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A multi-Physics Experiment for Low-Yield Nuclear Explosion Monitoring

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Introduction

A series of multi-physics experiments, referred to as Physics Experiment 1 (PE1) is underway at the United States' Nevada National Security Site (NNSS) (Figure 1). The PE1 series includes detonations of three underground chemical explosions in P-tunnel, with fully coupled (PE1 A), partially decoupled (PE1 D_L), and fully decoupled (PE1 B) emplacements (see Table 2). Canisters with gas tracers are imbedded in the explosives (Table 3), and the tracers are released when the canister is destroyed by the detonation. A dedicated electromagnetic (EM) experiment (EMX) generates well-characterized EM signals at an underground location near the chemical explosive experiments (Table 4). A series of atmospheric experiments (METEX, REACT, and METREX) release smoke and radioactive tracers (Table 3) around Aqueduct Mesa to test gas transport in complex topography. Each of the chemical explosive experiments includes a network of sensors to record seismic, acoustic, and electromagnetic waves, measurement of atmospheric conditions, and air sample collection for measurement of tracer concentration. EMX records EM signals underground and on the surface of Aqueduct Mesa. METEX, REACT, and METREX include measurement of atmospheric condition, as well as tracking smoke releases. REACT and METREX add low-level radioactive gas tracers to the atmospheric releases.

PE1 was designed to answer several fundamental science questions related to explosion monitoring, including:

1) What are the distinctive physical signatures (i.e. ground shock, EM, HE byproducts) of chemical explosions?
2) What are the differences between signals/signatures generated by coupled and decoupled explosions and do our models predict these differences?
3) How are signal/signature differences observable as a function of data type, distance, location, sensor configuration and other parameters?
4) Can data fusion (e.g. combining remotely recorded/collected waveform/gas data) help to determine source type and emplacement?

Varying emplacement of PE1 A, B, and D_L test the effects of detonation in chambers, and conducting the experiments at NNSS, where historic nuclear explosives tests were executed, facilitates direct comparison with historic nuclear test data. PE1 is sited at Aqueduct Mesa/P-Tunnel, in part, because the geology matches historical NNSS tests (e.g. Fourney et al., 1994 and Ford, 2020). Additionally, locating the experiment at the NNSS allows the project team to leverage the existing geologic framework model that is used for modeling. Finally, the site offers the operations support needed to conduct these complex experiments.

Ultimately, PE1 experiments guide further development and validation of simulation methods for generation and propagation of the multi-physics signals that are utilized in nuclear explosion monitoring. These simulation methods are the result of long-term investments by the Department of Energy, and they have been validated using a wide range of data. PE1 experiments fill data gaps in the experimental domain of emplacement conditions (i.e. depth of burial, geologic framework, emplacement conditions, etc.) and source energy density that are needed to ensure accuracy in a diverse set of application scenarios.

Several of the PE1 experiments have already taken place (Table 1), and PE1-A was the most recent experiment (https://www.energy.gov/nnsa/articles/nnsa-conducts-experiment-improve-us-ability-detect-foreign-nuclear-explosions-0). The PE1-A chemical explosion occurred on October 18, 2023. Seismic signals were record within minutes throughout southern and central Nevada, to at least 300 km. Acoustic and electromagnetic signals were recorded in the Aqueduct Mesa vicinity, and gas tracers detected in P-tunnel in the hours and days following the detonation. This paper provides a general description of the PE1 testbed and experiment series, with a more detailed focus on PE1-A.

PE1 Test Bed

Variability of the geology, topography, and atmospheric conditions around Aqueduct Mesa strongly affect generation and propagation of explosion signals at the local scale. Aqueduct Mesa, which rises approximately 300 m from Yucca Flat, is bordered by steep cliffs, resulting in complex atmospheric flow that varies seasonally, diurnally, and with storms. Geologically, Aqueduct Mesa is a series of layered and mostly flat-lying tuffs, which are variably indurated volcanic ash and pumice deposits (Prothro, 2018; Sawyer et al., 1994). These layers are illustrated in Figure 1: UNPWT represents the upper nonwelded to partially welded tuff, UWT is upper welded tuff, VNT is vitric nonwelded tuff, and UZNT is upper zeolitic nonwelded tuff. These units are underlain by strongly indurated Paleozoic sedimentary rocks, and nearby outcrops of granite and deep sedimentary basins exemplify the complex 3-dimension geology of the region. Detailed characterization of the PE1 testbed includes geologic mapping, geophysical borehole logging, as well as measurement of rock permeability, hydrology and material properties.

