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Monitoring Techniques for Field Scale Experiments

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PE1 Experiment Team

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U.S. DEPARTMENT OF ENERGY BATTELLE

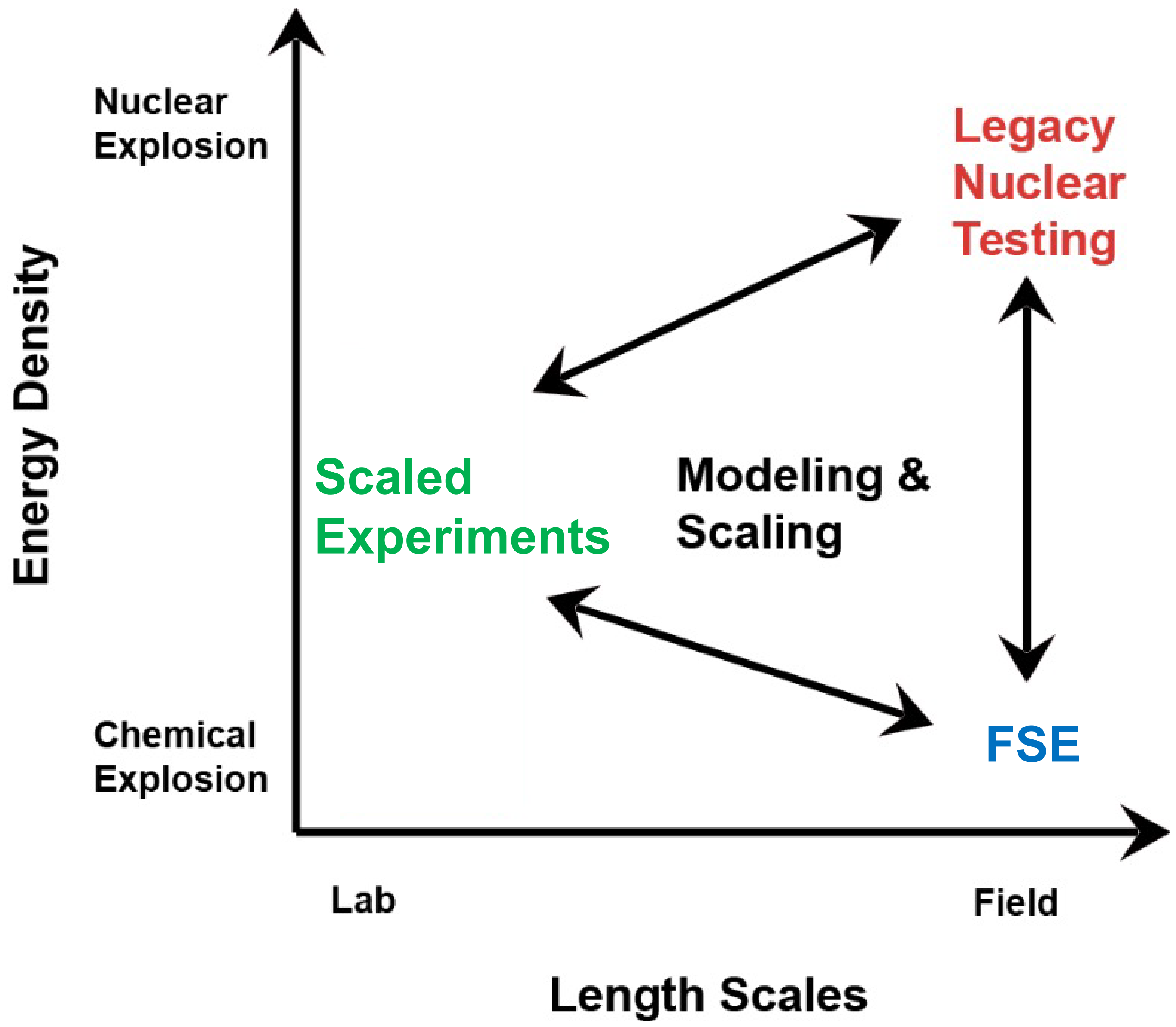
PNNL-SA-205079

Overview

- Field Experiment Motivation
  - Types of Field Experiments
- Nuclear Explosion Monitoring
- Field Experiment Monitoring
  - Comparisons with antineutrino detectors
- Conclusions

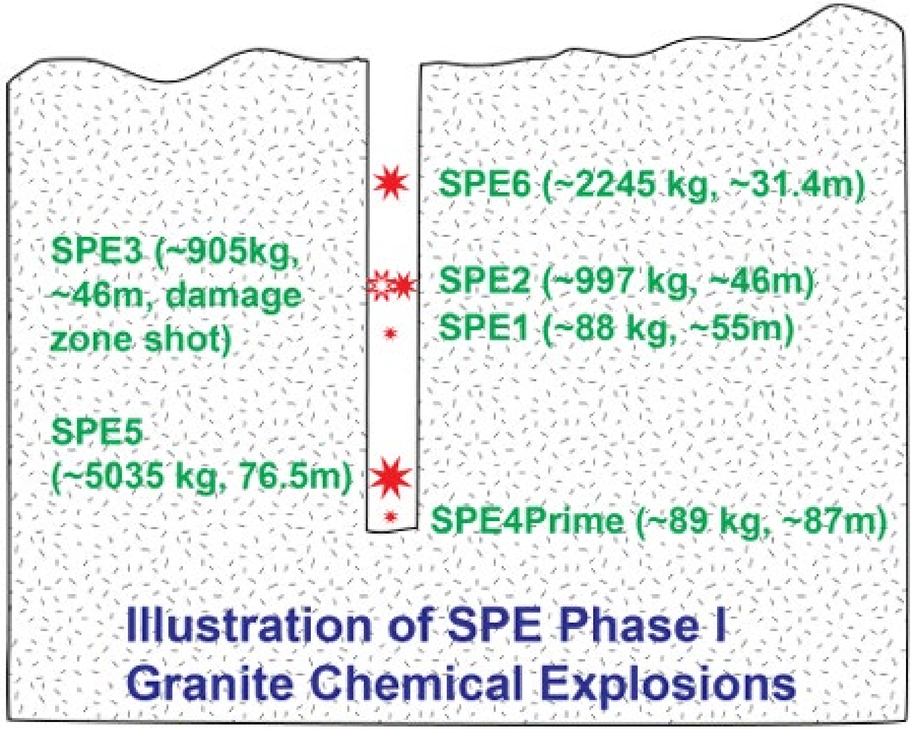
Motivation for Field Scale Experiments (FSE)

