to improve our understanding of how fractures, joints, and faults affect seismic wave generation and propagation. The Climax Stock experiments will consist of a 220 lb (TNT equivalent) calibration shot and a 2200 lb (TNT equivalent) over-buried shot conducted in the same emplacement hole. An identical 2200 lb shot at the same location will follow to investigate the effects of pre-conditioning.

These experiments also provide an opportunity to advance capabilities for near-field monitoring, and on-site inspections (OSIs) of suspected testing sites. In particular, geologic, physical, and cultural signatures of underground testing can be evaluated using the N-SPE activities as case studies. Furthermore, experiments to measure the migration of radioactive noble gases to the surface from underground explosions will enable development of higher fidelity radiological source term models that can predict migration through a variety of geologic conditions. Because the detection of short-lived radionuclides is essential to determining if an explosion was nuclear or conventional, a better understanding of the gaseous and particulate radionuclide source terms that reach the surface from underground testing is critical to development of OSI capability.

Note: The upcoming Nevada Test Site Source Physics Experiments (N-SPE) should not be confused with the 2003 Source Phenomenology Experiments (SPE) conducted in Arizona (Yang and Bonner, 2009).

OBJECTIVES

The Source Physics Experiments (N-SPE) will enhance the DOE National Nuclear Security Administration's (NNSA) efforts related to verification, arms control and nonproliferation, by providing computational improvements in our ability to predict ground motion, gas flow and nuclear cavity dynamics, and enhance our ability for near-field monitoring and on-site inspection. This predictive capability combined with advanced capabilities to compute synthetic seismograms through three-dimensional models of the earth will move monitoring science into a physics-based era. This capability should enable important advances in our ability to monitor worldwide for nuclear testing. Furthermore, the combination of the improved understanding of the source with the advanced ability to model synthetic seismograms in three-dimensional earth models should also lead to advances in the ability to locate and identify events. NNSA will conduct focused activities at the Nevada Test Site (NTS), which is the preferred location to conduct high-hazard experiments that are vital to our national security. Nuclear Security Technologies (NSTec), in its role as operations management for NTS will partner with the NNSA, and the DOE Nevada Site Office (NSO). The Defense Threat Reduction Agency (DTRA) will also play an important role in the N-SPE experiments. DTRA has expertise in the areas of explosive emplacement, detonation, and diagnostics, as well as in fielding instrumentation for recording explosion-related phenomena. This experiment series is sponsored by NA-22 (Nonproliferation and Verification Research and Development office), and provides an opportunity for collaborative experimentation at NTS among NSTec, and the NNSA National Laboratories, Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (SNL) for addressing many national nuclear nonproliferation and security R&D "Theme Areas," such as the Comprehensive Nuclear-Test-Ban Treaty (CTBT), Fissile Material Cutoff Treaty (FMCT), Nuclear Forensics, and START. The first "Theme Area" of CTBT is being addressed through a series of source physics and on-site inspection experiments.

RESEARCH ACCOMPLISHED

Building on the accomplishments of previous relevant field experiments such as the Non-Proliferation Experiment (NPE, 1994) and the Arizona Source Phenomenology Experiments (Yang and Bonner, 2009), the N-SPE series of chemical explosions is designed to gather specific ground truth information. These data are needed to fill knowledge gaps in our understanding of shear-wave generation by explosions, for improving numerical analysis, and to test and validate seismic explosion source and wave propagation models. NNSA has begun a multi-year research program beginning in FY2010 with technologies to simulate complex phenomenologies associated with explosions conducted in realistic geologic media. The N-SPE research includes geophysical characterization, geodynamic modeling (including strong shock propagation, seismic wave generation, and seismic wave propagation), infrasound measurements, near-field monitoring technologies (including on-site inspection, hyperspectral imaging, lidar, and InSAR), electromagnetic sensors, and noble gas migration.

Key research objectives related to understanding the prompt nuclear explosion phenomena that can be addressed through NTS experiments include:

- Model validation, e.g., explosion source physics, coupling, s-wave generation, energy propagation, and gas migration,
- Effects of explosion emplacement configurations and conditions,
- Differentiation between conventional and nuclear explosions,
- Detection and analysis of radiation transport mechanisms,
- Detection of testing-related operations and facilities (machinery, infrastructure, etc.),
- Detection of electromagnetic signatures from nuclear-related work, and,
- Unification of local, regional, and global monitoring technologies.

Key technologies include:

- Seismic
- Infrasound
- Seismo-acoustics
- Radionuclide sampling (particulates and noble gases)
- Energetic particles
- Radiation survey (x-rays, gamma rays)
- Electro-Magnetic Pulse

Current monitoring systems, including those of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), focus on long range monitoring of relatively large nuclear explosions. Near-field monitoring and OSI access to a suspected test site will greatly improve information about testing activities and phenomena, especially for smaller, nuclear and non-nuclear explosions. To be an effective deterrent, the OSI technologies and techniques need the benefit of scientific and operational credibility. This can only come through development and demonstration of capability.

