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The Source Physics Experiment (SPE) Science Plan

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Note: *This science plan was initially written the early days of the SPE project, roughly in 2014. It has required only slight updating (e.g., dates, executed shot specific parameters) as we completed the execution of SPE Phase I and II, and started work on Phase III.*

Project Description

The Source Physics Experiment (SPE) series is a long-term NNSA research and development effort designed to improve U.S. arms control and nuclear nonproliferation verification and monitoring capabilities. The findings from the SPE will advance the United States' nuclear explosion monitoring capabilities, particularly with respect to detection, discrimination and determination of yields associated with small nuclear explosions that can be lost amid the noisy seismo-acoustic background from other sources. The data generated from the SPE, a series of well-designed and recorded chemical explosions, will contribute to the development and validation of first-principles explosive source generated seismo-acoustic modeling codes. These codes will then facilitate the update of semi-empirical methods, currently based on historic test site data, such that key explosion observables can be reproduced, thus improving confidence in nuclear test monitoring in new areas and/or under novel emplacement conditions. The overall SPE project is comprised of both the development of the new explosion simulation codes and the chemical explosion test series. The chemical explosion test series will generate the empirical data required to both develop and validate the new simulation codes.

Scientific Basis

Current explosion source models used in monitoring are based primarily on historic measurements from test sites, where a variety of factors limited the range of geologic locations and emplacement conditions. For example, Figure 1 shows nuclear test data at the former Nevada Test Site (NTS) in terms of magnitude (which correlates with explosion size or yield) and absolute depth of burial. Note that the data come from a limited range of depths as a function of size. Scaled depth of burial (SDOB) is actual depth of burial divided by the cube root of the explosion's yield. Most NTS events fall close to values near 120 $m/kt^{1/3}$ (e.g., Gladstone and Dolan, 1977). Values of SDOB much greater than the "normal" 120 $m/kt^{1/3}$ are considered "overburied". There is very limited data available for small and/or over-buried events as shown in Figure 1. Furthermore, there is reason to be concerned about the ability to characterize explosions outside of our primary experience near the standard SDOB as shown by the poor discrimination behavior of the very deep Soviet shot Helium-1 (Figure 1).

The results of the 1993 Non-Proliferation Experiment (NPE) showed that chemical explosions produce similar seismic observables to nuclear explosions, with the exception of an overall scaling factor (Denny et al., 1994). Therefore, chemical explosions can be used as a proxy for nuclear explosions. The SPE chemical explosions are designed to provide data that bear directly on a number of inadequacies in how current models of nuclear tests generate physical observables (surface fractures, spall, etc.) and seismo-acoustic signals.

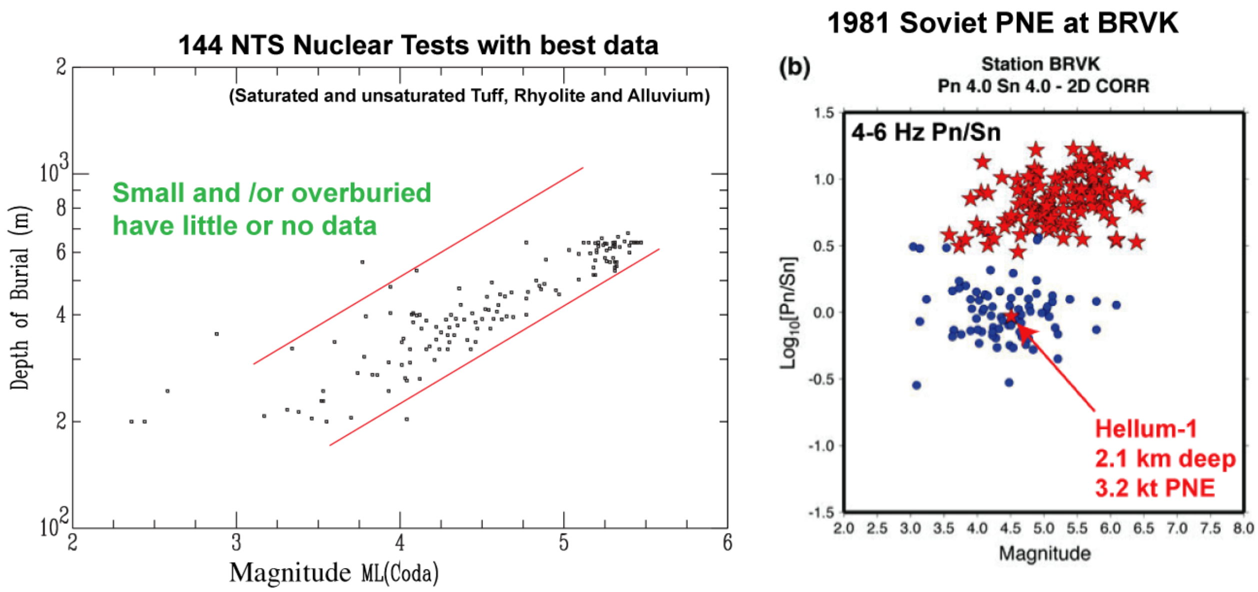

Figure 1. a) NTS nuclear tests plotted in terms of their size given by seismic magnitude versus depth of burial shows most events fall in a narrow range bounded by the red lines (data after Walter et al., 1995). Note there is little data available from small and/or over-buried explosions in the region of the plot indicated by the green text. b) Plot of a P/S discrimination method of separating former Soviet nuclear explosions (red stars) from earthquakes (blue circles) for historic events measured at the Borovoye observatory in present day Kazakhstan (after Pasyanos et al. 2014). Note the very deeply over-buried nuclear explosion Hellum-1 plots in the middle of the earthquake population for reasons we do not currently understand.

The SPE is designed to address questions about three fundamental seismic wave types, as well as coupled acoustic waves, all of which are used in identifying nuclear tests as well as determining their yield:

1) Seismic P-wave models - Accurate P-wave models are particularly important for determining the yield of an explosion, and can provide information on depth of burial as well. While current P-wave models are well developed for large explosions and/or explosions near normal scale depth of burial, two widely-used models show significant differences with each other for small and/or over-buried explosions (Rougier et al., 2011, Ford and Walter, 2013). Preliminary results from the initial SPE explosions indicate that revisions to seismic P-wave models are indeed needed.