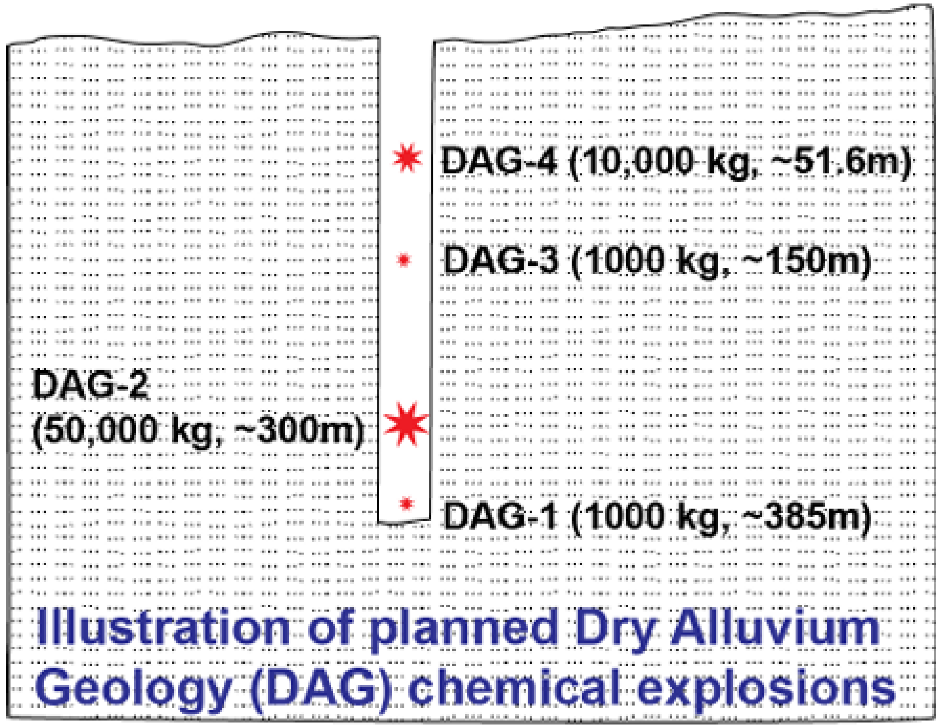
- Research into monitoring methods at local and regional length scales without a nuclear test
- Leverage laboratory/field experiments as surrogates
- Incorporate various length and timescales to identify potential signals
  - Chemical explosions
  - Radiotracers
  - Electromagnetic sources
  - Atmospheric releases



Example Field Experiments - Boreholes

- Deep central borehole with multiple small outer boreholes for sensors
- Long stand-off distances
  - Would expect minimal antineutrino signals if there were a fission source
- Seismic and Infrasound focused

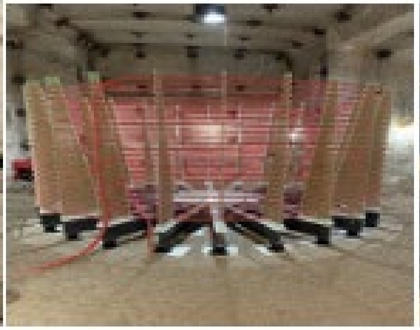


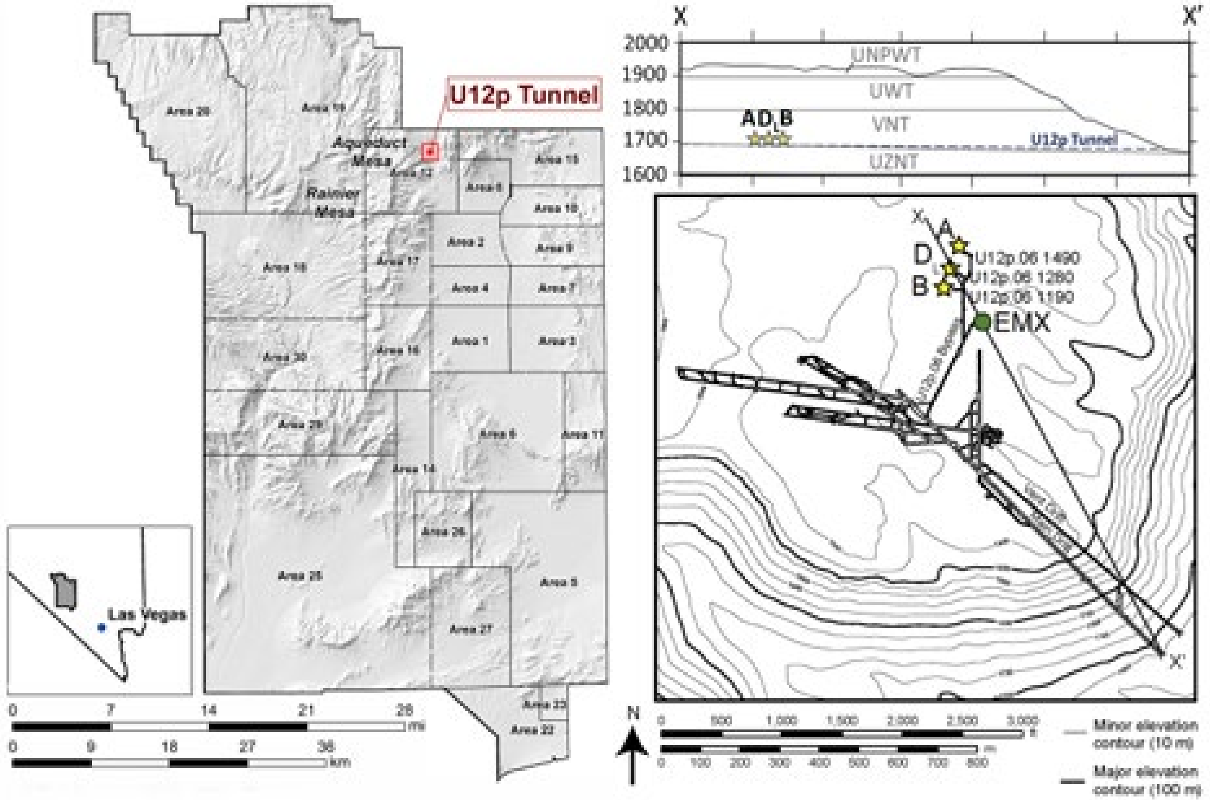


The Source Physics Experiment (SPE) Science Plan. doi:10.2172/1887003.