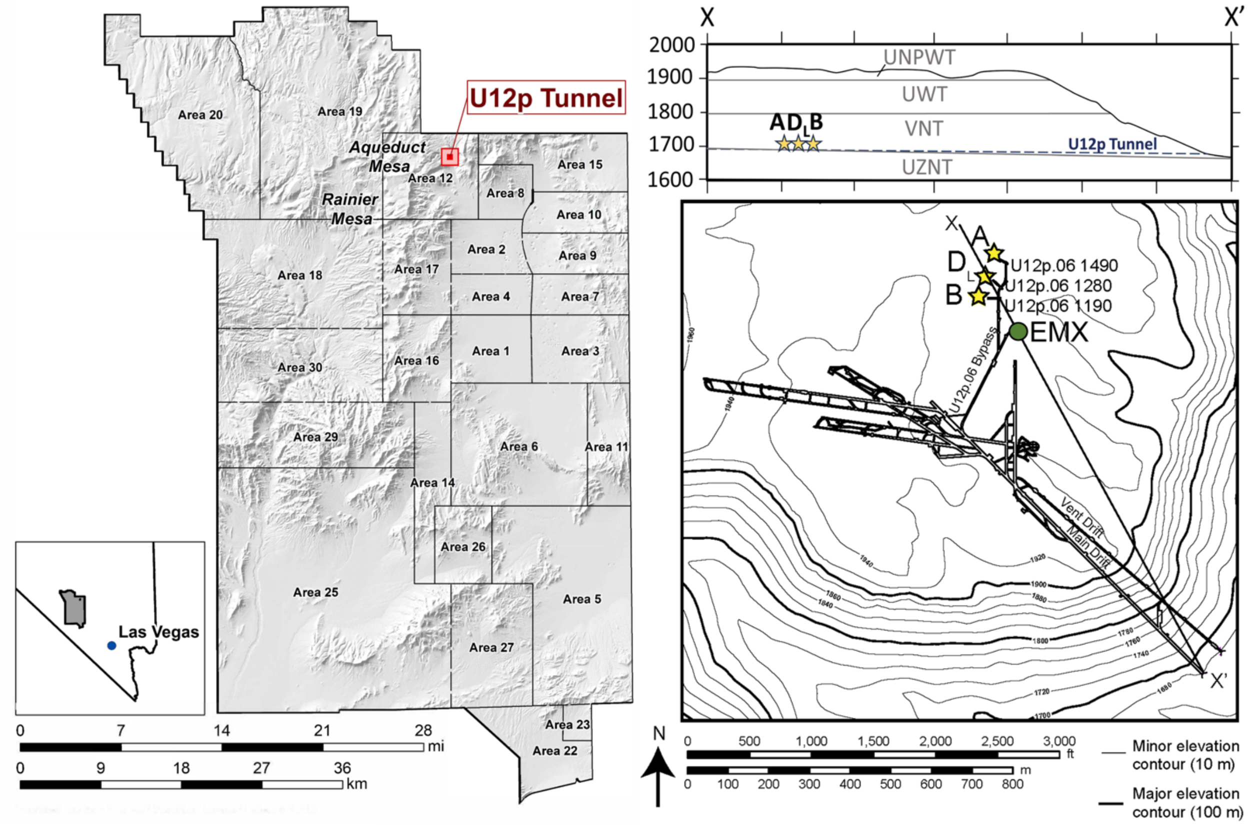

Figure 1. (left) Map of the NNSS with red box covering Aqueduct Mesa, U12p Tunnel (a.k.a. P-Tunnel). (right) Aqueduct Mesa showing topographic contours, P-tunnel complex, and cross-section. Yellow stars are locations of the 3 PE1 chemical explosives experiments: A, B, and D_L. Green circle is the location of the electromagnetic source used in PE1 EMX experiment. A cross section (X-X') also shows locations of A, B, and D_L, topography, and approximate U12p Tunnel grade.

Source components of PE1

As mentioned above, seven individual experiments, utilizing three types of sources, comprise PE1 (Table 1). PE1-A, -B and -D_L are the three distinct underground chemical high explosive (HE) experiments that include material tracers embedded in the explosives package; EMX is an electromagnetic (EM) experiment with a well-characterized electromagnetic coil source; METEX, REACT, and METREX are three meteorology and atmospheric transport experiments that make use of surface tracer-gas releases.

Table 1. Experiments comprising PE1 which are conducted on or within the Aqueduct Mesa.

Experiment Name	Description	Execution Year
METEX	Measure atmospheric conditions (air flow, temperature, humidity, etc.) and transport of smoke to ~5 km distance	2021
REACT	Field test radionuclide sensors using an atmospheric tracer release and meteorological measurements to ~5 km distance	2022

EMX	Measure electromagnetic signals underground and on the surface from a well-characterized source in P-Tunnel	2022
PE1-A	Measure multi-physics signals underground and on the surface from a **fully coupled** chemical explosion in P-tunnel	2023
METREX	Measure concentrations of atmospheric tracers (stable and radioactive) to 10 km distance	TBD
PE1-B	Measure multi-physics signals underground and on the surface from a **fully decoupled** chemical explosion in P-tunnel	TBD
PE1-D_L	Measure multi-physics signals underground and on the surface from a **partially decoupled** chemical explosion in P-tunnel	TBD

Chemical Explosions A, B, and D_L

Three chemical explosions are planned in the underground testbed. PE1-A occurred on October 18, 2023, and was fully coupled (no airgap between the chemical explosive and surrounding rock), while PE1-B and PE1-D_L, planned for 2026 and 2027 respectively, will be detonated in hemispherical chambers of differing size with horizontal floors (see Table 2). The high-explosives (HE) source, composed of Comp B (59.5% RDX, 39.5% TNT, 1% wax), has eight ~2.8 m^3 HE shaved cubes, each ~1698 kg, fit together to form the overall package weighing ~13,580 kg (Figure 2a). The package is detonated with 16 detonators, 2 detonators at each of the 8 shaved edges of the cube, resulting in an implosion source that ensures full HE burn.

Table 2. Chemical explosive source parameters

	Chemical Explosion Sources		
	A	**B**	**D_L**
Seismic Source (kg Comp B)	13,580	13,580	13,580
Chamber Radius (m)	~2.2 (backfilled with dry sand)	11.00 (Hemisphere)	3.8 (Hemisphere)
Chamber Volume (m^3)	N/A	2788	134
Coupling	fully coupled	decoupled	partial

In addition to chemical explosive byproducts, additional materials tracers (Table 3) are inserted into the HE configuration between the upper and lower stack (Figure 2a). Migration of HE byproducts and tracers, as measured in boreholes and within the P-tunnel complex, provide data that can be used to test predictions of particulate and gas migration through the damaged and undamaged rock. Since each explosion has a different emplacement condition and therefore differing degrees of resultant damage, the field-scale experiments provide a first in kind comparison of material transport between fully coupled to decoupled high explosive experiments.

It is important to note that all three explosive experiments are (or will be) confined in their experiment drifts by a long grout plug. This confinement is necessary for not only the safety of the tunnel complex, but also to help ensure that material transport can be measured through the geology, rather than just in the tunnel complex. For PE1-A, the confinement feature, an approximately 70' long grout plug, was abutted against the HE Chamber, which had been filled with sand providing a fully coupled emplacement condition.