2) Seismic S-wave models – Accurate S-wave models are particularly important for identifying explosions and are also used in some types of regional yield estimation. There are many physical mechanisms proposed to explain how explosions produce S-waves, as shown in Figure 2. Each of these plausible mechanisms may be active in different proportions, depending upon the explosion emplacement conditions and scaled depth of burial. An accepted model to predict S-waves from explosions is needed.

3) Seismic surface wave models – There is no accepted model that can predict why some, but not all, explosions show significant surface wave anomalies. For example, NTS explosions in granite have reversed Rayleigh waves, as if they came from implosions instead of explosions (e.g., Brune and Pomeroy, 1963). Similar reversed Rayleigh waves have been observed for nuclear explosions in Kazakhstan and India. While plausible explanations involving release of tectonic stress have been invoked, recent studies (e.g., Patton and Taylor, 2011) have demonstrated the considerable effects rock damage and driven block motions can have on surface-wave generation. In addition, the DPRK declared nuclear tests had larger relative surface waves than expected causing them to intermingle with earthquakes on a plot of M_s:m_b, a long-standing empirical method of identifying explosions. This led to a revision of the empirical M_s:m_b international screening line (e.g., Selby et al., 2012). A predictive capability for these effects is not possible without a deeper understanding of explosion damage mechanisms and the implementation of these mechanisms into physics-based numerical simulation codes (e.g., Vorobiev, 2010).

4) Seismo-acoustic wave models – Underground explosions as well as other underground sources such as earthquakes produce acoustic waves in the atmosphere through coupling with seismic energy (e.g., Arrowsmith et al., 2010). The presence or absence of recorded acoustic energy, particularly if combined with seismic measures can further constrain estimates of depth of burial and yield of an explosion (e.g., Ford et al., 2014). In addition, spall, rock damage and driven block motions above a buried explosion will produce acoustic signals and the seismo-acoustic waves may provide important constraints on these phenomena. Finally, as with the seismic waves, a predictable model of the acoustic wavefield produced by underground explosion will be important to their use in nuclear explosion monitoring applications.

The SPE series is focused on addressing fundamental uncertainties and unknowns in the current modeling effort. A much more detailed list of scientific questions to be addressed under the SPE is provided in Appendix I. The approach is to conduct chemical explosions designed to generate key data for source media and emplacement conditions lacking such data. The SPE Phase I (consolidated/hard rock geology), Phase II (unconsolidated/weak rock geology) and Phase III (discrimination) form a carefully planned comprehensive series of explosive tests designed to provide the key data. These data are required to improve and validate the physics-based seismic-acoustic simulation codes and models to reduce uncertainty and therefore improve confidence for nuclear explosion verification and monitoring. The code improvements will be evolutionary and may be revolutionary (e.g., full-wave anisotropic, dynamic, moving media acoustic), and may consider other prompt geophysical signals such as EM waves. The development of these new simulation codes and their direct application to explosion identification, yield estimation and other monitoring applications are the principle objective of the SPE program.

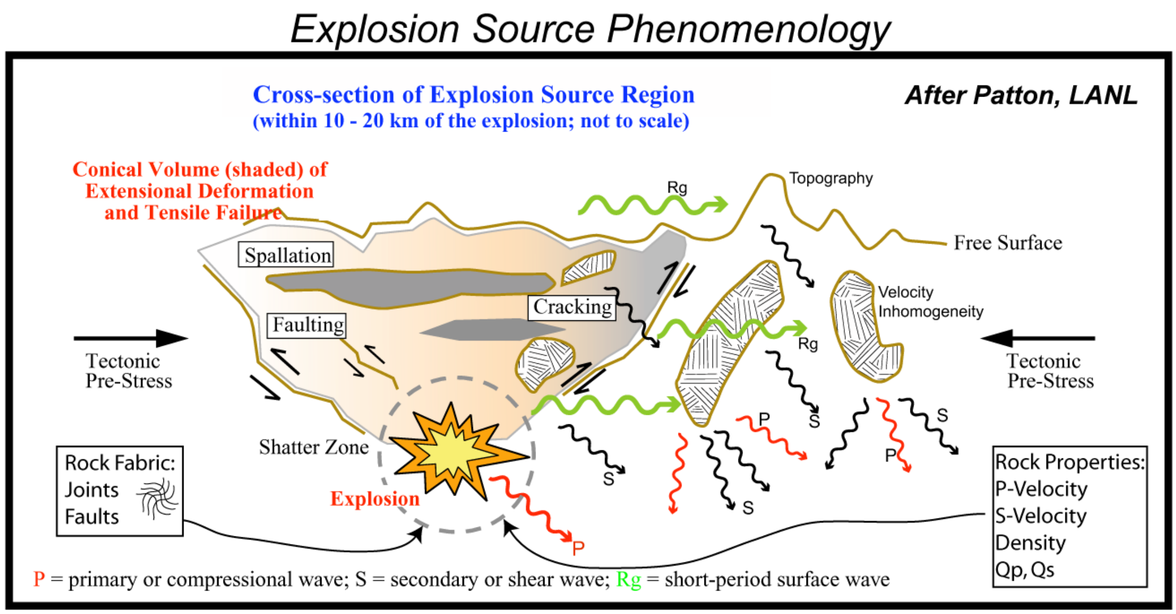

Figure 2. An illustration showing many potential sources of explosion S-waves created as the initially spherically symmetric pure P-wave explosion interacts with emplacement rock and the free surface of the Earth (after Patton, written comm.).

SPE Goals, Objectives and Requirements

General goals and objectives/products for the SPE were developed first. As a result, these lead to specific requirements that in turn drive parts of the specific explosion test plans, sensor network setup, logistics, data analysis and modeling.

Goals and Objectives for the SPE:

- The **fundamental goal** of the SPE is to improve the U.S. nuclear test monitoring capabilities. These capabilities include the detection, identification and yield determination of small nuclear tests in a wide range of potential geologies and emplacement conditions, amongst a background of noise and other source signals.
- The **fundamental objective** of the SPE is to achieve physics-based simulation of the SPE and related nuclear test observable data that can be applied to foreign testing scenarios in order to advance U.S. nuclear test monitoring capability, including improving event identification and yield estimation.
- To achieve the fundamental objective a variety of **intermediate objectives** will be necessary, particularly the development of seismic P-wave, S-wave, surface wave and seismo-acoustic, observable models, along with the determination of the materials and emplacement conditions that affect these observables. Additional intermediate objectives include further development of full physics modeling codes that are able to represent the broad variety of phenomena in Figure 2 and Earth models to allow the propagation of observable energy via such codes out to local and regional distances where small explosion nuclear monitoring would be conducted.