Key research objectives related to post detonation evidence that can be addressed through NTS experiments include:

- Explosion effects detection and documentation,
- Methods to identify key inspection areas of interest
- Effectiveness of near-field monitoring and OSI geophysical techniques,
- Development and evaluation of prototype sensor systems,
- Advanced data analysis techniques that are faster, more sensitive, more selective,
- Performance estimation software development,
- Transport and deposition of materials of interest,
- Radionuclide sample collection and analysis at, or near, the collection site.

Key technologies include:

- Visual inspection,
- Geophysical techniques (seismic, electrical, magnetic, etc.) to detect surface and underground anomalies,
- Soil gas sampling and analysis,
- Environmental sampling and analysis,
- Radiation survey,
- Remote sensing techniques to support OSI,
- Collection of samples from strategic locations in a timely manner,
- Analysis of samples quickly and accurately, and
- Identification of morphological, chemical, and isotopic signatures.

Motivation and Opportunity

Monitoring and verification issues are a fundamental part of this NTS research. The NNSA laboratories possess an extensive collection of verification seismic data for near- and far-field seismic data, and the NTS provides the ideal setting for field experiments. The local seismic networks provide the basis for optimal sensor placement and performance specifications required for effective seismic monitoring. Electromagnetic pulse (EMP) and radionuclide sensor technology will be used in controlled source experiments to determine detection thresholds. Current lab expertise regarding ground-based visual observations, geophysical techniques, and other OSI supporting technologies such as hyperspectral imaging will significantly add to the US efforts in detection and monitoring. The ability of the U.S. to effectively verify nuclear testing treaties is heavily dependent on our experience, innovative application of technologies, and validation of those technologies via demonstration tests. The planned experiments involve moderate to large quantities (kilograms to 1000s of kilograms) of high explosives.

Source Physics Experiments

The N-SPEs will support computational improvements in our ability to predict ground motion, gas flow, nuclear cavity dynamics, and surface effects. The effective use of the limited testing resources will require predictive calculations and then a verification and validation component. The NNSA laboratories have a long history and extensive earth materials database to support explosive testing and experiments. Along with historic DoD study results (e.g. Defense Nuclear Agency (now DTRA) tests and Soviet data), the proposed work will advance our ability to model and predict phenomena from tests in various environments. Fundamental questions regarding the effects of depth of burial and the generation of shear waves by explosive sources will be answered through the combined experimental and computational research.

The source physics experiments will be well-instrumented with both near- and far-field measurements to provide an outstanding dataset that will allow us to advance our understanding of the basic physical processes that affect the seismic signal generated by an underground explosion. Time-domain reflectometry measurements will provide information about explosive performance and yield, and free-field accelerometers will provide information about

source conditions and strong shock propagation. Data collected from an extensive array of seismometers, with good azimuthal coverage, will give us the ground truth necessary to fully comprehend the mechanisms for shear wave generation. Additional instrumentation, including infrasound and EMP sensor, will further enhance our understanding of underground explosion phenomenology.

Development of high performance hydrodynamic modeling will allow us to predict and enhance our understanding of coupling experiments conducted in simple (e.g., Climax Stock) and complex (e.g., U16b) geologies. Experiment datasets will then be used to validate equations of state for hard rock, further populate parameter spaces (rock type, cavity geometry, source type, etc.), and improve the understanding of seismoacoustic coupling and propagation and its implications for monitoring explosions under the CTBT.

Experimental plan: The N-SPE is a series of physics experiments involving buried explosives. The N-SPE provides a unique opportunity to gather precise data on well-designed experiments to test and enhance our modeling codes.

The first source physics experiments will be conducted in the granite of Climax Stock, near the locations of the HARD HAT and PILE DRIVER nuclear tests (Figure 1). This site not only provides a fairly homogeneous and well-documented geology, but also an opportunity to improve our understanding of how fractures, joints, and faults affect seismic wave generation and propagation. The Climax Stock experiments will consist of a 2200 lb (TNT energy equivalent) calibration shot and an over-buried 2200 lb (TNT energy equivalent) shot conducted in the same emplacement hole. Ideally, an identical 2200 lb follow-on shot would be conducted at the same location to investigate the effects of rock pre-conditioning.

Subsequent experiments in this series over the next few years will likely vary in source strength, emplacement configuration, sensor placements and be conducted in different geologic settings.