Figure 2. Left (a) High-explosives (HE) source for PE1-A. Eight cubes with shaved outer edges comprise the source. Tracer gas canisters are placed in the open space between upper and lower halves of the source. PE1-B and PE1-D_L sources will be replicates of the PE1-A source. Center (b) electro-magnetic coil source for EMX. Right (c) smoke releases from METEX experiment on and around P-Tunnel entrance (a.k.a. P-Tunnel Apron).

Table 3. Material tracers released during each explosive and atmospheric PE1 experiment.

Tracers	**Experiments**					
	PE1-A	**PE1-B**	**PE1-D_L**	**METEX**	**REACT**	**METREX**
Xe-127[*]	X		X		X	X
Xe-133[*]		X				X
D_2O	X	X	X			
Tritium Gas (HT)	X	X	X			
Stable Tracers DU, I	X	X	X			
HE byproducts (from explosion)	X	X	X			
Geogenic gases (from rock damage)	X	X	X			
Smoke				X	X	X

[*]Specific Xe tracer may depend on availability.

Electromagnetic source

The EMX experiment recorded electromagnetic pulses generated by a precisely characterized electromagnetic (EM) coil in P-Tunnel (Figure 2b; Table 4). During the EMX experiment, EM measurements were made within P-Tunnel and on the surface of Aqueduct Mesa to measure signal strength and distortion (i.e. attenuation) after propagation through Aqueduct Mesa geology. For the three explosive experiments, EM data are recorded on a common set of EM sensors both in the subsurface and at the surface. This careful consideration enables a comparison between EMX and the chemical explosions, providing an empirical correction for EM propagation. Additionally, using these EMX empirical corrections enables more accurate assessment of EM signal generation by the chemical explosives and elucidates the signal differences between coupled and decoupled emplacements.

Table 4. Electromagnetic source

	Coil source
Magnetic Moment	10^5 A-m^2
Rise time	0.68 millisecond
Pulse duration	367 milliseconds
Timing accuracy	0.01 milliseconds
Coil radius	2 meters
Coil height	2 meters
Number of conductor turns comprising the coil	24

Atmospheric Releases

As part of the PE1 series, atmospheric tracer releases and high-resolution meteorological measurements have been collected in the vicinity of Aqueduct Mesa and P-tunnel. These measurements are then used to test the accuracy of atmospheric transport models (materials and gas) and the ability to adequately model high-resolution, and potentially turbulent, wind fields in complex topography. As mentioned above in Table 1, two of the three atmospheric experiments have already been conducted. The first atmospheric experiment, called METEX (Wharton et al., 2023) focused on tests of meteorology equipment and used visual tracking of smoke releases to characterize the flow regime at and around Aqueduct Mesa (Figure 3). A second meteorology experiment REACT included release of Xe-127 to test radioactive noble gas (NG) sensors and study atmospheric transport and plume reconstruction within ~5km of release locations. A third experiment (METREX), which is planned for the fall of 2025, will include more complex releases of radiotracers (i.e. dual releases, horizontal and vertical offsets, etc.) and measurement of the atmospheric plume using NG sensors to distances between 5-10km. In all of these experiments, the focus is on transport of gases (not particulates), as these are the most common releases for underground nuclear explosions and most relevant to nuclear explosion monitoring. Additionally, these releases are conducted in combination with a comprehensive set of meteorological measurements and local atmospheric modeling (e.g. Wiersema et al., 2023).