Example Field Experiments - Tunnel

- Tunnel layout for chemical explosives and surrounding sensors
- Shorter stand-off distances
  - Easier to get much closer to the experiment, but there are limits
  - Driven by safety and material migration
- Easier sensor deployment
  - More accommodating to large sensors



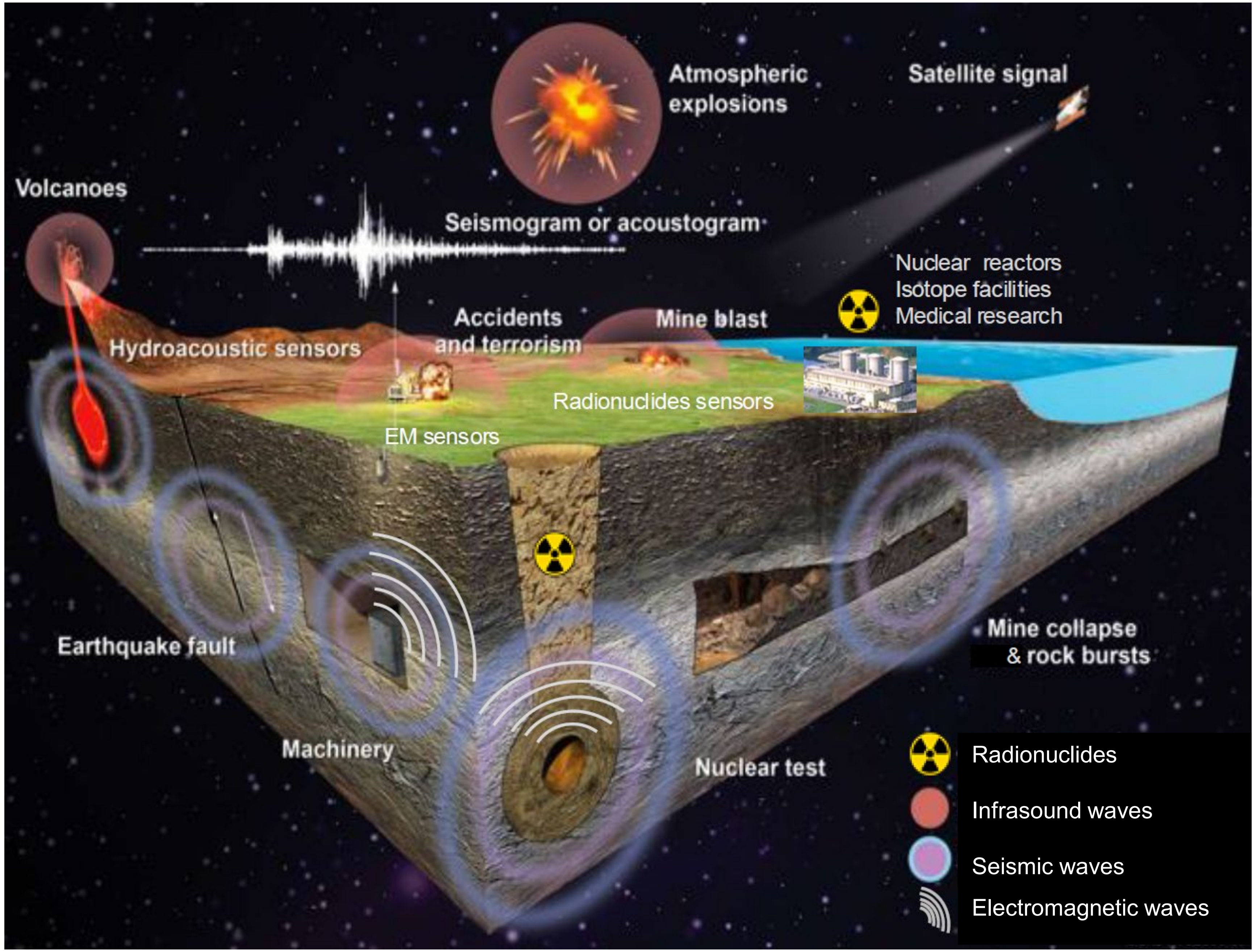


A multi-Physics Experiment for Low-Yield Nuclear Explosion Monitoring. doi:10.2172/2345984.

Nuclear Explosion Monitoring

- Earthquake versus Explosion
  - Seismic
  - Infrasound
  - Hydroacoustic

- Chemical versus Nuclear
  - Radionuclide
    - ✓ Aerosol
    - ✓ Noble Gas



Types of Monitoring During Field Experiments

- Seismic
  - Near source accelerometers
  - Far-field seismic
  - Distributed Acoustic Sensing
- Infrasound
  - Acoustic monitoring
- Electromagnetic Sensors
- Radionuclide
  - Aerosol
  - Noble Gas

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

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

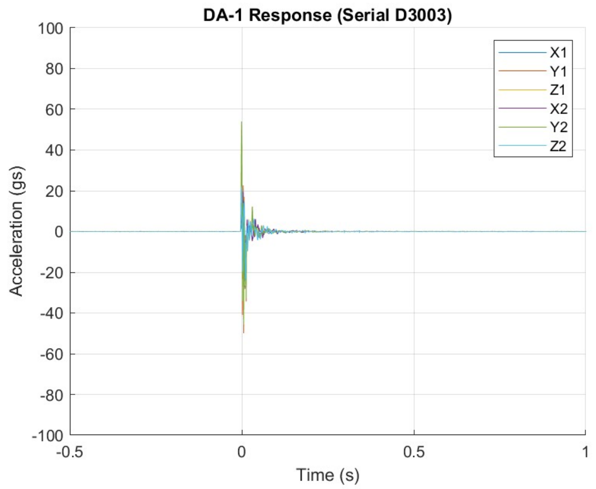
Tracers	Experiments					
	PE1-A	PE1-B	PE1-D_L	METEX	REACT	METREX
Xe-127*	X		X		X	X
Xe-133*		X				X
D_2O	X	X	X			
Tritium Gas (HT)	X	X	X			
Stable Tracers DU, I	X	X	X			
HE byproducts (from explosion)	X	X	X			
Geogenic gases (from rock damage)	X	X	X			
Smoke				X	X	X

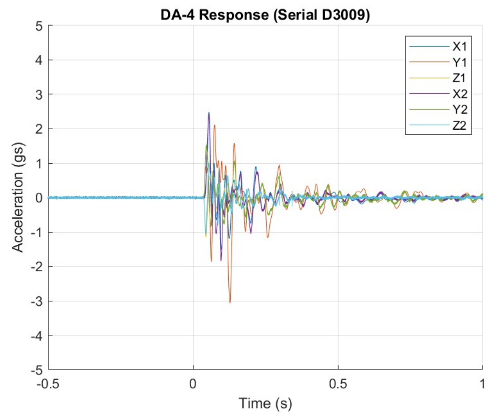
*Specific Xe tracer may depend on availability.