I. General requirements

1) SPE Phase I and II are conducted in source media geologies for which nuclear test data exists in order to compare and establish relationships between chemical and nuclear tests in that media. Phase III may be conducted in novel media as part of simulation validation testing.
2) Each SPE chemical explosion geology must have foreign analogs (past, existing and potential future test sites)
3) Must be able to compare local and regional observables (e.g., seismic waves, acoustic waves, EM, venting gases and particles, etc.) with past nuclear tests for the variable source conditions (e.g., geology, SDOB, yield, etc.)
4) Must set up a sensor network that allows comparison of observed data from multiple shots at same site to provide precise relative results
5) Must record enough background data from network sensors to allow characterization from noise and comparison with other events (e.g., explosion aftershocks, earthquakes, mine blasts, etc.)
6) Must characterize bulk site properties that are related to observables (e.g., surface topology, geology, faults, fractures, joints, velocity, density, attenuation, etc.)

II. Explosive Test Requirements

1) Need chemical explosions in at least two or more contrasting geologies.
2) In each geology, need one or more chemical explosions at very high SDOB (>1600 m/ $kt^{1/3}$) to minimize free surface damage (spall) effect.
3) In each geology, need one or more chemical explosion near normal NTS nuclear testing SDOB (~120 m/ $kt^{1/3}$) to contrast with chemical high SDOB shots, and to provide direct chemical explosion comparison to historic nuclear explosion SDOB.
4) In each geology, need one or more chemical explosions at an intermediate SDOB to fully test SDOB effects and modeling.
5) In each geology, need one or more chemical explosions at large yield (≥5 metric ton in hard rock, ≥50 ton in weak rock) to ensure seismic data can be recorded with sufficient bandwidth at regional distances (~300 km).
6) The SPE chemical explosions need to simulate nuclear explosions as much as feasible (e.g., minimize aspect ratio, achieve near simultaneous detonation, etc.).
7) Need to acquire accurate metadata on chemical explosion yield, dimensions, coupling and timing.
8) Need to detonate a chemical explosion at or very close to the site of a prior earthquake of sufficient size to be recorded by sensors at local and near regional distances that recorded the earthquake. The purpose is to compare mechanisms holding other factors such as source depth and medium properties constant in order to test the physical basis for event discrimination.

III. Sensor Network Requirements

1) Need "permanent" (for duration of shot sequence), well-coupled sensor network in near-field, far-field and free surface damage region that can record for long periods of time

before, during, and after SPE chemical explosive tests.

2) Need some sensors at sites that recorded past nuclear tests to record the SPE shots for comparison at local and regional distances.
3) For specific shot goals may need to install additional temporary sensors for purposes such as dense sampling of the seismic wavefield, experimental arrays to measure seismic properties or reoccupying regional stations that have recorded past earthquakes and/or explosions.
4) For Phase III event discrimination, need some sensors to better characterize the targeted earthquake region, and re-occupy some sites that recorded the targeted earthquake in order to record the dedicated explosion at the same site for comparison.
5) Crucial that the sensor network be maintained with minimal change over life of experiment to allow differential/ratio analysis of shots at the same site.
6) Crucial that the sensors have accurate metadata (e.g., location, timing, instrument response, etc.)
7) Data from sensors needs to be shared with SMEs in as close to real time as is achievable (e.g., via telemetry) for both shots and background signals/noise.
8) Quality control on acquired data should be conducted by all SME's and results fed back to collective archive for fixing or at least verifying issues
9) After a two-year hold for SPE validation, acquired sensor and site characterization data should ultimately be released to broad research and development community for maximizing analysis.

IV. Logistical Requirements

1) For a sequence of shots in each geology, use single borehole or tunnel, start from deepest point and work up (for borehole or farthest for tunnel and work toward entrance) to minimize costs, interference of shots with each other and free surface.
2) Sensor network should be deployed well in advance of first shot in the series to acquire background data (and if possible necessary permits pulled to allow site preparation (e.g., digging) to allow good coupling).
3) Bulk site characterization work should be conducted in advance of drilling and site prep for shots.
4) Pre- and post-shot characterization should be conducted over the site area for each shot (e.g., fracture mapping, LIDAR and/or other imaging data, etc.).
5) For event discrimination an accessible (e.g., shallow) earthquake of sufficient size to be recorded at local and regional distances needs to be identified and very well characterized (e.g., refined depth, location) in order to be targeted for a planned explosion.
6) To ensure shot success and maximize data return an experienced field team should be employed, and explosion execution and sensor fielding plans created for each planned shot, as well as for the sensor collection of background signals.
7) To oversee the SPE details and utilize lessons learned as the SPE proceeds, a group of SPE Subject Matter Experts (SME) should be formed to meet regularly for the life of the SPE.

V. Data Analysis and Modeling Requirements

1) Where possible and feasible, SPE scientists should use current modeling capabilities to

document their predictions for some of the observables expected prior to each chemical explosion (e.g., Pre-shot reports).

2) As soon as practical after a shot, SPE scientists should perform and document a quick data analysis for initial evaluation of pre-shot predictions, as well as to provide "lessons learned" and sensor network QC to SME's planning the next shot (e.g., Post-shot reports).
3) For peer-review purposes, and to shorten the time to reach useful results, SPE scientists should present data analysis results to each other and the broader scientific community at workshops and professional society meetings on a regular basis.
4) SPE scientists should document progress in data acquisition, analysis and modeling capabilties in written technical reports and especially peer-reviewed scientific journals.
5) Comprehensive geologic and geophysical characterization of the test bed is required as inputs to the models and should be primarily conducted in advance of the shot series.
6) When feasible, legacy data (which may require significant pre-processing) should be utilized to further the understanding of the geologic environment or provide additional inputs for modeling efforts.
7) To provide peer-review checks and confirmation for some significant SPE technical advances, groups from multiple insitutions may need to perform independent modeling on the same data.
8) Preservation of new and legacy data are required to sustain future capabilities for NNSA.