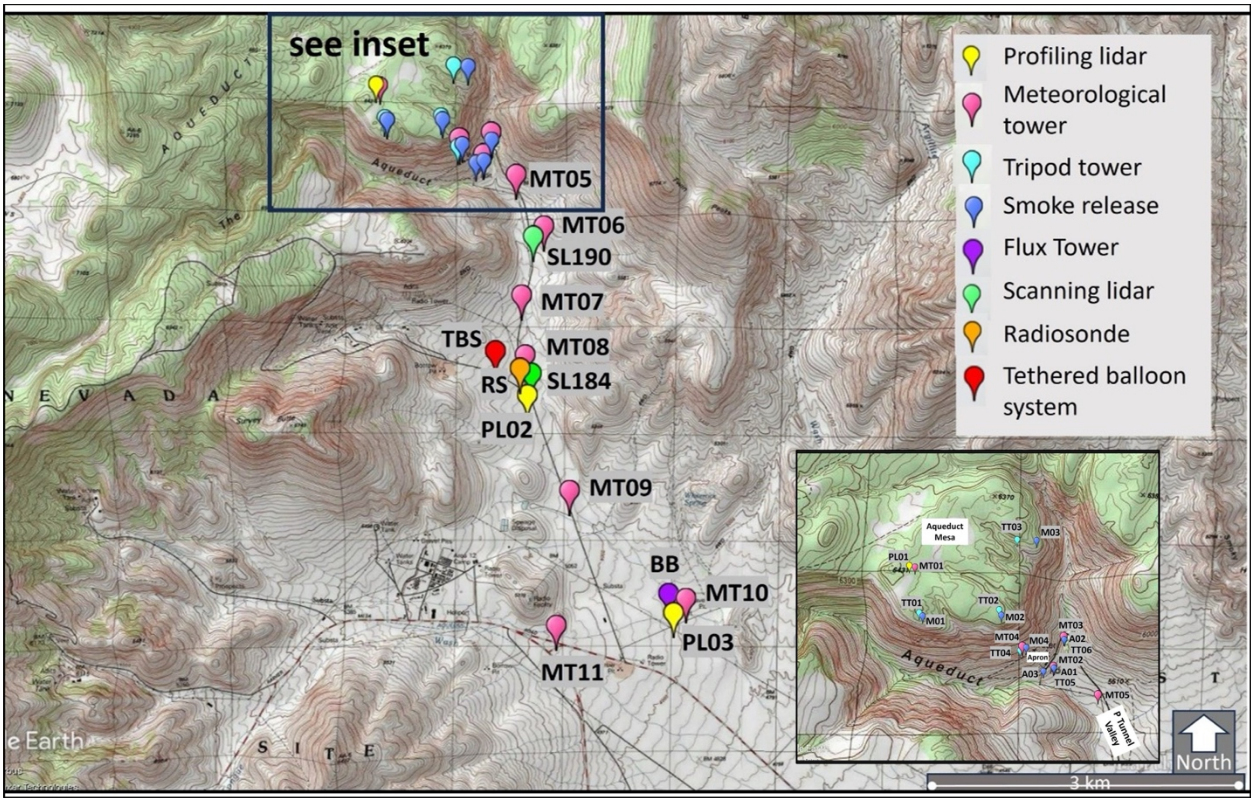

Figure 3. Instrument and smoke source deployment used during METEX. Atmospheric instruments were deployed on top of Aqueduct Mesa, along the P tunnel valley and out to a distance of 5km from the apron. The instrument type and placement was designed to capture atmospheric conditions in both the horizontal and vertical directions during the duration of the nine day experiment.

Sensor Networks

Instrumentation networks for the PE1 experiments are designed to extend from the sources themselves, through the nearfield, and out to local and sometimes regional distances. Specifically, for the explosive experiments, sensors measure seismic, acoustic, electric, and magnetic waves, as well as concentrations of HE byproducts, radionuclide, and stable tracers. During the EMX experiment, these electrical and magnetic instruments were utilized for measurements. Additionally, a network of metrological instruments measures atmospheric conditions (e.g. temperature, wind, and humidity) during both the explosive experiments and the atmospheric tracer experiments, as the measurements are required input into infrasound propagation and atmospheric transport models. Networks and instrumentation are standardized as much as possible across experiments to facilitate direct comparison of measurements. Description of the sensor networks is provided for recently executed experiments (METEX, REACT, EMX, and PE-1A) with the understanding that changes may be made for future experiments (see Table 5 for a summary).

Table 5: Instrumentation Description for PE1

Instrument Type	Surface	Tunnel	Approx. Time Duration (w/r/t T_0)	Approx. Distance from Source
Cavity Sensors		X	- 1 week to + 4 weeks	10 cm - 25 m
Accelerometers	X	X	T_0 to + 48 hours	10 m – 1 km
Real Time Gas Monitoring	X	X	- 4 weeks to + 4 weeks	15 m – 5 km
Gas & Particulate Sample Analysis	X	X	- 4 weeks to + 4 weeks	15 m – 5 km
Distributed Acoustic Sensing (DAS)		X	T_0 to + 24 hours	30 m - 1.3 km
Tunnel Environment Monitoring		X	- 4 weeks to + 4 weeks	30 m - 1.3 km
Seismic	X	X	-6 months to + 6 months	60 m – 375 km
EM Sensors	X	X	-12 hours to + 12 hours	50 m – 1.3 km
Acoustic	X	X	-6 months to + 6 months	240 m – 4.5 km
Meteorological	X		-6 months to + 6 months	1.3 km - 30 km

Herein we describe the instrumentation networks, starting with those closest to the HE source for PE-1A and proceeding to the furthest sensors. The exception to this is the *Surface Gas Monitoring and Sampling* instrumentation and the *EM Sensors*. The *Surface Gas Monitoring and Sampling* modality had sparse representation in PE1-A, with only three sensors deployed between 1.5 – 10 km, but more dense networks for the atmospheric tracer experiments. We have chosen to describe both deployments here, so the table represents approximate distances from the HE detonation and tracer release points. For EMX, the subsurface network of *EM Sensors* was approximately the same distance from the EM coil as they were from the PE1-A detonation, so the distances are representative of both experiments. We have also listed here the recording durations with respect to the timing of the source (T_0), which may represent a HE detonation, EMP, or tracer release as described above. We have noted in the descriptions where instruments were used for multiple experiments.

Figure 4 illustrates the layout of the near source testbed and highlights some of the subsurface instrumentation modalities including electromagnetics, borehole accelerometers (AC) and gas sampling (GS) zones for PE1-A. In relation to the rest of the P-Tunnel facility, Figure 4 shows the region with yellow stars in Figure 1. Note that additional boreholes for acceleration and gas-sampling are planned for PE1-B and PE1-D_L but are not shown here as the boreholes have not yet been drilled.

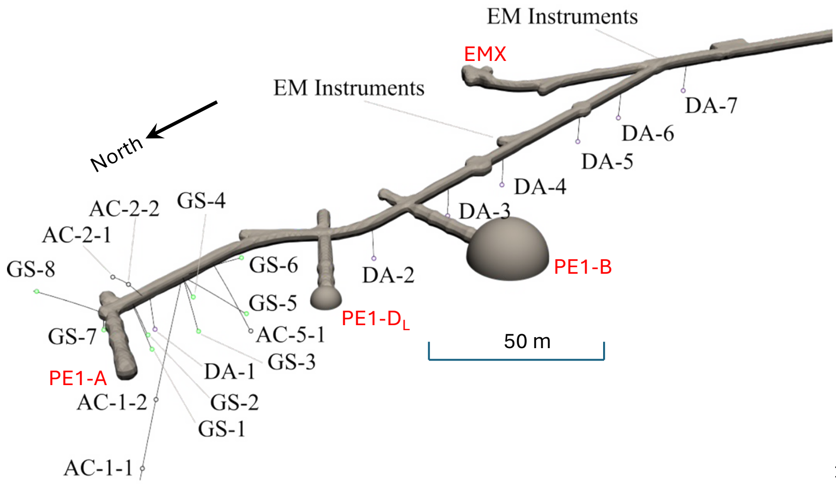

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Figure 4. Layout of PE1 testbed in Aqueduct Mesa P-Tunnel. Locations of HE experiment chambers and the EMX source are labeled in red. Boreholes containing gas sampling zones (GS-<#>) and accelerometers (AC-<#>, DA-<#>) are shown with a circle at the end of the line depicting the borehole. DA-<#> boreholes are in the invert (aka floor) of P-Tunnel and are nominally 3 meters in length. The location of the subsurface electromagnetic (EM) instrumentation are at the Y intersection of the tunnel and an alcove close to the EMX source. Additional instrumentation will be added for execution of experiments PE1-B and PE1-D_L for 3-D measuring accelerations and sampling gases.