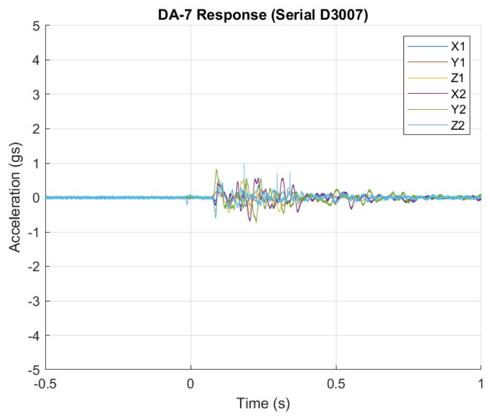
A multi-Physics Experiment for Low-Yield Nuclear Explosion Monitoring. doi:10.2172/2345984.

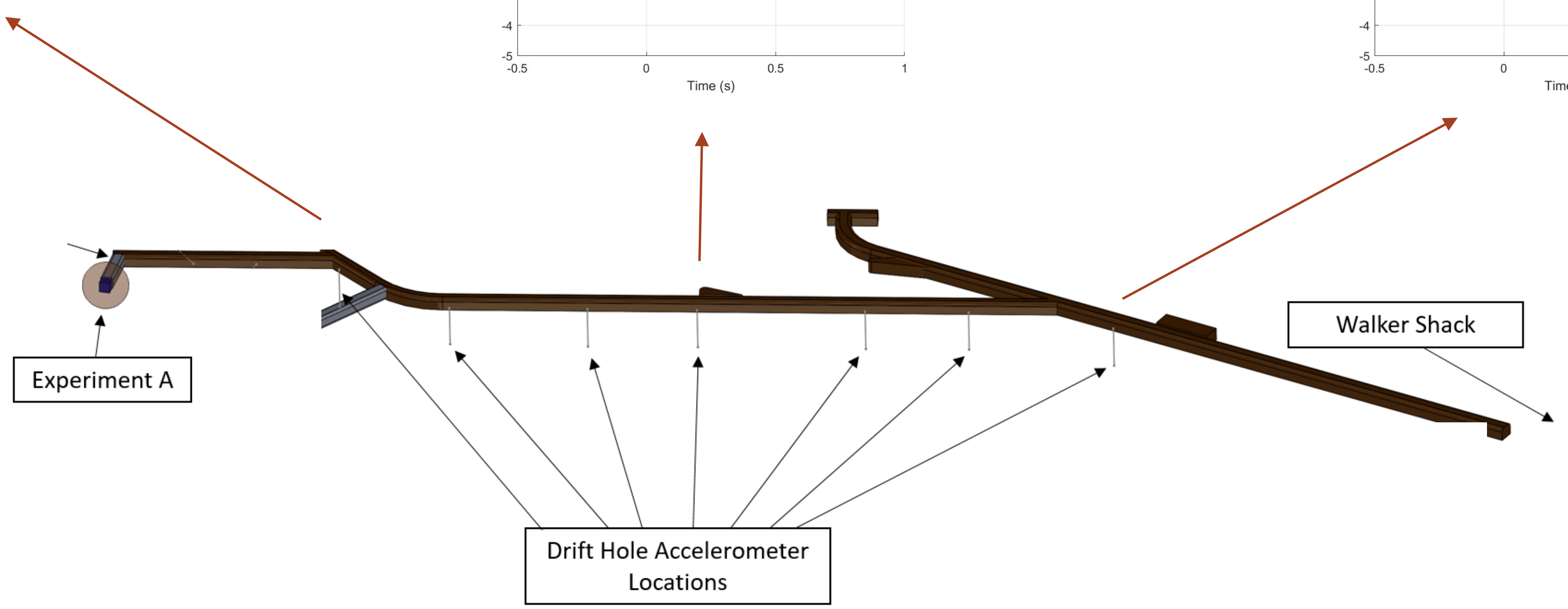
High G Environment throughout the Tunnel