Conceptual Source Physics Testbed

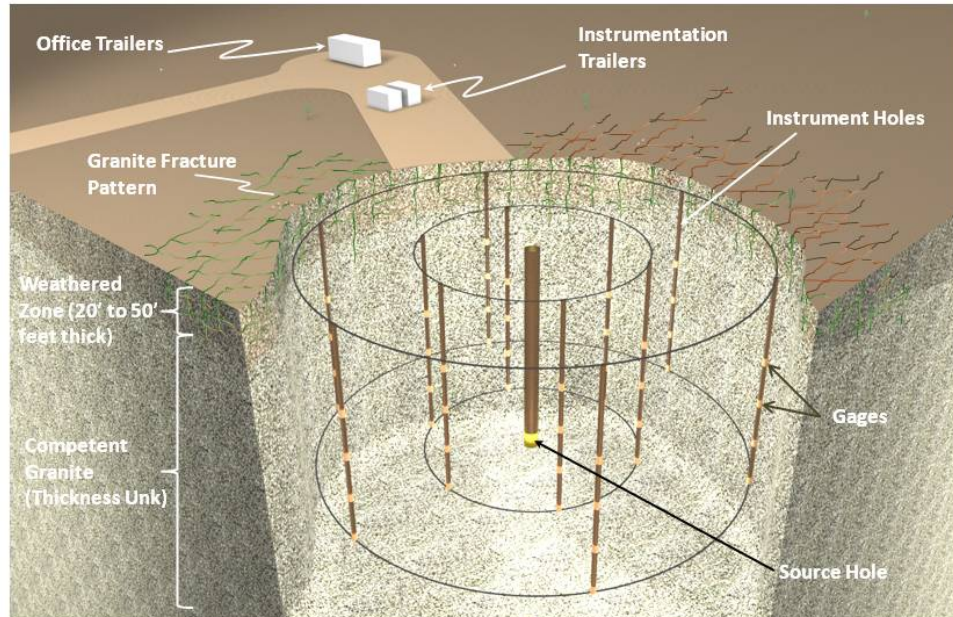


Figure 1. The first N-SPE test in Climax Stock granite will consist of a 65-meter deep emplacement hole and six instrument holes, three at 10 meters from the emplacement hole and three at 20 meters from the emplacement hole.

There are three major elements of the initial N-SPE efforts. These are geophysical characterization, hydrodynamic and seismic source modeling, and near-field monitoring technologies.

Geophysical characterization: Geophysical methods provide information about the physical properties of the subsurface. There are two general types of methods: 1) active, which measure the subsurface response to seismic, electromagnetic, and electrical energy; and 2) passive, which measure the earth's ambient magnetic, electrical, and gravitational fields. Geophysical methods fall into several broad categories including seismic methods (e.g., refraction, reflection, and tomography), ground-penetrating radar (GPR), electrical methods [e.g., electromagnetics (EM), electrical resistivity, induced polarization (IP) and self potential (SP)], and potential field methods (e.g., gravity, geoid, and magnetics). In addition, the tectonic history will be included for a comprehensive geophysical characterization.

Geophysical data are often difficult to interpret. For any given set of geophysical data a variety of subsurface conditions or parameter distributions can explain the data (i.e., solutions are not unique). The proper way to interpret geophysical data is to use the measured parameters as a description of a suite of solutions that can be used in combination with other site information (e.g., data from different geophysical methods, sampling and analytical tools, geological and historic records, anecdotal information) to arrive at the most plausible solution.



Figure 2. A variety of geologic and geophysical data will be combined to create a geologic framework model for the Source Physics Experiments in Climax Stock granite.

The interpretation of the geophysical data will be used to build a geologic framework model (Figure 2). This model will include stratigraphic layers, physical and material properties, ambient stresses, and surface topography. The model will then be meshed for use by the hydrodynamic modelers.

Modeling: Our goal is to develop analytical and simulation capabilities that will provide a physical basis for modeling the important facets of explosion phenomena (Figure 3). The important components of our approach include 1) utilizing three-dimensional fully-coupled strong motion hydrodynamic codes that will allow us to explicitly model near source finite displacement on faults as well as surface spall/slapdown (the gravitationally derived signal from lofted earth material) that is an important source of shear waves; 2) developing and implementing models that will allow us to realistically treat the microcrack releases that dominate near-source energy; 3) coupling the strong motion code to higher order spectral element codes with variable gridding to accurately model the effect of surface topography; 4) coupling our hydrodynamic calculations to seismic source models that utilize Compensated Linear Vector Dipole (CLVD) models in order to unequivocally separate source-generated shear waves from scattering-generated shear waves; and 5) using a coupled Eulerian Lagrangian approach to model decoupled shots or shots near voids or rubble columns where the momentum transfer at the air-rock interface plays a crucial role in energy coupling, shock propagation, and permeability to radioactive gases.

The combination of these efforts will provide a unique and unified capability to model nuclear explosions in realistic conditions including complex layering, uneven topography, pre-existing stresses, hard rock with fractures, joints, and faults, pre-conditioned rock, and cavities, rubble shields and other scenarios. All of these conditions are

extremely relevant to our efforts to understand and monitor underground nuclear test activities at test sites of interest.