The SPE Approach

The SPE consists of three phases: **Phases I and II** to compare and contrast very different emplacement media and **Phase III** to compare and contrast two very different source mechanisms. For each SPE Phase a carefully designed sensor network needs to be deployed and operational for the duration of the series as well as to operate before, during, and after the planned shots to record background signals and noise. Where possible dense networks of sensors (e.g. Large-N) will be employed to get closer to sampling the unaliased seismic wavefield and map out scattering and wave conversion properties. Detonating the shots in the same hole and recording the signals on the same stations allows high precision ratios to be formed, canceling propagation, receiver, and instrument effects so that only the near source effects being varied can be examined. Because of the importance of the ratio analyses the phases should be carried out sequentially.

The physical parameters explored in the SPE chemical explosions are:

- Explosion size.
- Absolute depth (depths range from 15 m to >1 km).
- Spall and scaled shot depth (greatly over-buried relative to normal-scale depth of burial shots are planned).
- Emplacement geology (shots in granite, alluvium and dolomite are planned).
- Effects of faults, joints, and various material properties (e.g., velocity, density, porosity, saturation), which are determined through associated geophysical studies and laboratory measurements on core samples.
- Effects of damage (all shots are affected by damage due to prior shots).

- Effects of scattering and conversion on observed signals (e.g. scattering from topography, inhomogeneities; conversion of P and Rg to S-waves)
- Comparison of sources (e.g., earthquakes and past nuclear tests).

For each test that varies these physical parameters, we will systematically examine the changes in the geophysical observables recorded on the sensor network. The SPE test plan is constructed to gather the necessary science data in a cost-effective manner. While it would be possible to execute phases in parallel, that would require at a significant additional investment in hardware and would slow down the progress for each ongoing phase. The overall timeline for each of the phases is given in the table below, and in more detail in the text that follows.

SPE shot series	Number of shots	Time window
Phase I (Saturated Granite)	6	FY10-FY16
Phase II (Dry Alluvium Geology - DAG	4	FY17-FY19 (FY20-21 SPE-FAR analysis work)
Phase III (Rock Valley Direct Comparison in saturated Dolomite)	2	FY22- FY30

The **SPE Phase I series** was conducted in a hard rock geologic formation that is close to past underground nuclear tests. The site location on Climax Stock has a known history of anomalous Rayleigh surface wave measurements for past nuclear tests. These past measurements established the basis for this experimental series and allow us to model and observe how S-waves are developed from explosions. Driven motion on the pre-existing joints in the granite is hypothesized to be a significant source of the near field S-waves. In addition, there are foreign analog nuclear tests in similar rock types with similar anomalous Rayleigh surface waves that the results of the Phase I data analysis should help understand.

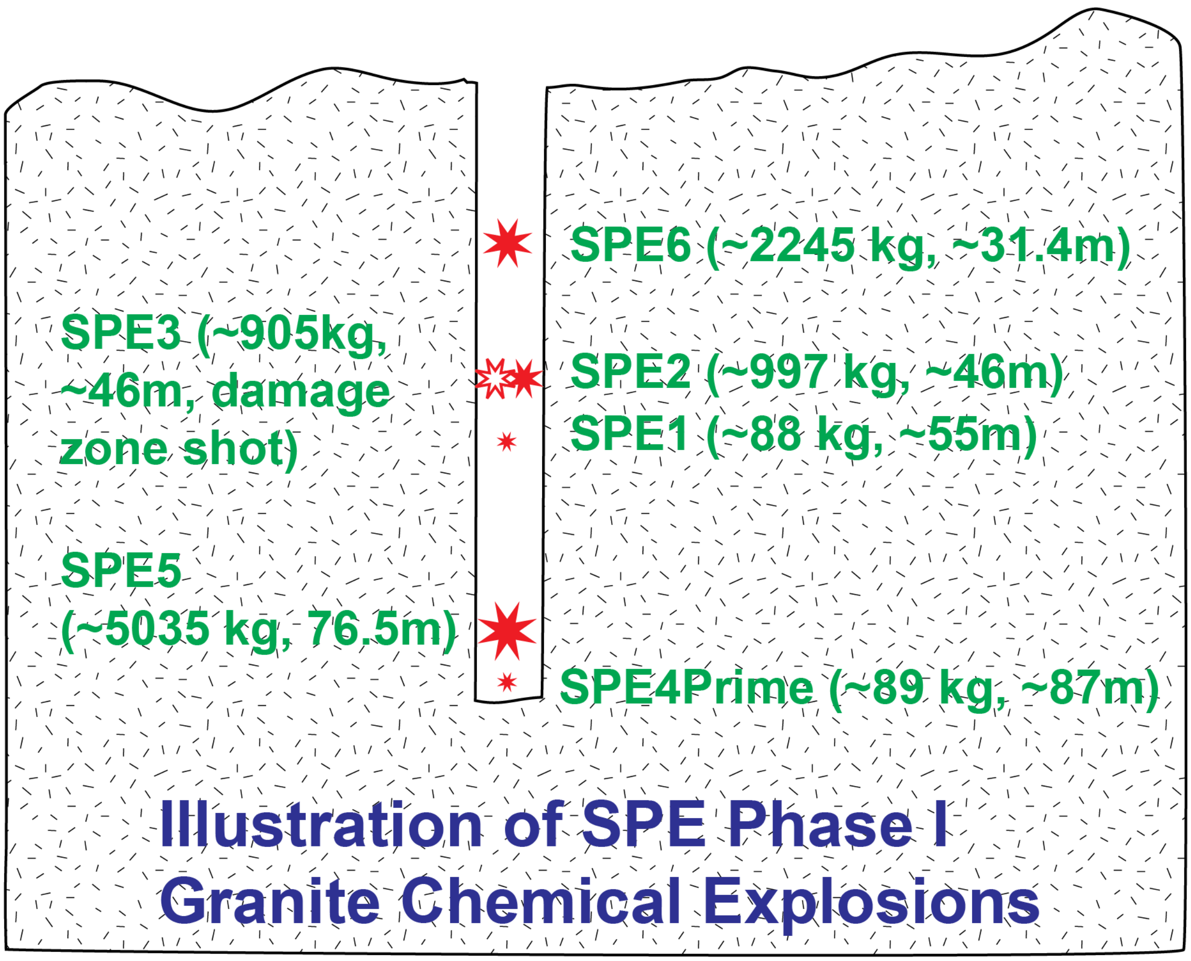

Figure 3. Illustration of relative size, depth and order of the Phase I shots in the granite hard rock hole on Climax Stock. Shots were carried out between 2011 and 2016. Details for each shot are given in the Table 1.