Peak acceleration over 50g	Peak acceleration under 5g	Peak acceleration under 1g





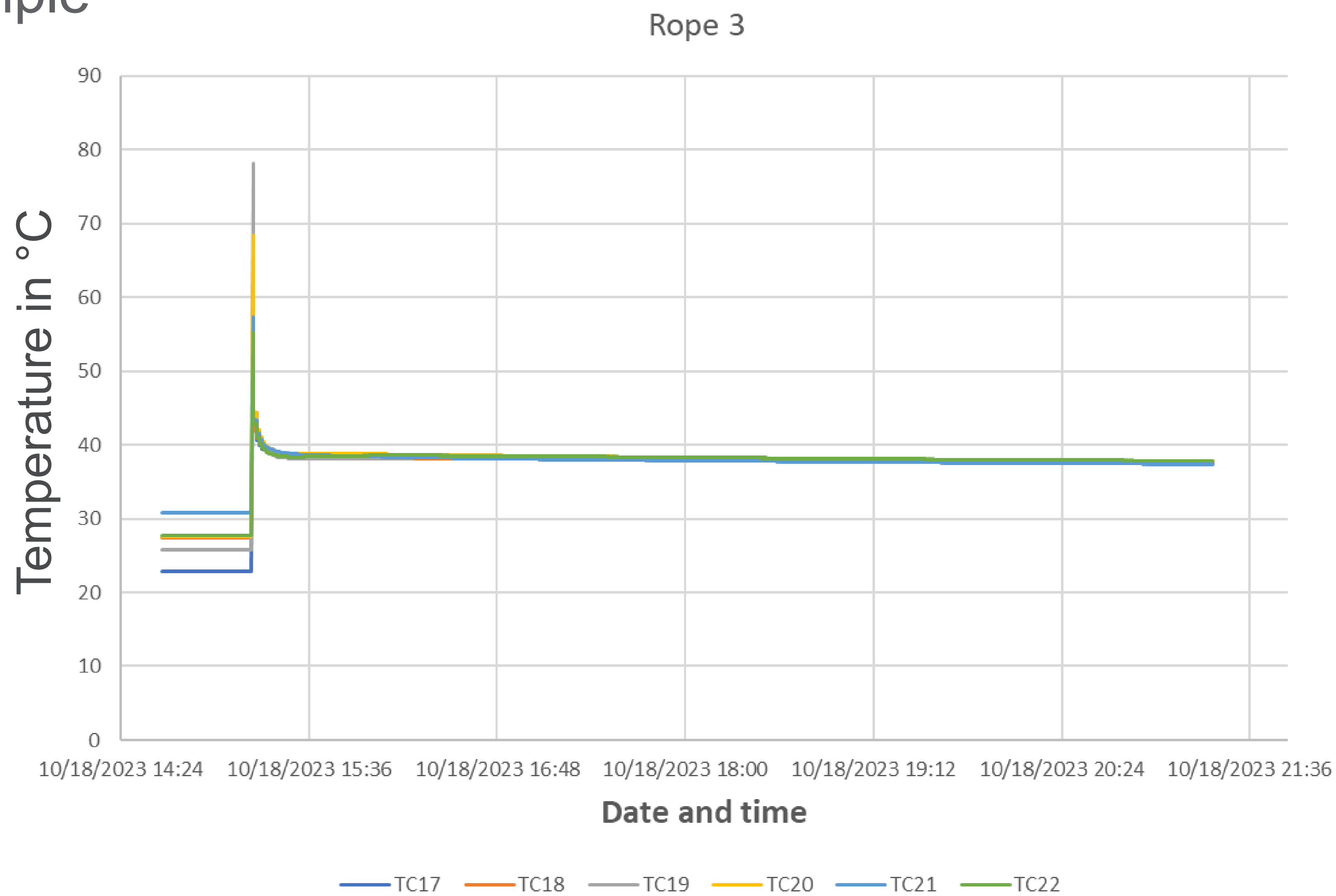




High G environment ~25m away

Cavity sensors recorded temperature and pressure

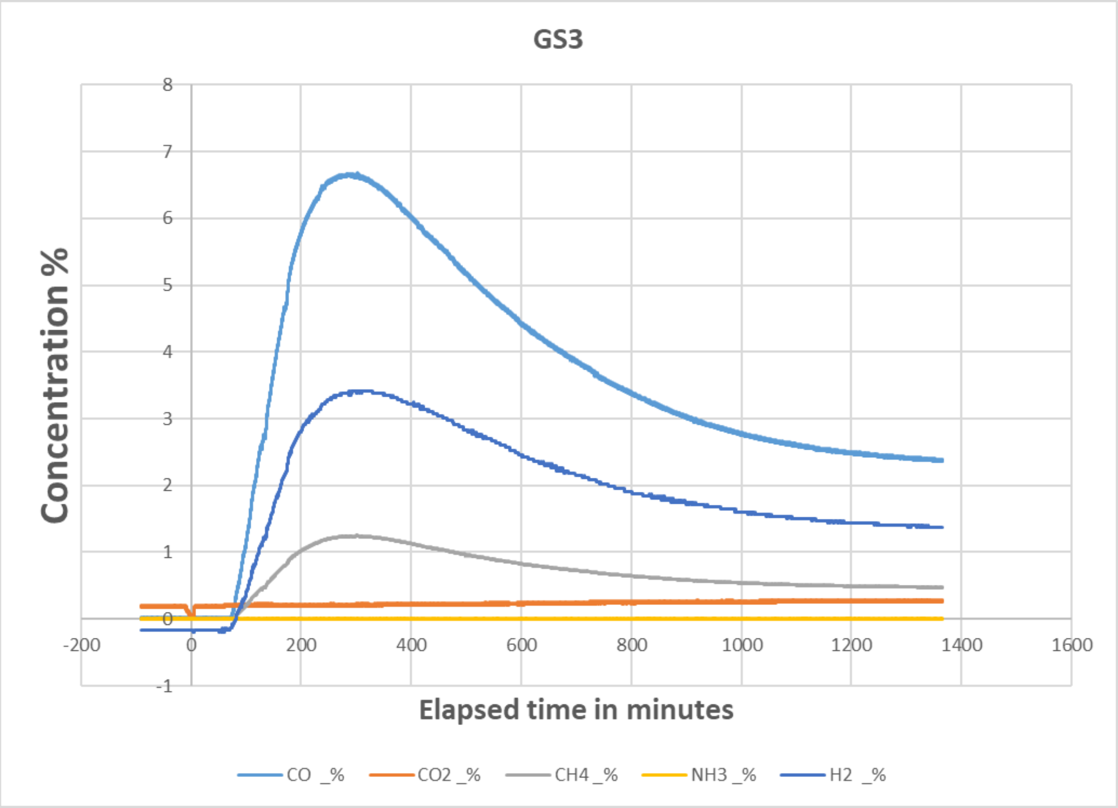
Example

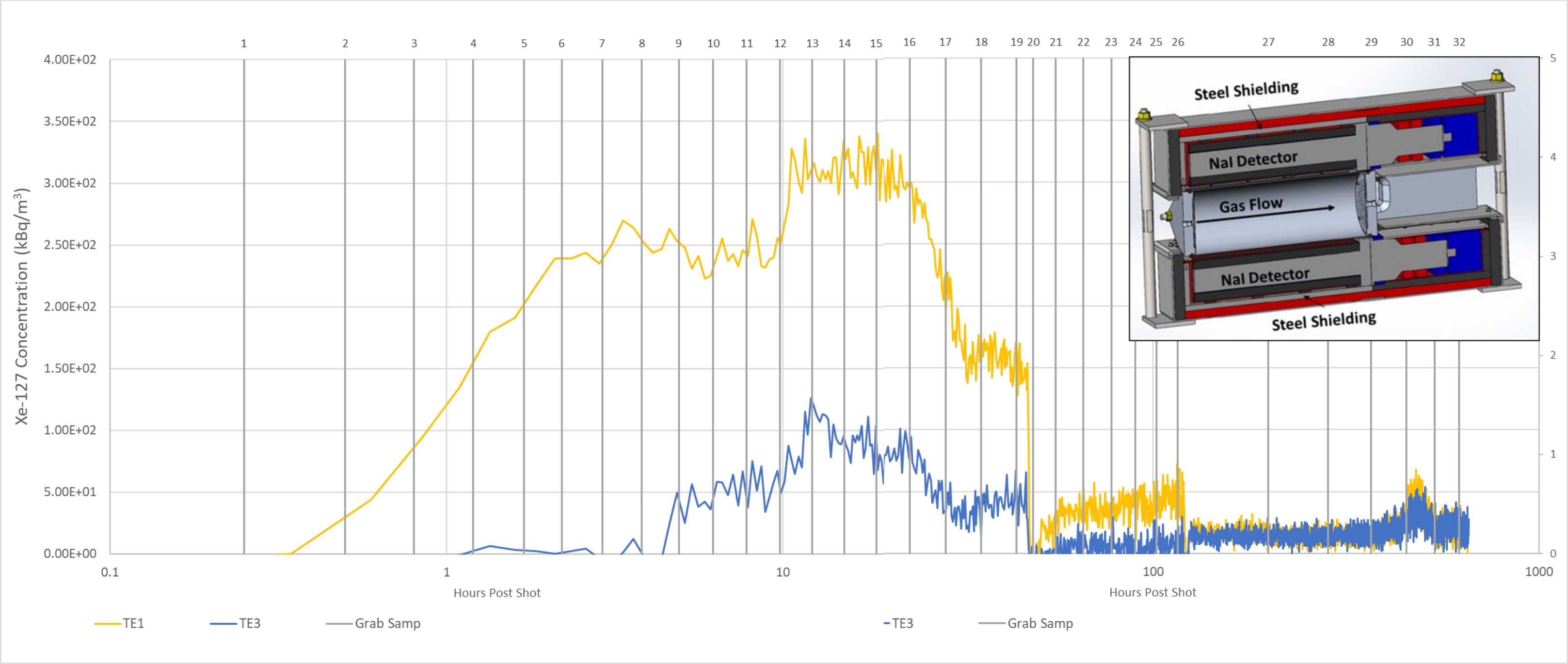


TC - Thermocouple

Tracer Gas Observations

- High explosive and tracer (^{127}Xe) gases observed in all the boreholes, the three tunnel locations and the ventilation.
- An antineutrino detector positioned near the experiment would also see tracer radioactivity