Cavity Sensors (HE experiments)

Instrumentation is emplaced in the chambers of chemical explosions and in the grout plug confining the experiment in its drift. These instruments record dynamic pressure, as well as early-time (i.e. first second following the explosion) and late-time (i.e. 1-4 weeks after the explosion) temperature. An optical spectrometer captures light from the fireball for the first second of the blast. The spectral plot for each frame is used to calculate the evolution of maximum temperature. Early-Time Pressure is measured with a pressure transducer in the grout plug that is connected to the high-pressure line extending to the explosive chamber. The system was designed to measure the pressure two seconds before the HE detonation and 15 seconds after.

Instrumentation was also deployed to capture late-time pressure and temperature. Two pressure transducers, placed at approximately 5 and 6 m from the chamber, were attached to 1-inch welding wire serving as a pressure conduit into the chamber. The late pressure transducers collected data at 650 Hz for one hour and 1 Hz for up to 4 weeks. Fiber optics equipped with Bragg gratings were deployed in the grout plug about 2 feet above the floor to capture intermediate-time temperatures at a frequency of 250 Hz. A network of 24 thermocouples at varying distances from the chamber record late-time temperature.

A Continuous Reflectometry for Radius vs Time Experiment (CORRTEX) system was deployed to understand the HE explosion by recording the symmetry and continuity of the detonation shock wave to confirm whether the wave was representative of detonation of the HE (as opposed to

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deflagration). Four CORRTEX cables were run in the right trench next to the wire ropes being used to transport the pressure pulse to the late time pressure transducers, and four in the left trench. The cables also extended into the sand and grout and onto the package surface to provide time-of-arrival data for the shock front as it passed through those features (after analysis of the cable length vs time data) and how the crush affected the wire ropes.

Accelerometers (HE experiments)

Ground motion measurements of PE1-A were recorded with accelerometer instruments positioned from tens to hundreds of meters distance to the HE. The two accelerometer arrays, which are meant to be complementary, are divided into near-source and drift categories. The near-source instrument package contained two orthogonal sets of 5,000g piezoelectric accelerometers enclosed in small cannisters at tens of meters distance from the HE. These instruments were emplaced in boreholes that emanated from the tunnel rib (aka wall). After instrument emplacement, the boreholes were grouted to help couple the measurements to the in-situ geology. The near-source units utilized onboard inertial measurement units (IMU) to determine azimuthal orientation of sensors in the boreholes.

At further distances from the HE detonation, drift accelerometers were emplaced in the invert at ranges of 30 to 240m. Using a similar overall package design, these Instrument cannisters contain two orthogonal sets of single-axis accelerometers with maximum range of 50g and 500g. These data were recorded on a Pacific Instrument DAQ placed approximately 350m from the PE1-A detonation using a sample rate of 80 kHz for the accelerometers and 1.5 kHz for the IMUs. The DAQ was triggered using a network of high precision timing and firing systems.

Three surface accelerometer stations were installed on Aqueduct Mesa near the surface projection of the PE1 HE sources (e.g. A, B, D_L). They consist of one Endevco triaxial accelerometer with a 25g range and one Kistler triaxial accelerometer with 100g range. Both accelerometers were emplaced in the same hole at each station and were recorded on REFTEKs with GPS timing at 1kHz sampling rate.

Gas Monitoring (HE and Atmospheric Experiments)

Gas monitoring and sampling campaigns have been undertaken for both the HE experiments (e.g. PE1-A) and the atmospheric tracer releases, and are planned for future experiments (METREX, PE1-B, PE1-D_L). Here we will describe both instrumentation networks starting with the campaign for PE-1A and then highlighting the campaign for REACT. Gas monitoring and sampling plans for remaining experiments are like those described here for both HE experiments and tracer releases.

The PE1-A gas monitoring and sampling campaign had a total duration of 8 weeks, starting 4 weeks before the October 18th detonation and proceeding until 4 weeks after. HE-byproducts and tracer gases (derived from the tracers described in Table 3) were monitored and collected in boreholes in the near-field (see Figure 4 GS# designation) and at discrete locations within the tunnel complex. The borehole measurements and sample collection were executed in dedicated gas sampling boreholes, which were grout sealed providing an isolated sampling zone embedded in the geologic formation. Gas from these sampling zones were evaluated for radiological tracers and HE byproducts in real-time. Additionally, whole-air samples for laboratory analysis were collected from a selection of the boreholes and tunnel locations, these are herein referred to as grab samples, the analysis of which is discussed in the next section.

To deliver gas from the dedicated boreholes and the tunnel sampling locations to the analyzers and grab sampling systems without changing pressure in the isolated sampling zone, a custom gas circulation system was designed and built. The system pulls gas from the sampling locations, delivers it to the measurement and collection systems, then reinjects it back to the sampling location with an absolute travel time of approximately 5 minutes and a temporal resolution of seconds. The circulation system for each sample location included a dedicated pump, mass flow controller and water trap. Additionally, the system included temperature, pressure and humidity measurements of the circulating gas. Absolute pressure was also measured at each sampling location in the borehole and tunnel.