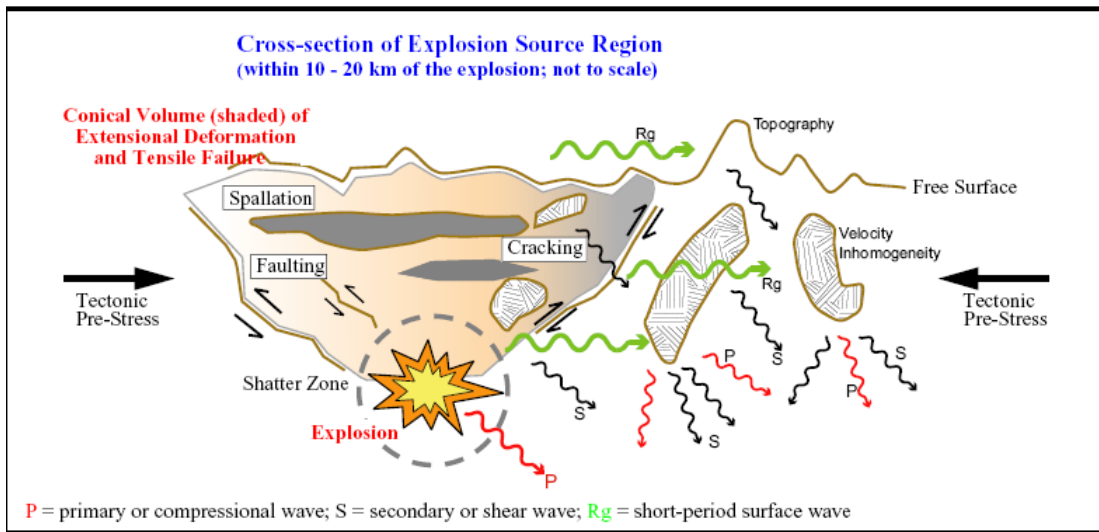


Figure 3. Currently employed simple seismic source models of nuclear explosions are inadequate for addressing the ever more challenging monitoring requirements. New models will include source complexities of tensile failure and near-source scattering.

Near-Field Monitoring and OSI Technologies: Experiments to investigate and validate near-field monitoring and OSI techniques will greatly enhance the understanding of the efficacy of these techniques. OSI is one of the verification elements specified in the CTBT. Once a general search area has been determined by other monitoring technologies (e.g., seismic), the challenge of OSI is to detect, identify, and describe features (Figure 4) in order to clarify whether a nuclear explosion in violation of the CTBT has occurred. The treaty allows specific inspection techniques that must be applied during a limited time frame. OSI includes visual observation, geophysical, and radiological techniques. Visual observation also involves the identification and documentation of features and activities that are part of the support operations associated with nuclear testing. The conduct of a high explosive experiment at the NTS will be a surrogate to a nuclear test to determine the types of observables that are associated with the conduct of the explosion. Some of the OSI geophysical methods (active seismic, gravity, electrical, magnetic, etc.) are not well understood for OSI applications. Experiments to explore and validate techniques will greatly enhance the understanding of the efficacy of these techniques for OSI. NTS as a former nuclear explosion test site is uniquely suited to be a test bed for near-field monitoring and OSI verification techniques. The application of these techniques in conjunction with the enhanced understanding of field deployments issues will then become more effective in addressing the objective of the field activity. The general concept of operations for an OSI requires narrowing the possibly 1000-km² search area down to smaller, focused areas of interest, with the possibility of further selecting a specific site for drilling to obtain radioactive samples (Figure 5).

Visual observation (VO) methodologies can increase the effectiveness of OSI and will be integrated with an N-SPE. The specific objective is to calibrate near-field manifestation of visual observables by analyzing the degree of surface feature expression as a function of experimental design. To fully realize the results of N-SPE, assessments of the geological and geomorphological features are required to analyze source conditions. Changes in these characteristics that occur as a result of the experiments need to be thoroughly documented and quantified.

Passive seismology survey lines of seismometers over an explosion ground zero will be used to detect and record aftershocks. Data would be collected through the period where individual aftershocks can no longer be detected, but background noise levels will continue to be measured at individual stations to determine if an elevated background noise signature persists for a long time after detonation in the area near ground zero. An active seismic experiment

using either an explosive or non-explosive source, would establish the effectiveness of seismic instruments to detect and locate the damage zone of the explosion. Areal multispectral/infrared imagery can be acquired before and after an explosion to determine the usefulness of this type of imagery for detection of disturbed ground. Relatively shallow surveys with DC resistivity or electromagnetic methods after the explosion will provide an assessment of the contrast of electrical properties in the damage/rubble zone indicating the relative level of resolution of the technique for damage/rubble zone detection and characterization. These methods will provide baseline knowledge that will be valuable supporting information for the modeling efforts.