No Impact of Tracers on an Antineutrino Detector During Experiment Preparation

- ^{127}Xe
  - Decays via electron capture (neutrino emitted)
  - ~10^{10} neutrinos/s emitted from the tracer source
  - Not a major background for an inverse beta decay detector

- ^{133}Xe
  - Decays via beta decay (antineutrino emitted)
  - ~10^{10} antineutrinos/s emitted from the tracer source
  - Still orders of magnitude lower than a fission source

- Fission
  - ~10^{22} antineutrinos/10 tons in 10 seconds

Impact of Tracers on an Antineutrino Detector During Experiment Execution

- The tracers wouldn't result in an antineutrino background while emplaced, but what about following gas migration?
- Diluted contributions of ~10^6 (anti)neutrinos/second near the sensor location
  - Still insignificant compared to fission even with the stand-off distance
- Larger background would be from gamma ray emissions from ^{127}Xe or ^{133}Xe
- Without a prompt vent, any backgrounds would likely be after the first 10 seconds of interest for an antineutrino detector

Measurement Distances

- Adjacent to High Explosive
  - CORRTEX (COntinuous Reflectometry for Radius versus Time Experiments)
    - ✓ Consumed
- Out to ~10m
  - Cavity sensors (e.g., temperature and pressure)
    - ✓ Consumed
    - ✓ Large seismic shock
- Out to ~100m
  - Seismic, infrasound, and gas sensors
    - ✓ Persistent
    - ✓ Smaller seismic shock

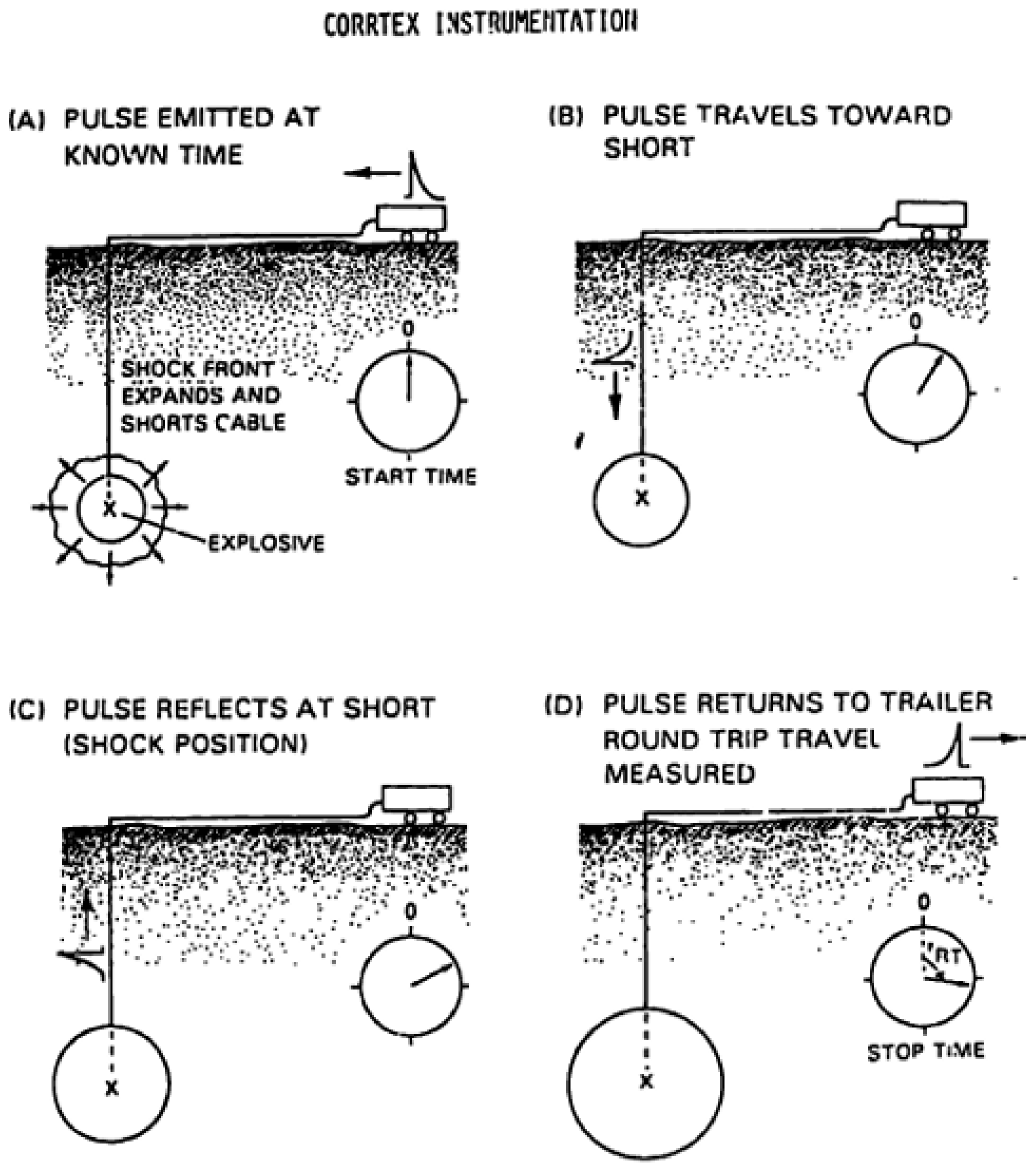


Fig. 1. Schematic of CORRTEX system operation.