For the HE experiments, real-time sensors for HE-byproducts, radioxenon, radon, and tritium were deployed. Radioxenon levels in each borehole, the three tunnel locations, and in the vent stack were measured with a dedicated pair of NaI(Tl) detectors. HE-byproducts (H2, CO, CO2, NH_3, CH_4) were measured with a series of commercial sensors (e.g., electrochemical and GasCard NG analyzers) at each location. Radon was measured using RAD7 sensors in the tunnel and vent stack locations, along with the NaI(Tl) detector pairs. At each of the tunnel environment and vent stack locations, tritium level measurements were made using an ionization chamber active/veto pair to isolate the contribution of tritium tracer gas in the air. Outside of the tunnel, a SAUNA Qb was placed approximately 5 km away from the tunnel to collect air and monitor for radioxenon tracers. Skyward-facing gamma detectors were also placed near the tunnel entrance to monitor for the release of radiotracers from the ventilation system.

For atmospheric experiments involving release of a radioactive xenon tracer, skyward-facing gamma detectors are installed out to 10 km from the tracer release points. The sensor placement is guided by modeling plume dispersion under a variety of atmospheric conditions common at NNSS during the selected time of year. These sensors report measurements via cell router to enable real-time monitoring. The SAUNA Qb was deployed to the same location as during the HE experiments for METREX but wasn't present for REACT.

Gas and Particulate Sample Analysis (HE and Atmospheric Experiments)
Laboratory measurements of tracer materials have been made on grab samples and filter material collected during PE1-A and REACT and are planned for subsequent experiments. These laboratory measurements are designed to either provide additional analyte and timing information or serve as confirmatory measurements to real time measurements made in the field. For PE1-A, 192 gas grab samples each with a volume of 2.5 liters were collected from four borehole and three tunnel environment locations, with the addition of water traps that were collected from each of the gas sampling lines. Air filters from the instrumentation ventilation were collected following the experiments for particulate analysis.

Gas subsamples were aliquoted to perform chemical separation and measurement of D2O, HT, HTO, CH_3T, Xe-126 (from the irradiation to produce Xe-127), and geogenic gases. The laboratory measurements include optical spectroscopy for D2O, proportional counter radiometric analysis for HT/HTO/CH_3T, and mass spectrometer measurements of Xe-126. Water grab samples were targeted for analysis for D2O, HTO, and other stable tracers. Laboratory analysis also includes optical spectroscopy measurements for D2O, liquid scintillation measurements for HTO, and chemistry and mass spectrometry analysis for stable tracers. Filter analysis may include particle size analysis and HE residue analysis, among other potential analyses as available. In addition to laboratory measurements, tritium is sampled from 3 locations in P-tunnel and the tunnel vent stack and measured in real time.

For REACT, whole air samplers were co-located with selected gamma detectors. These whole air samplers were pre-programmed before each release with a sampling schedule, storing individual samples in separate bottles. After each sampled tracer release, the bottles are collected and selected bottles that are expected to have high concentrations of radioactive gas are analyzed on-site. All bottles of interest were shipped to low-background counting facilities at the national laboratories for full gamma and beta-gamma analysis of the Xe-127 activity concentrations.

Distributed Acoustic Sensing (HE experiments)
Fiber optic cables were direct buried in the P-Tunnel complex from the portal (i.e. entrance) to within 30 m of the PE1-A experiment location for the purposes of conducting Distributed Acoustic Sensing (DAS) measurements before, during, and immediately after the high explosive experiments. These fibers were interrogated with Silixa's Carina interrogators during the PE1-A experiment, and similar acquisitions are planned for the remaining two explosive experiments (PE1-B and PE1-D_L). DAS provides remarkable spatial and temporal resolution of strain rate changes in the subsurface resultant from both high explosives detonation and subsequent aftershocks.

For DAS data acquisition, straight and helically wound (helical) sensing cables were used throughout the tunnel. Each cable contains two multimode, five single mode, and one Constellation optical fibers, which is suitable for measurements with the Carina sensing system. The helical cable has a calculated 7.5 degree winding angle measured axially and a helix angle of 82 degrees measured from the radial plane. Data were recorded at sampling rates of 80 kHz for the minutes surrounding the explosive detonation and at lower sampling rates for aftershock monitoring.

Tunnel Environmental Monitoring (HE experiments)
To understand the interaction of the explosion with the tunnel complex, a variety of environmental measurements were made at a number of locations both before the experiment and for four weeks after the detonation of PE1-A. These measurements have a basis in both safety monitoring and scientific understanding and included temperature, pressure, humidity, flow rate, and video data. Measurement of the environmental parameters provide a basis for

understanding how transport occurred through rock and into the tunnel facility as well as how operations affected the real time gas measurements within the tunnel and the formation. Additionally, these real time measurements provided verification that the experimental facility was in the desired configuration.

Seismic Instrumentation (HE experiments)

The seismic network for the PE1 high explosives experiments spans the NNSS (Figure 5), collecting waveform signals at local and regional distances for the year surrounding the explosive detonation. The seismic data, and other surface sensing modalities, use a telemetry network to deliver data to the experiment team in real time. The seismic network is comprised of stand-alone seismic sensors (e.g. geophones or broadband sensors), seismic arrays, and borehole instruments. Stand-alone seismic sensors consist of a triaxial geophone (i.e. GS11-D) or broadband sensor (i.e. Trillium Compact Posthole) recorded on REFTEK 130 digitizers. Additionally, the network incorporates the use of seismic arrays, which in this case are circular with one element at the center, five elements at a radius of 15 m from the center element, and another five elements at a radius of 50 m from the center element. One array has 3-component geophones and the others use vertical single component sensors.