Table 1. SPE Phase I – Granite (Hard Rock) Geology

Event Plan	Yield (tons)	DOB (m)	SDOB ($m/kt^{1/3}$)	Science Goals
SPE-1	0.09	54.9	980	Initial ~Green function (GF) shot (Direct measurement of the explosive source) in a hard rock geology. Establish baseline simulation capabilities.
SPE-2	1.0	45.7	363	Increase shot size to record signals to 100 km. Investigate depth of burial (DOB) effects with SPE-6 and SPE-7.
SPE-3	0.9	45.8	376	Investigate damage zone effects relative to SPE-2.
SPE-4	0.1	99	1693	Minimize spall, ~GF for SPE-5, DOB relative to SPE-1. Shot Misfired.
SPE-4Prime	0.089	87.2	1549	Minimize spall, ~GF for SPE-5, DOB relative to SPE-1.
SPE-5	5.035	76.5	355	Increase shot size to record signals to 300 km for regional recordings. Correlating with the monitoring arrays that recorded historic nuclear tests.
SPE-6	2.245	31.4	190	Final granite SPE near standard SDOB for a nuclear test, allows DOB investigation with prior overburied shots.

The **SPE Phase II series** was conducted in a weak rock, Dry Alluvium Geology (DAG) on Yucca Flat and located near past underground nuclear tests. The series was executed in a location where the rock is homogenous and without fractures. Therefore, there should be no S-wave generation developed from driven motion on pre-existing joints by the explosions. The dry alluvium has very different material properties to maximize contrast to the wet granite in SPE Phase I. The type of shots should correlate with SPE Phase I with the same instrumentation types to provide one-to-one comparisons. Alluvium reduces seismic amplitudes by up to an order of magnitude compared with granite, therefore all the shot sizes have been scaled up by a factor of 10 and the depth adjusted accordingly to have comparable SDOBs.

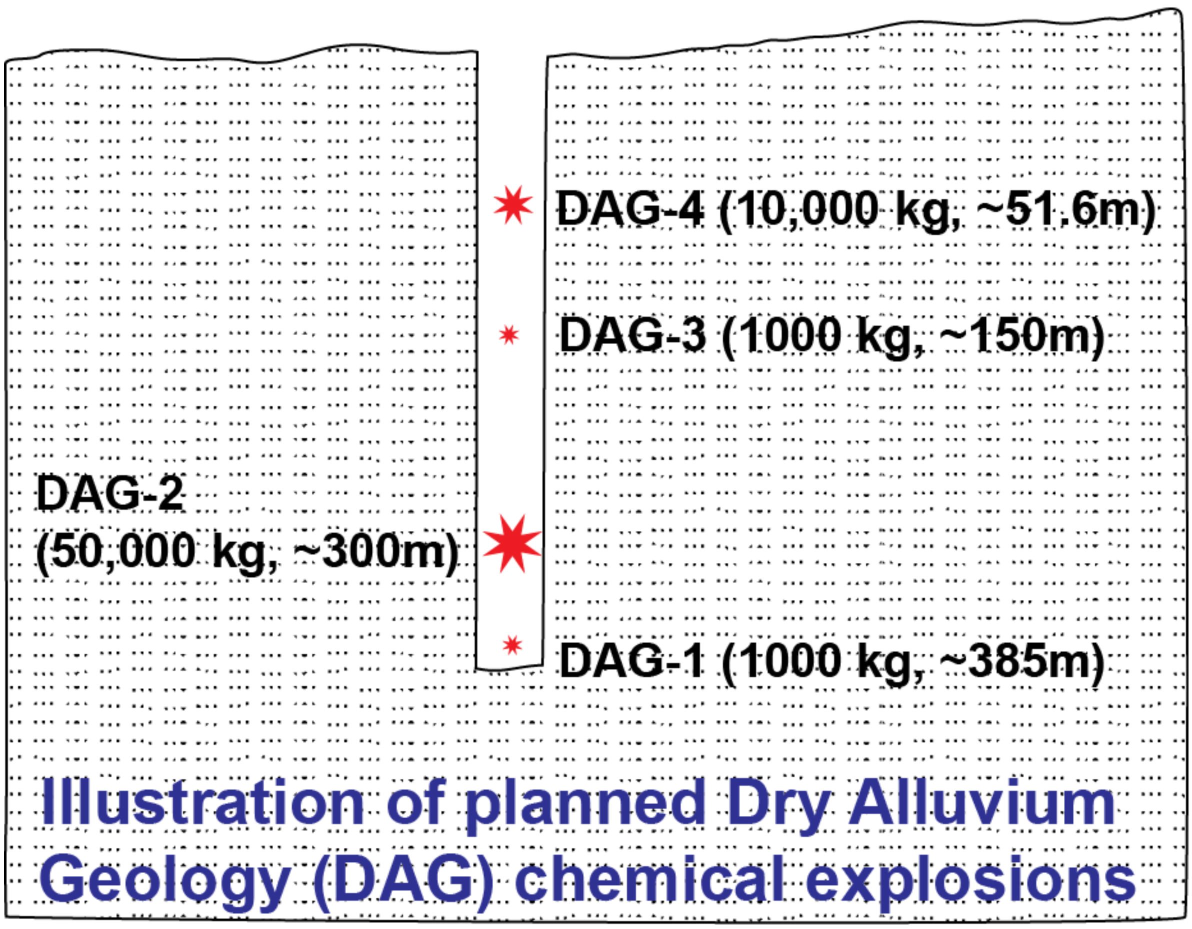

Figure 4. Illustration of relative size, depth and order of the Phase II chemical explosions in the dry alluvium geology (DAG) hole. Because of the reduction in coupling of explosion energy for explosions in dry alluvium relative to granite, the yields have been increased by an order of magnitude and the depths adjusted accordingly. In addition, because the hole has already been drilled in Phase II, the explosions started at the deepest point and proceed upward in sequence. Details for each explosion are given in the Table 2.