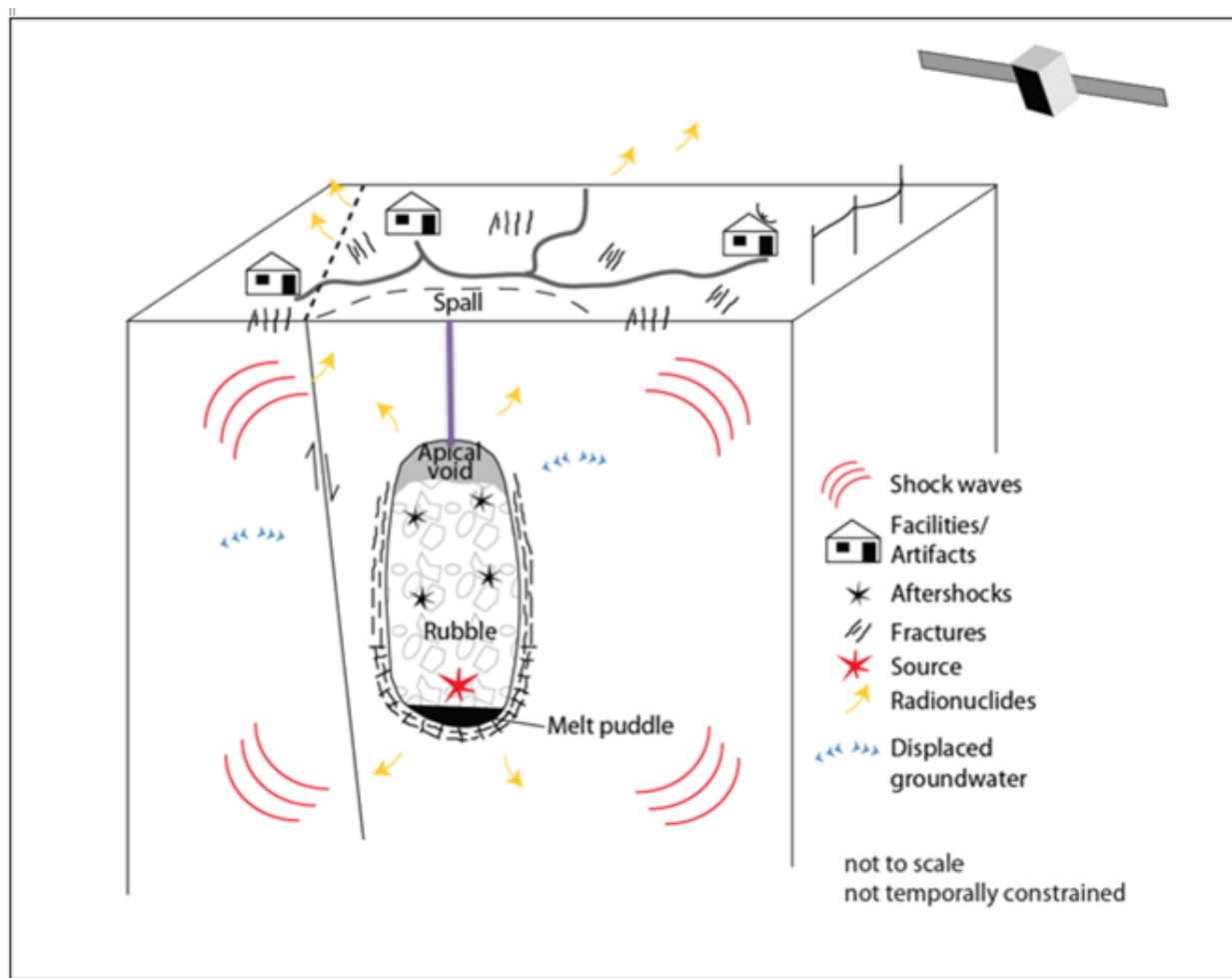


Figure 4. Potential observables from an underground nuclear explosion that may be detected and described using near-field monitoring and OSI technologies.

Hyperspectral Imaging, LIDAR and Laser scanning (HILL) is an especially powerful technology for evaluating transparency, quantifying N-SPE effects, and improving the effectiveness of OSI. HILL technology will provide and preserve a high-resolution, digital, dynamic-range, scale-variable dataset that has vast applications; for example, HILL data can be integrated with historical NTS data into a searchable, interactive observable phenomena atlas/database. Underground nuclear detonations can carry volatilized materials away from the source through fissures to the surface, Hyperspectral thermal imaging may also provide additional spectral signatures and emissivity changes that could result from disturbed soil.

Observable explosion effects are variable and depend upon several parameters including: emplacement site material properties, experiment design, explosive yield, depth of burial, and tamping. Consequently, N-SPE effects will

drastically range in scale and demonstrate the fact that an apparent lack of explosively produced effects may be a resolution artifact. Experimentation of HILL technology and further development will augment the systematics required to produce objective, repeatable, and quantifiable documentation during OSI. Given that NNSA laboratories possess a large collection of verification seismic data for near- and far-field seismic data, HILL technology is a complementary dataset that will allow for improved modeling and predictive capabilities. HILL technology would significantly reduce personnel time within potentially dangerous field situations, and provide a dramatic savings in person-hours and equipment/field costs. Current LANL expertise regarding ground-based visual observations and other field-based technologies will significantly add to the US ability for monitoring and transparency.

During near-field monitoring and on-site inspection the monitoring technologies and inspectors look for radioactive debris that has escaped an underground nuclear explosion and settled on the surface near and downwind of ground zero. For development of OSI capability, it is necessary to understand the surface source term created by short-lived particulate radioactive debris. There is much data available regarding the type and quantity of airborne particulate radioisotopes that were detected off-site during the era of nuclear testing at NTS. However, there is a dearth of data on near-field debris distributions for underground tests in which venting occurred.