Use of CORRTEX to measure explosive performance and stem behavior in oil shale fragmentation tests, https://digital.library.unt.edu/ark:/67531/metadc1110100

Potential Measurement Methods

- Explosion
  - CORRTEX – immediate
    - ✓ (COntinuous Reflectometry for Radius versus Time Experiments)
- Chemical versus Nuclear
  - Core samples – long duration drill back
  - Radionuclide monitoring – gas migration time scales (immediate to slow)
  - Neutrons - immediate
  - Gammas - immediate

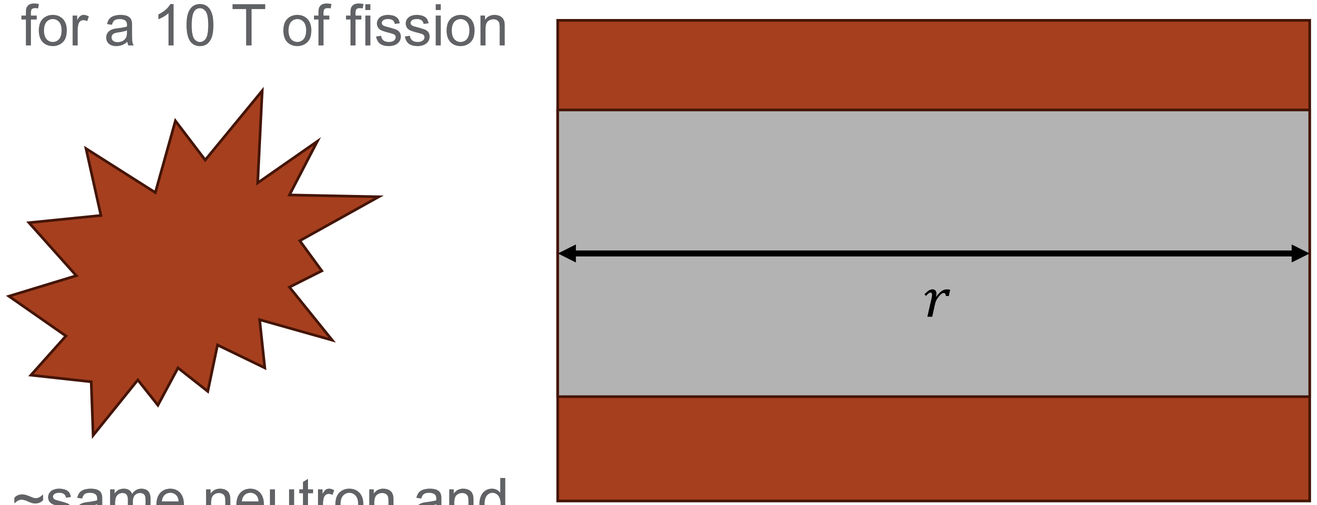
https://www.sciencebase.gov/mercury/#/images/rock-sample

PE1-A Measurement

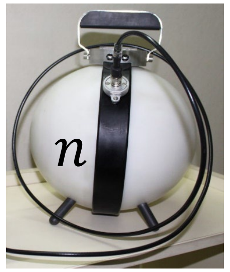
SAUNA QB - Array: The realization of a new concept in radioxenon detection, https://doi.org/10.1016/j.jenvrad.2023.107136.

Prompt Monitoring Signal Comparison

~10^{22} antineutrinos
for a 10 T of fission



~same neutron and
gamma ray flux



$\bar{\nu}$

$Antineutrino\colon\ \sigma_{IBD} \sim 10^{-43}\ cm^2$

- When does the flux of neutrons or gamma rays equal 1 cm^{-2}?

Prompt Monitoring Comparison

$$I = \frac{I_0}{4\pi r^2} e^{-\Sigma r}$$

$$Neutrons\ @\ 1\ MeV:\ \Sigma \approx 0.1\ cm^{-1}$$

$$I = \frac{1\ n}{cm^2} = \frac{10^{22}}{4\pi r^2} e^{-0.1r}$$

$$\mathrm{r} \approx 3.5\ meters$$

$$I = \frac{I_0}{4\pi r^2} e^{-\mu r}$$

$$Gamma\ rays\ @\ 1\ MeV:\ \mu \approx 0.05\ cm^{-1}$$

$$I = \frac{1\ \gamma}{cm^2} = \frac{10^{22}}{4\pi r^2} e^{-0.05r}$$

$$r \approx 6\ meters$$

- At these distances, the flux of neutrons or gamma rays equals 1 per cm^2
- Beyond this distance the size of the detectors will start to increase beyond a handheld detector
- Outside of a 25 m concrete plug the attenuation decreases neutron and gamma rates beyond detection levels.
  - Detectors would either rely on leakage or being put closer at the above distances and sacrificed after the prompt signal.

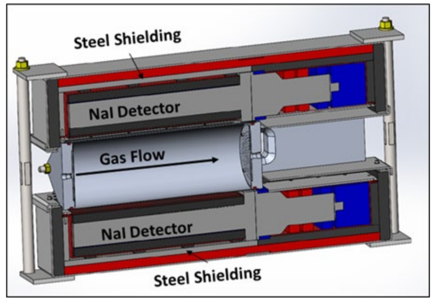
Monitoring with Noble Gas Detection

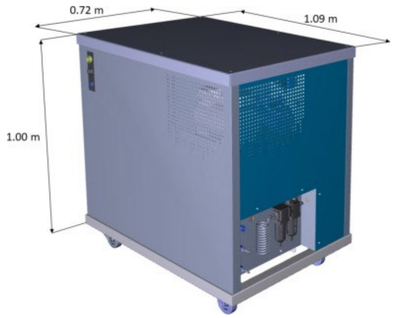
- 1 Ci tracer source: gas sensors saw ~100 kBq/m3 of ^{127}Xe in the tunnel

$$\frac{100\,\frac{kBq}{m^3}\ detected}{1\ Ci\ ^{127}Xe\ source} = 2.7\ \times 10^{-6} dilution\ factor$$

$$\frac{Detection\ Limit}{Dilution} = Source\ Activity$$

$10\ T{\sim}10^{13}\ Bq\ of\ ^{133}Xe$



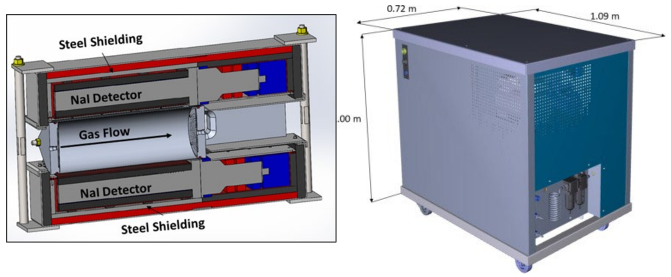
	^{133}Xe Detection Limit	Minimum Source Activity	Comparable Fission Yield
	$\sim 5\ kBq/m^3$	$\sim 10^9\ Bq$	$\sim 10^{-3}\ T$
	$\sim 0.5\ mBq/m^3$	$\sim 10^2\ Bq$	$\sim 10^{-10}\ T$