Table 2. SPE Phase II – Dry Alluvium Geology (DAG)

Event Plan#	Yield (tons)	DOB (m)	SDOB ($m/kt^{1/3}$)	Science Goals
DAG-1	~1	~385	~3056	Initial ~Green function (GF) shot in a weak rock geology. Minimizes spall and surface interactions. Analogous to SPE-4Prime in different material.
DAG-2	~50	~300	~650	Increase shot size to record signals to 300 km. Correlate with monitoring arrays that recorded historic nuclear tests. Analogous to granite SPE-5 in weaker material.
DAG-3	~1	~150	~1190	Mid-depth Green function for Large-N. Different SDOB to compare with other DAG shots. Analogous to granite SPE-1 in weaker material.
DAG-4	~10	~51.6	~190	Final Dry Alluvium Geology shot, near standard DOB for a nuclear test. Allows DOB and SDOB investigation with deeper shots. Analogous to granite SPE-6 in weaker material.

The **SPE Phase III series** will be close to a series of past earthquakes. The locations of these past events needs to be well-characterized both geologically and geophysically. In particular, the hypocenters of the closest target earthquakes needs to be well known. In 1993, a sequence of unusual and very shallow (1-3 km deep) earthquakes in Area 27 at Rock Valley occurred. By setting off an explosion very close to the hypocenter of a prior Rock Valley earthquake and recording it at sites where we previously recorded those earthquakes we can directly compare the two sources where their depth and material properties are in common. Observed differences will be solely due to differences in the source mechanism and spectral character. This will allow us to put earthquake/explosion discrimination on a much firmer physical footing and test our ability to model each source type. This will require a multi-year effort to characterize the location. More details on the initial feasibility study for Phase III can be found in Walter et al. (2012).

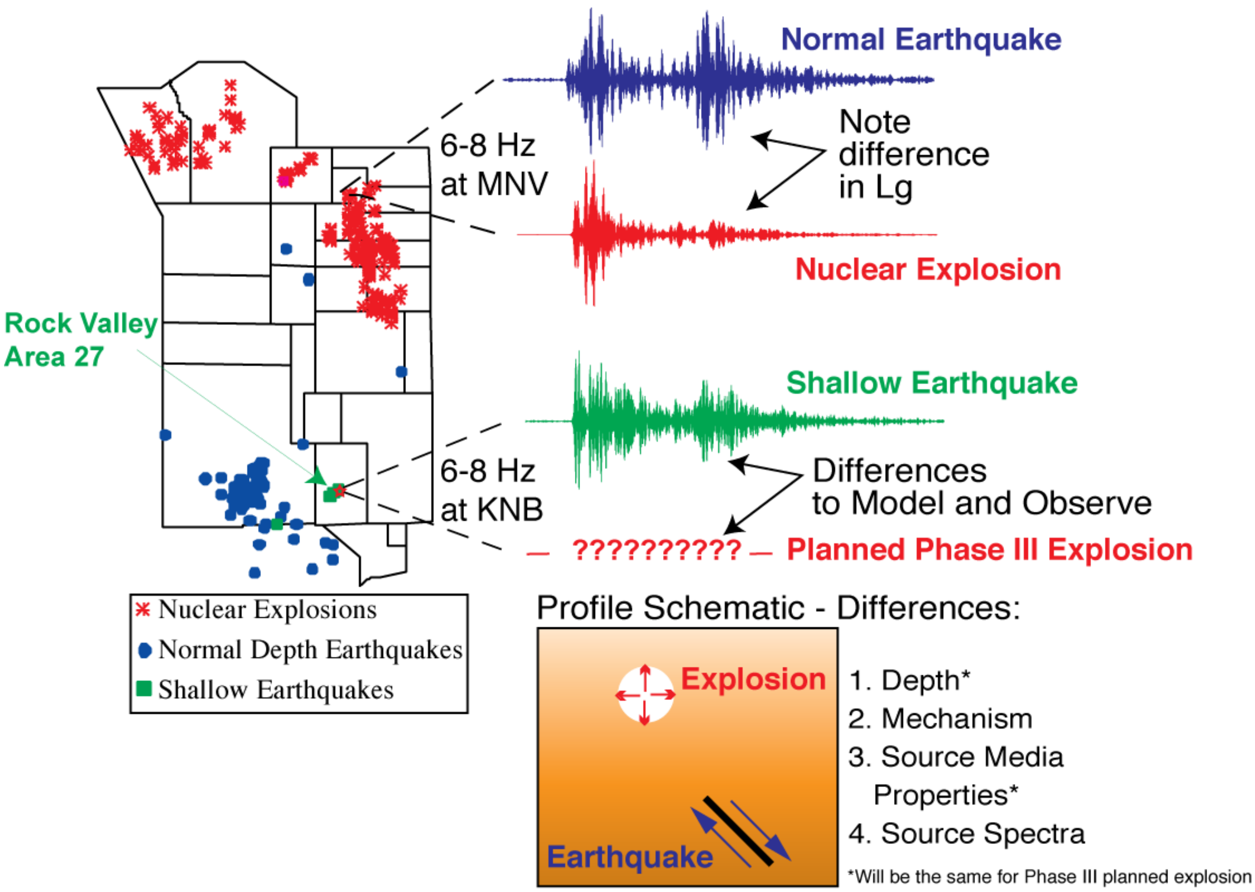

Figure 5. Map of nuclear tests (red), normal depth earthquakes (blue) and unusually shallow earthquakes (green) at NNSS. Phase III is designed to examine the physical basis of explosion identification. At the top of the plot the seismogram of a 9 km deep earthquake located nearly below a near surface nuclear explosion is shown in terms of the difference in their relative S-waves ("Lg") observed at high frequencies at a station a few hundred km away. The observed signal difference must be due to differences in depth, mechanism, source media properties and the source spectral characteristics as shown in the schematic at the bottom of the figure. Phase III will conduct a large chemical explosion that is nearly co-located with a shallow earthquake. In Phase III the depth and source media properties will be the same for the explosion and

earthquake (marked with an asterisk) and therefore the observed signal differences will only be due to differences in mechanism and source spectra as shown at the bottom of the figure.