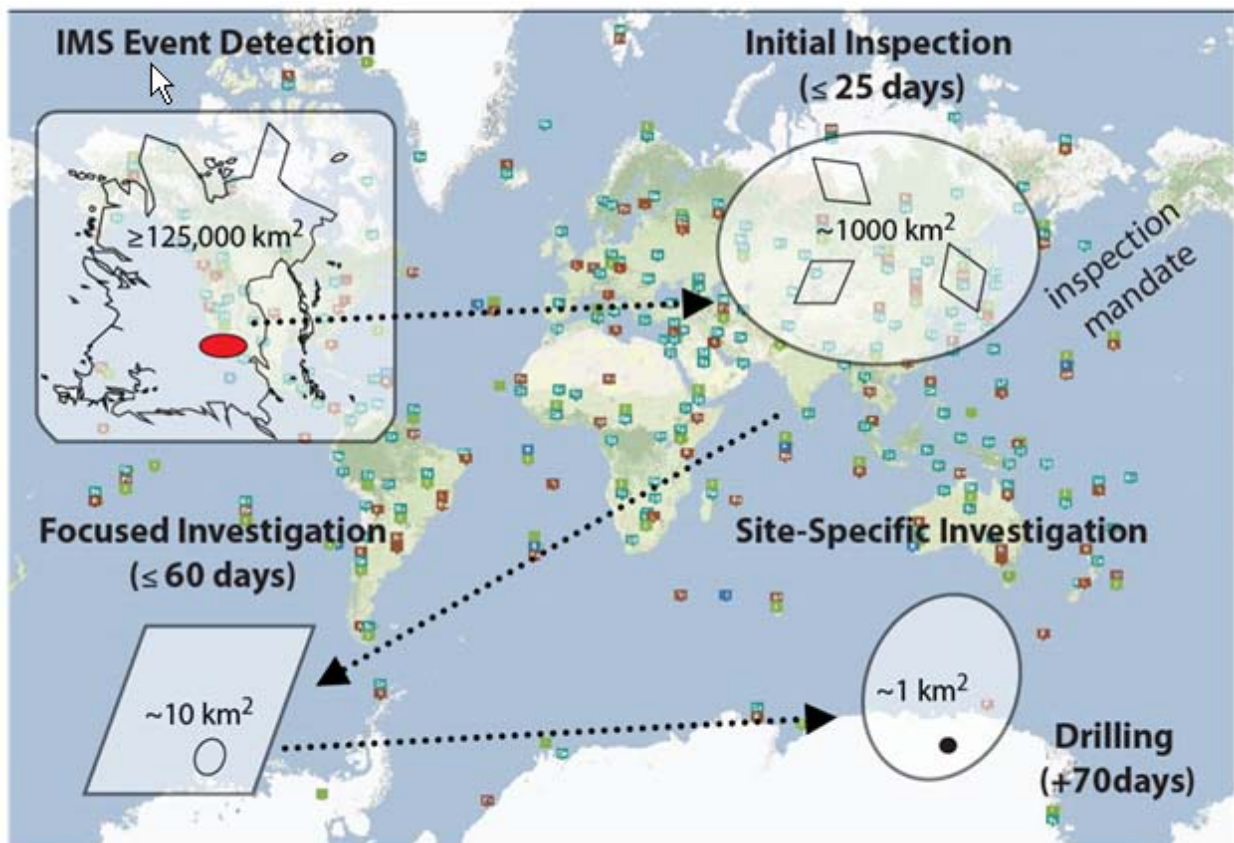


Figure 5. The primary objective of CTBT On-Site Inspection activities is collect evidence to clarify whether a nuclear test in violation of the treaty occurred. The concept of operations requires narrowing the search area (up to 1000^2 km) to identify areas for detailed investigation that includes sampling for radioactive gases and particulates in the soil. Drilling may also be conducted to search for underground radioactive material near a suspected test cavity.

Atmospheric transport and search methodology studies will help in determining instrument sensitivity requirements, developing concepts of operations, evaluating sampling methodologies, estimating instrument performance

(including spectral blinding techniques), and validating the list of relevant radionuclides for CTBT OSI. A release of short-lived isotopes (e.g., via shallow underground chemical explosion, direct spraying, or other controlled release) will be used for high-fidelity radiometric measurements at the surface with no permanent contamination introduced to the site. Radioactive debris will decay to below background levels within 1 year.

Various search strategies will be evaluated using gamma-ray spectroscopy equipment over the short-lived debris field via *in situ*, handheld, mobile, and aerial platforms. In addition, environmental sampling from the proposed site will occur before the execution of the experiment and then immediately after at predetermined locations. Sampling will consist of surface soil samples, swipes across exposed surfaces and continuous air sampling via a whole air particulate sampler. The samples will then be measured on existing spectrometry systems, including ultra-low-background gamma-ray detectors. Isotopes under consideration include a combination of treaty-relevant nuclides and other short-lived species that can be conveniently produced.