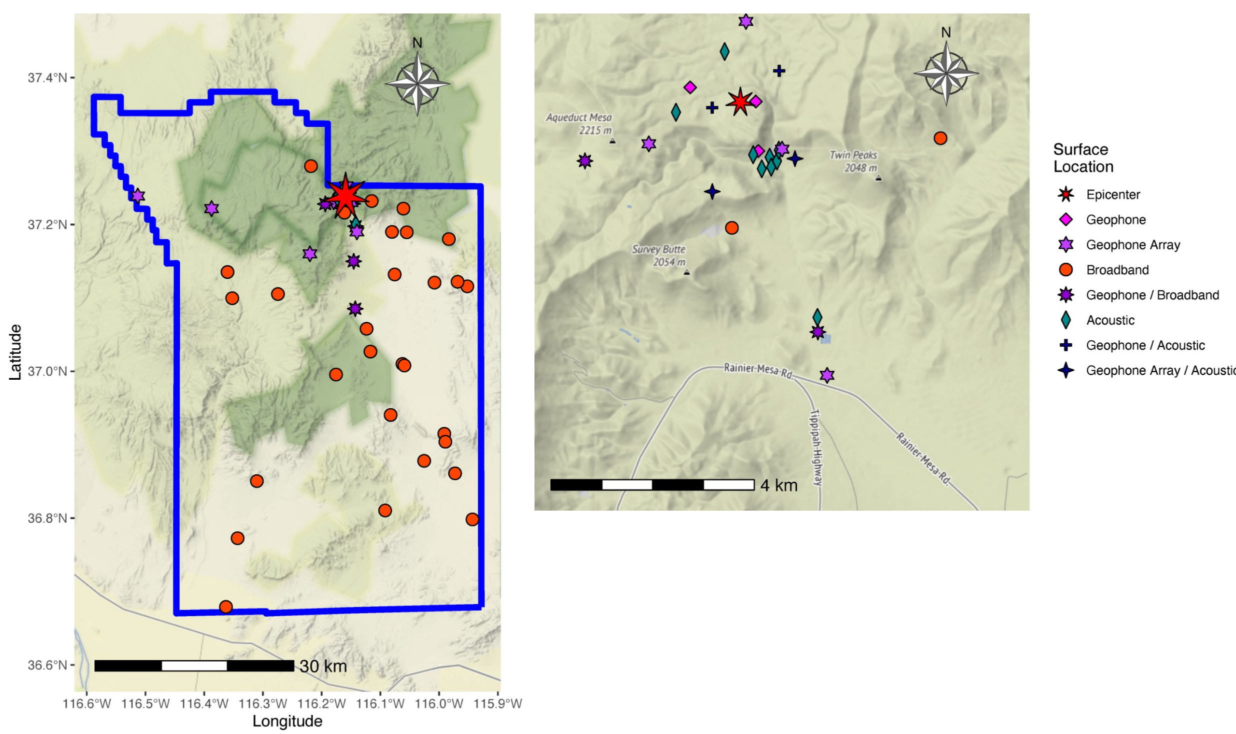

Figure 5. PE1 Surface seismo-acoustic network map. Left: Sitewide network map, with the NNSS boundary shown in blue. Right: Zoomed in view of the array in and around Aqueduct Mesa. Note that a handful of stations offsite are monitored for the explosive signatures and are not shown here.

The borehole seismometer station consists of three different sensors, one of which is permanently emplaced in a borehole approximately 50 m deep. The borehole sensor is a Silicon Audio 20-60 instrument packaged to withstand up to 5000 PSI hydrostatic pressure. A posthole version of this instrument was directly buried about one meter away from the borehole to measure surface noise levels. In addition, a Trillium Compact posthole sensor is directly buried about one meter away from the borehole to provide a comparison with the remainder of the PE1 broadband seismic network.

To increase recording density for PE1-A, temporary seismic stations were deployed on the NNSS in a linear network of single component seismic stations (i.e. Inova Hawks) extending southward from below Aqueduct Mesa to the Rock Valley region. Additionally, a set of three Inova Hawk arrays were deployed closer to the P-tunnel complex. These arrays have the same design as the permanent seismic arrays except that the center sensor is a 7-element gradiometer.

EM Measurements (HE and EM Experiments)
Electromagnetic signals were collected at two locations in P-Tunnel and eight locations on Aqueduct Mesa for both the PE1-A and EMX experiments. Similar acquisitions are planned for the remaining HE experiments. The mesa stations are arranged in two, roughly-radial lines: one radiating westwards from the surface projection of the HE sources and the other to the South-East. The tunnel measurement locations are approximately 50m and 60m from the EM coil and approximately 150m and 215m from the HE sources.

The magnetic measurements use orthogonally arranged induction magnetometers. Phoenix Geophysics MTC150 are used on the mesa and for low frequency measurements in the tunnel. AH Systems HFR-2 are used at high frequencies. Quasar Federal Systems, based on capacitive sensing and deployed as orthogonal triplets, measure electric field on the mesa. The tunnel electric field measurements use 3 orthogonal pairs of stainless-steel electrodes grouted into the walls and floor. On the mesa, signals are digitized at 24 kHz, while the tunnel signals are collected in 2 frequency ranges: 10 kHz and 1 MHz. Each electromagnetic station incorporates an accelerometer to allow discrimination of speed-of-light electromagnetic signals from induced signals caused by the mechanical shaking of the electromagnetic sensors.

Acoustic instrumentation (HE Experiments)
For the purposes of monitoring acoustic signatures emanating from the HE experiments, acoustic instrumentation was placed in and around the P-tunnel complex and on the Aqueduct Mesa. Within the P-tunnel complex, infrasound microbarometers and condenser microphones have been deployed to record sound waves inside the tunnel for minutes to hours before, during, and after each high explosive experiment. The system was designed to capture pressure fluctuations ranging from 100 seconds to 20+ kHz, or from the low infrasound to the high audio range. These signals are recorded on a custom-built National Instruments DAQ. Additionally, two acoustic deployments were undertaken around the P-tunnel apron: one six-stations array of microbarometers that were placed in an arc 200m from the tunnel entrance and a six-station linear array that extended into the tunnel and out over the apron.