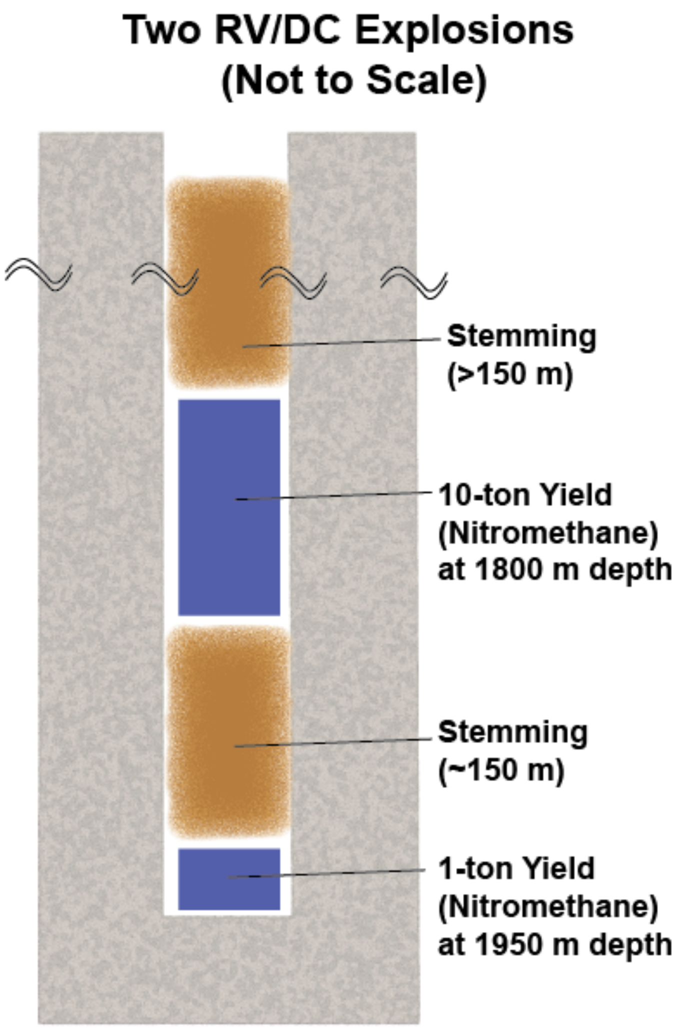

Figure 6. Illustration of SPE Phase III (RV/DC) planned explosive sizes and depths. The expected water table depth is roughly 400 m and the expected geology is Paleozoic dolomite. So, the shots are expected be in saturated hardrock. A planned Core Hole (CH) to be drilled near the main test hole will provide more accurate details on the emplacement conditions prior to executing the explosion. Details for each explosion are given in the Table 3.

Table 3. SPE Phase III – Discrimination (Rock Valley Discrimination – RVDC)

Event Plan	Yield (tons)	DOB (m)	SDOB (m/kt$^{1/3}$)	Medium	Complexity	Comments
RVDC-1	~1	~1950	~15,000	Dolomite	Extreme: Initiation of test series. Deep hole and small target. Logistical components will take time to resolve.	Rock Valley (Fault region). Initial ~Green function (GF) shot Direct measurement of the explosive source in the geology.
RVDC-2	~10	~1800	~6600	Dolomite	Extreme: Deep hole and large yield. Logistical components will take time to resolve.	Rock Valley (Fault region). Shot performed close to the hypocenter of a previously recorded 1993 earthquake. Large yield required due to the depth of the hypocenter and correlating with the monitoring arrays and capabilities at local to regional distances.

Summary

This Science Plan provides a high-level overview of the Source Physics Experiment (SPE), a carefully planned, multi-institutional, NNSA research and development effort designed to improve U.S. nuclear verification and monitoring capabilities. The SPE will generate novel data derived from a systematic series of chemical explosions conducted under a wider range of emplacement conditions than was done during underground nuclear testing. The SPE will compare the new chemical explosion data to historic nuclear test data and utilize both to develop and validate new first-principle simulation codes. These codes update our current historic-test-site based semi-empirical models, improving confidence in nuclear explosion monitoring, particularly yield estimation and event identification in new areas and/or for tests done under novel emplacement conditions. The findings from the SPE will advance the United States' nuclear explosion monitoring capabilities, particularly for small nuclear explosions that otherwise might be lost amid the noisy seismo-acoustic background from other sources.

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Appendix I - SPE Detailed Science Questions:

These are to be addressed as part of the development of new physics-based simulation capability

P waves:

P.1 Far-field Spectral Models – What are the observed far-field P-wave displacement source spectra from the SPE explosions and how do they relate to those from historic nuclear tests? How do these source spectral shapes and their characteristics such as moment, corner frequency and high frequency roll-off, change as a function of yield, depth of burial, scaled depth of burial and material properties?

P.2 Near-field Spectral Models - To first order under spherical symmetry, the reduced displacement potential (RDP) is a description of the P-wave source function for underground explosions, and then the displacement spectra is proportional to the reduced velocity potential. What are the measured RDPs for SPE tests using near-field data? How do these RDPs change with yield, depth of burial, and material properties? How do the SPE RDP's compare with those derived from historic nuclear tests?

P.3 Near and Far-field Relationships - What relationships are observed between the RDP from near-field data and features measured on far-field P-wave spectra, such as low-frequency level, corner frequency, and high-frequency roll-off? Can we identify path and site effects that distort the spectra of local P-waves and develop methods to mitigate these effects?

P.4 Analytical Models – How well do analytic models predict the shapes and characteristics (moment, corner frequency and roll-off) of observed P-wave source spectra for the SPE's and historic nuclear tests? How well do analytical source models predict characteristics of the RDP, such as static level, rise time, and overshoot? What fundamental aspects of these near and far-field models and their scaling need to be modified to improve predictions at small yields and large SDOBs? Can we develop new and improved near and/or far-field analytic models for P-waves?

S waves:

S.1 Transverse Energy - How energetic are signals recorded on transverse components in the near-field from SPE explosions and historic nuclear tests? Can the source location of this energy be pinpointed and mechanisms ascertained? What are the relationships between the S-wave source and the geology of the host medium (e.g., joints, faults, impedance contrasts, material properties, etc.)?

S.2 Spectral Models - What characteristics, such as frequency content, strength, azimuthal variability, etc., do observed S-waves have in the far field? Are there relationships between P- and S-wave radiation that could bear on mechanisms for S-wave generation as seen at regional distances where a putative corner frequency relationship was conjectured?

S.3 Near and far-field Relationships - How does the strength and frequency content of S waves recorded in the far-field compare with measurements on transverse components in the near-field?

Can we partition the S-wave generation between near-field, free-surface interaction and far-field regions and understand the different contributions to the S-wave field in each region? Can we understand and model S-wave generation due to plastic sliding on joints, faults and other boundaries and differentiate that from P-to-S-wave conversion due to rock anisotropy?