National Security Benefits of the N-SPE

The Source Physics Experiments will contribute significantly to our ability to detect, locate, identify and understand underground nuclear explosion phenomena. This understanding will assist the US in exploiting many data sources including: the International Monitoring System, the U.S. Atomic Energy Detection System, local and regional arrays, and National Technical Means. These experiments will add significantly to our predictive modeling capabilities and will greatly improve our understanding of emplacement, deployment, and processing techniques for sensors as well as the application of other monitoring technologies. Finally, the experiments proposed herein will greatly improve our ability to interpret, and potentially predict, signals from global events such as in the ever-expanding number of regions of interest for our national security.

The primary user of the increased understanding gained by this research is intended to be the Air Force Technical Applications Center (AFTAC) in their role as the US National Data Center. High performance modeling of the near source environment will give researchers improved source models which will translate into operational improvement for AFTAC's mission. Other potential users include other governmental agencies, such as the State Department for treaty verification (e.g., CTBT, TTBT and NPT), and DTRA for non-proliferation and site specific database development. It is expected that the user base will expand as more interests and applications arise as a result of greater understanding of source region effects on seismic radiation and general understanding of coupling, including near-field monitoring and OSI.

Seismic data are used by AFTAC to detect, locate, and identify earthquakes from explosions in their national mission of ground-based nuclear explosion monitoring (GNEM). Seismic yield estimation is an important function of their GNEM mission. Problems facing accurate yield estimation have new challenges due to (a) inherent difficulties monitoring broad areas, and (b) different approaches to testing taken by today's proliferant nations. A common thread in all of these challenges is greater uncertainty posed by unknowns surrounding geologic conditions of the source and uncertainty in the regional propagation effects. In the past, improvements in yield estimation for known test sites could be made through research that exploited empirical calibrations better. But today a proliferant nation by definition will not have tested many (or any) nuclear explosives. There is a great need to improve our yield estimation capabilities by developing a stronger physical basis for traditional and emerging methods. This includes and requires better understanding of how earth materials behave in the strong shock environment and how this behavior affects the propagated seismic wave field. These improved material models, implemented in numerical simulations of nuclear tests, will fill the gaps in our observationally based empirical models and, in doing so, make better quantification of error bounds and better corrections to yield estimates when information about source emplacement and geologic conditions is available.

Many data, analysis, and numerical simulation products coming out of N-SPEs will be integrated into a new explosion source model framework with the ultimate goal being a Source Prediction Capability for global monitoring applications (Figure 6). These experiments will also serve as the foundation for future efforts, including: the effect of different rock types at and near the source and along the propagation path, the range of energy densities and how this affects both containment prospects and detection probabilities, the effect of cavity geometry, explosive source equation of state and burn rate, and near-source phenomenology (including seismic wave conversion).