Single acoustic stations were deployed on the Aqueduct Mesa, often co-located with seismic stations, and recorded on REFTEK RT130s. These data were also telemetered in real time to the execution team. These arrays consist of a 4-element array of microbarometers, with one element was located at the center, and the other three at the vertices of an equilateral triangle at a range of approximately 20 m from the center. All but one acoustic array, the one with the furthest offset, has one "seismically decoupled" sensor as a center element, to reduce interference of ground motion. Acoustic sensors have a dome-type wind screen installed above them to reduce the effects of hydrodynamic noise.

Meteorological (HE and Atmospheric Experiments)
For nearly every experiment in PE1, the weather conditions play an important role and therefore must be monitored by a network of sensors across the NNSS. This monitoring is done with support of the National Oceanic and Atmospheric Administration Special Operations and Research Division (NOAA SORD) and the data are telemetered in real time to the experiment team. Since each experiment has unique needs, meteorological instruments and network geometry vary for each experiment. For METEX and REACT, eleven 10-m tall meteorological towers (MT), six 2-m tall tripods with 3-d sonic anemometers (TT), one 3-m tall eddy covariance flux tower (BB), three Doppler profiling lidars (PL), two Doppler scanning lidars (SL), weather-balloon launched radiosondes (RS), and a tethered balloon system (TBS) equipped with wind, temperature, and aerosol sensors at multiple heights up to 800 m were deployed. For PE1-A, the eleven 10-m tall meteorological towers were in operation as well as the launch of two radiosondes to measure temperature and wind profiles in the planetary boundary layer. Additionally, ARL/SORD Mesonet network are included in the PE1 data set. Mesonet consists of twenty-five 10 m tall towers across the NNSS site (https://www.sord.nv.doe.gov/index.php) and a sodar at the southern end of NNSS.

Data Management and Availability

The PE1 experiments have a data management plan that includes details on how the data are acquired, what metadata are required, how data are checked (QA/QC'ed), and then how data will be made available to the multi-institution project team. Additionally, the plan provides guidance on releasing the data publicly after a 2-year hold. This data hold allows the project team, who contributed to the design, planning, and execution of the experiment, time to review and analyze the data prior to public release. We note that the 2-year hold applies separately to each phase the PE1-experiment (see Table 1). Therefore, data for each PE1 experiment will be released 2-years after that component is completed. Public release of waveform data is expected to be via a public, open-data repository, e.g. the EarthScope Consortium, and other types of data will be available directly from national laboratory points of contact or established data distribution platforms.

Conclusions

PE1 is a series of experiments conducted at NNSS Aqueduct Mesa/P-tunnel over the course of several years (Table 1). The experiment does not detonate nuclear explosives, but instead uses a series of chemical explosions, electromagnetic sources, and gas tracers to generate the types of multi-physics data needed to augment data collected during the U.S. nuclear explosives testing era (a.k.a. legacy data), which ended in 1992. In the aggregate, PE1 and legacy data address the science questions listed in the introduction. These questions include determination of whether an explosion was fully coupled or decoupled in an underground chamber and how signals from chemical and nuclear explosions differ. PE1 data are used to test models (numerical simulations, analytical calculations, and empirical relationships) of multi-physics signal generation from explosions and signal propagation to a local-distance, multi-physics sensor network. In addition to immediate use for model development and validation, PE1 data will be documented and archived for the benefit of future scientific studies.

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References

Ford, Sean R., Free-field Ground Motion Induced by Underground Explosions at Aqueduct Mesa with Predictions for Physical Experiment One (PE1). *Lawrence Livermore National Laboratory Report*. https://doi.org/10.2172/1605054, 2020.

Fourney, W. L., R. D. Dick, Steve R. Taylor, and T. A. Weaver, An analysis of three nuclear events in P-tunnel. *Los Alamos National Laboratory Report* LA-UR-94-1750, 1994.

National Security Technologies, LLC., A Hydrostratigraphic Framework Model and Alternatives for the Groundwater Flow and Contaminant Transport Model of Corrective Action Unit 99: Rainier Mesa-Shoshone Mountain, Nye County, Nevada, *Nevada National Security Site Report* DOE/NV/25946—146 (OSTI ID 934454), 2007

Prothro, L. B., Geologic Framework Model for the Underground Nuclear Explosions Signatures Experiment, P-Tunnel Testbed, Aqueduct Mesa, Nevada National Security Site. *Nevada National Security Site Report* DOE/NV/03624—0312, (OSTI ID 1495705), 2018.

Sawyer, D. A., R. J. Fleck, M. A. Lanphere, R. G. Warren, D. E. Broxton, and M. R. Hudson, Episodic Caldera Volcanism in the Miocene Southwest Nevada Volcanic Field: Revised Stratigraphic Framework, $^{40}Ar/^{39}Ar$ Geochronology and Implications for Magmatism and Extension, *Geological Society of America Bulletin*, v. 106, pp. 1304-1318, 1994.

Stauffer, Philip H., Otto, Shawn, Boukhalfa, Hakim, & Bodmer, Miles, Permeability Measurements in P-Tunnel, Nevada National Security Site. United States. *Los Alamos National Laboratory Report*, https://doi.org/10.2172/1883116, 2022

Wharton, S., Brown, M.J., Dexheimer, D., Fast, J., Newsom, R.K., Schalk, W.W., Wiersema, D.J., Capturing smoke plume behavior in complex terrain: an overview of the Nevada National Security Site Meteorological Experiment (METEX21), *Frontiers in Earth Science (11):* 11:1251153, doi: 10.3389/feart.2023.1251153, 2023.

Wiersema, D.J., Wharton, S., Arthur, R.S., Juliano, T.W. Lundquist, K.A., Glascoe, L.G., Newsom, R.K., Schalk, W.W., Brown, M.J., Dexheimer, D., Assessing turbulence and mixing parameterizations in the gray-zone of multiscale simulations over mountainous terrain during the METEX21 field experiment. *Frontiers in Earth Science (11)*: 11:1251180, doi: 10.3389/feart.2023.1251180, 2023