S.4 S-wave Generation - Do relationships exist between observed S waves and other signals generated by the source? Rg-to-S scattering is a proposed S-wave generation mechanism. Rg waves are Rayleigh waves typically observed between 2 and 10 Hz on SPE tests. In order to make a tie to this mechanism, there needs to be evidence for imprinted Rg features onto far-field S wave signals or spectra. For regional distances, a putative tie was based on amplitude scalloping predicted for Rg source spectra, which was observed in Lg waves.

S.5 Analytic Models – How well do analytic models predict the shapes and characteristics (moment, corner frequency and roll-off) of far-field S-wave source spectra for the SPE's and historic nuclear tests? Can we develop new and improved near and/or far-field analytic models for S-waves?

Surface waves:

SW.1 Observed Rayleigh Waves - What characteristics, such as frequency content, amplitude, phasing, azimuthal variability, etc., do Rg waves from SPE explosions display? How do these characteristics vary with yield and depth of burial of SPE tests?

SW. 2 Free Surface Interactions and Damage Effects - Are features of Rg waveforms tied to near-source phenomenology, such as free-surface interactions and a related damage source? Rg excitation is a strong function of source depth. A damage source related to free-surface interactions will radiate Rg waves efficiently. On the hand, the explosion itself generates strong Rg waves, and high-precision methods are needed to separate the effects of the damage source from the explosion source. What are the effects of the surface geology and topography, including the weathered layer on the generation surface waves and their conversion to body and acoustic waves?

SW.3 Damage Mechanisms and Analytic Models - If the effects of a damage source can be detected in Rg waves, what is learned about the damage source, including mechanisms, source spectrum, timing relative to explosion origin, centroid depth, and spatial distribution both in depth and lateral extent?

SW.4 Love Waves - What characteristics, such as frequency content, amplitude, azimuthal variability, etc., do high-frequency Love waves display for SPE tests? How do these characteristics depend on near-source phenomenology? What can be learned about mechanisms of source asymmetry from observed Love waves?

Seismo-acoustic waves:

SA. 1 Observed Acoustic Waves - What characteristics, such as frequency content, amplitude, phasing, azimuthal variability, etc., do the observed acoustic waves from SPE explosions display? How do these characteristics vary with yield and depth of burial of SPE tests?

SA. 2 Acoustic Wave Models – How well do simple models predict the shapes and characteristics of observed acoustic waves from SPE explosions? Can we develop new and improved analytic models for buried explosion generated acoustic waves?

Multiple Phenomenologies

MP. 1 Moment tensors - What characteristics are seen in moment-rate tensors obtained from inversions of far-field data, such as the strength and frequency content of diagonal elements? How do predictions of analytical source models compare with moment-rate spectra? Can we detect evidence of seismic radiation for source medium damage in moment tensor results? If so, what can be learned about the properties of this source, for example its strength as a function of SDOB and medium properties and its frequency spectrum for P and S waves?

MP. 2 Near and Far-field Physics-based Codes – Can we couple non-linear near field modeling codes to far field elastic codes to allow detailed end-to-end modeling of buried explosion source to remote observations? Based on SPE and historic nuclear test data analysis, what additional physics is missing from current numerical simulation codes and how do we best incorporate it into those codes?

MP. 3 Earth Models – How do we best generate Earth models of key properties (e.g., velocity, density, attenuation, geology, fabric, joints, fractures, etc.) of sufficient resolution to allow simulation of key observables (e.g., near and far-field seismic signals, acoustic signals, etc.)? How does the scaling of Earth properties affect geophysical signals (e.g., grain dislocation to single fracture to fracture network, to rock fabric, etc.). How are these scaling properties characterized? How do we best measure tectonic stress present in the Earth, incorporate it into the Earth models and how does it affect geophysical signals (e.g., reversed Rayleigh waves)? How can legacy data (e.g., borehole logs, refraction lines, etc.) be incorporated into the building of Earth models? What aspects of these kinds of Earth models could be produced in remote and not directly accessible areas and how much would this degrade signal predictions? How do we represent and make use of the uncertainty in parameter values in our Earth models?

MP. 4 Damage Characteristics – What are the damage effects on the material between the explosion depth and the free surface (e.g., spall, block motions, etc.)? What are the damage effects in the immediate vicinity of the shot (i.e., fracturing, cavity formation, etc.)? How does damage affect wave generation and propagation from subsequent shots? How do the physical properties of the material near and above the shot change with subsequent shots and how does that affect measurements such as spall, and seismo-acoustic data?

MP. 5 Near and far-field Modeling – Using our best physics-based codes, Earth models and damage models, how well are we able to fit the SPE data? How well are we able to fit historic nuclear test data? How do we quantify uncertainty in our modeling due to uncertainties in the source models, damage models and the Earth models?

MP. 6 Other Signatures – What prompt (within seconds of the explosion) non-seismo-acoustic signals, such as EM waves, are emanated by chemical explosions such as the SPE ones? Can we create physics-based models for such prompt signals from chemical and nuclear tests? What are the implications of these signals and models for nuclear monitoring and chemical/nuclear explosion discrimination?

MP. 7 Chemical/Nuclear Relationships – The 1993 NPE experiment and its analysis (e.g., Denny et al., 1994) established an overall scaling factor of about 2 between seismic signals from chemical and nuclear explosions. Can we better refine and physically model the chemical/nuclear explosion seismic relationship in terms of parameters including yield, source media, DOB, SDOB and other factors as a function of frequency? Are there any implications of such models for nuclear monitoring and chemical/nuclear discrimination?

MP. 8 Event Detection & Discrimination – What are the implications of the updated seismic P, S, and surface wave models and simulations, as well as the new seismo-acoustic simulation capabilities on small event detection in a noisy background of other signal sources? How does model-based detection strategies compare to empirical ones based on techniques like cross-correlation? What are the implications of updated P, S and surface wave source models (analytical and/or numerical) on the discriminants such as P/S amplitude ratios or M_s-m_b? What are the implications of new moment tensor models for event discrimination?

MP. 9 Depth and Yield Estimation - What are the implications of updated P, S and surface wave source models (analytical and/or numerical) on the determination of explosion depth and yield? What are the implications of new moment tensor models for explosion depth and yield estimation?

MP. 10 Preservation of Data – What data are crucial to reproducing results from the SPE? How are all these data preserved? Are there historic or legacy datasets that need to be identified for preservation?