Toward an Explosion Source Prediction Capability for Seismic Monitoring

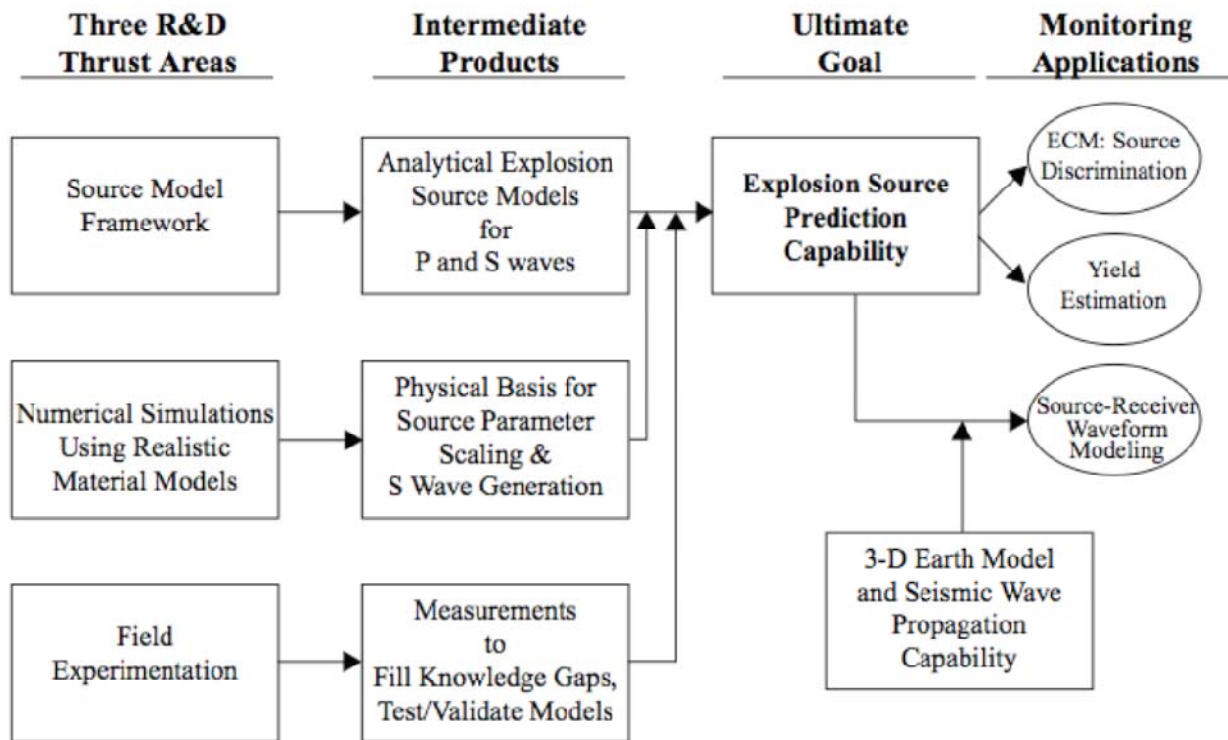


Figure 6. Source model development integrating data, analysis, and numerical simulation products resulting in an Explosion Source Prediction Capability for global monitoring applications including event identification, yield estimation, and end-to-end modeling for special event analysis.

CONCLUSIONS AND RECOMMENDATIONS

The execution, data collection and analysis, and modeling of the NTS Source Physics Experiments will produce results that will lead to significant improvements and breakthroughs in our capabilities and understanding in several areas:

- The experiments will provide valuable information about the expected detection threshold for events in hard rock with a number of monitoring technologies, utilized both separately and in combination, including seismoacoustic, radionuclide, geodetic, imaging, and electromagnetic methods.
- We will gain valuable experience in how to design and field sensors and sensor arrays, collect, process and analyze sensor data, and optimize the deployment and placement of sensors under a variety of conditions. It is expected that novel sensor technologies as well as modeling and signal processing techniques will be developed. Forensic analysis of all the signals will lead to a probabilistic approach to our capabilities and confidence in the event detection and discrimination.
- These experiments could serve to develop cost effective experimental designs for explosion monitoring and proliferation detection data acquisition. Over 20 years of proliferation and explosion monitoring research has led to scientific questions on theory and model development/validation that are best resolved with well designed experiments. Experimental cost efficiencies can only be realized with well-designed experimental campaigns that have multiple uses and are based on proven statistical experimental design theories. Properly applied, these theories target an experimental campaign to relevant research questions through a mathematical down select of less relevant questions.
- Development of greatly improved weapons effects modeling capabilities will be based on a better physical understanding of the behavior of explosives, rock, and man-made structures. Gaps in current datasets will

be filled in to provide a basis for dimensional analysis of the effects of: source size and geometry, burn rates, energy density, geologic setting, signal generation and propagation paths such that predictive capability can be improved for events in different geologic scenarios with varying sources, yields, and emplacement geometries. In particular, our plan to evaluate the modulating effects of the ambient tectonic stresses, inherited geologic features, and the effects of topography-induced anisotropic responses to shock propagation, will improve detection capabilities for any potential proliferant nations' test sites.

- In the absence of dynamic experimentation for stockpile stewardship, these experiments will also serve to continue improving our understanding of containing underground explosions with a rather unique approach to testing our numerical predictions, fielding of newer sensors and materials, and provide valuable first-hand experience for containment science.
- OSI is one of the critical verification elements for the CTBT. The challenge of OSI is to detect, identify, and describe features that may indicate that a nuclear explosion in violation of the CTBT has occurred. Experiments to investigate and validate near-field monitoring and OSI techniques will greatly enhance the understanding of the efficacy of these techniques.

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Large field activities like the Source Physics Experiment require the cooperation of individuals from many organizations. We thank each of the team members for contributing their particular expertise to make the N-SPE benefit multiple objectives with each explosive shot.

REFERENCES

- Symposium on the Non-Proliferation Experiment: Results and Implications for Test Ban Treaties, CONF-9404100, (1994), <https://na22.nnsa.doe.gov/cgi-bin/prod/nemre/index.cgi?Page=Symposium+1994>
- Garwin, R. L., and F. N. von Hippel (2006). A Technical Analysis of North Korea's Oct. 9 Nuclear Test, Arms Control Today, November 2006.
- Garbin, H.D. (1997). Diamond Fortune Seismic Attenuation Measurements, Sandia National Laboratory Report, SAND96-2544 UC-703.
- National Academy of Sciences (2002). Technical Issues Related to the Comprehensive Nuclear Test-Ban-Treaty, *National Academy Press*, 2101 Constitution Avenue, N.W. Washington, D.C. 20418.
- U.S. Congress, Office of Technology Assessment (1988). Seismic Verification of Nuclear Testing Treaties, OTA-ISC-361 (Washington, DC: U.S. Government Printing Office, May 1988).
- Karlykhanov, N.G., et al., (2004). Magnetic Dipole Moment from a One-kiloton Underground Nuclear Explosion in a Cavity, *J. Appl. Mech. Tech. Phys.* 45: No. 3, 311–315.
- Richards, P.G. and W. Kim, (2009) Monitoring for Nuclear Explosions, *Scientific American*, March 2009, Vol. 300, no 3, pp 64–71.
- Yang, X. and J. L. Bonner, 2009 Characteristics of Chemical Explosive Sources from Time-Dependent Moment Tensors, *Bull. Seismol. Soc. Am.* 99: No. 1, pp. 36–51.