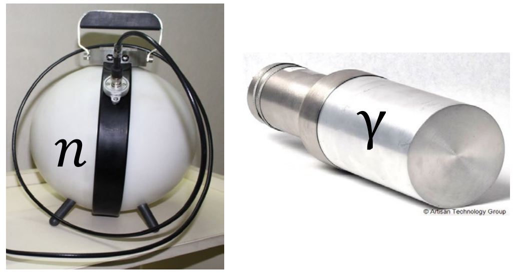
*Assumes same driving force as the experiment for the gases into the environment

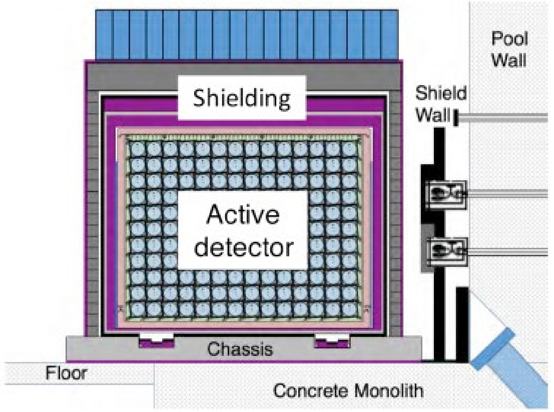
SAUNA QB -
doi.org/10.1016/j.jenvrad.2023.107136.

Detection Mechanism Comparisons

	Noble Gas	Neutron/Gamma	Antineutrino
Advantages	- Sensitivity - Sample at a different location from detector - Isotopic discrimination	- COTS detectors available	- No shielding the signal - No attenuation - No spoofing
Disadvantages	- Gas migration dependent - Potentially delayed response	- Attenuation of signals - Other sources as possible backgrounds	- Size (space and shock impact) - Cost







The PROSPECT reactor antineutrino experiment, doi.org/10.1016/j.nima.2018.12.079.

Detector Operational Requirements and Needs

- Needs to survive high G-forces
- Need well understood backgrounds
- Sensitivity calculations for detector options – Yield vs Distance
  - Understanding how that compares to potential sites

- **No false positives**
- What does “zero” mean?
- Cost-benefit analysis
  - How does it compare to other methods?
  - How does it impact the field experiments?
  - Additional risks?

Conclusions

- Field scale experiments are used to progress nuclear explosion monitoring
- Seismic monitoring alone isn't enough to demonstrate the chemical nature of the experiments
- Monitoring for non-nuclear nature
  - Could be performed with radioactive material, neutrons, gammas, or antineutrinos depending on time and distance requirements
- Distance of closest approach may be limited

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Experiment Report: LLNL-TR-864107

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PE1 team: multi-institution and multi-disciplinary

Abbot, G.[6], Alexander, T.[2], Alger, E.[1], Alvarez, A.[5], Annabelle, N.[2], Antoun, T.[1], Auld, G.[6], Malach, A.[4], Banuelos, H.[5], Barela, M.[3], Barnhart, T.[3], Barrow, P.[4], Bartle/, T.[5], Bockman, A.[1], Bodmer, M.[4], Bogolub, K.[7], Bonner, J.[11], Borden, R.[4], Boukhalfa, H.[3], Bowman, D.[4], Bri/, C.[2], Broman, B.[9], Broome, S.[4], Brown, B.[5], Burghardt, J.[2], Chester, D.[6], Choens, C.[4], Chojnicki, K.[2], Churby, A.[1], Cole, J.[3], Coleman, T.[9], Collard, J.[6], Couture, A.[2], Crosby, G.[1], Cruz-Cabrera, A.[4], D'Saint Angelo, D.[5], Dea, M.[3], Dekin, W.[1], DeVisser, B.[5], Dietel, M.[5], Downs, C.[4], Downs, N.[5], DzeniQs, E.[1], Eckert, E.[5], Eras, S.[4], Euler, G.[3], Ezzedine, S.[1], Fast, J.[2], Feldman, J.[2], Featherston, K.[5], Foxe, M.[2], Freimuth, C.[5], Fritz, B.[2], Galvin, G.[6], Gamboa, S.[5], Garner, L.[5], Gascoigne, T.[5], Gastelum, J.[2], Gaylord, J.[1], Gessey, D.[5], Glasgow, B.[2], Glavin, G.[6], Glomski, A.[1], Goodwin, M.[6], Green, D.[6], Griego, J.[4], Grover, S.[5], GuQerrez, J.[3], Haas, D.[8], Hall, R.[3], Hall, A.[1], Hardy, D.[5], Hauk, D.[2], Heath, J.[4], HoldcroT, J.[6], Holland, A.[4], Honjas, W.[7], Howard, K.[3], Hudson, C.[8], Ingraham, M.[4], Jaramillo, J.[4], Jenkins, A.[6], Johnson, C.[2], Jones, K.[4], Falliner, J.[4], Junor, W.[3], Keillor, M.[2], Kent, G.[7], Keogh, M.[5], Kibikas, W.[4], Kleadbeater, K.[6], Knox, H.[2], Knox, J.[2], Kuhlman, K.[4], Kwiatkowski, C.[3], Laintz, K.[3], Lapka, J.[8], Larotonda, J.[5], Layne, J.[3], Ledoux, N.[3], Li, S.[3], Linneman, D.[2], Lipkowitz, P.[5], MacLeod, G.[3], McCann, E.[2], McCombe, R.[3], Meierbachtol, C.[3], Mellors, R.[1], Memmo/, B.[5], Mendenhall, W.[9], Mendez, J.[2], Myers, S.C.[1], Miller, X.[5], Miller, A.[5], Miranda, F.[5], Montano, M.[4], Moore, M.[2], Morris, J.[1], Munley, W.[2], Murillo, E.[5], Myers, T.[4], Navarro, A.[2], Nippress, S.[6], O/o, S.[3], Peacock, S.[6], Pemberton, S.[3], Perea, R.[2], Peterson, J.[2], Pierre-Yves, L.[3], Plank, G.[7], Podrasky, A.[9], Podrasky, D.[9], Pope, J.[4], Poskey, M.[5], Powell, M.[4], Price, A.[1], Puyleart, A.[2], Quintana, B.[3], Rahn, T.[3], Rendon, C.[5], Reppart, J.[5], Rico, H.[5], Roberts, B.[4], Robey, E.[4], Rodd, R.[1], Rodriguez, M.[4], Rogall, A.[3], Romanczuk, A.[1], Roth, M.[2], Salyer, G.[5], Savran, B.[7], Schalk, W.[10], Seifert, C.[2], Seitz, D.[3], Shao, X.[3], Sirota, D.[2], Slack, J.[2], Slater, D.[7], Smith, K.[7], Smith, D.[5], Spears, B.[3], Sprinkle, D.[2], Stead, R.[3], Stephens, M.[5], Strickland, C.[2], Tafoya, A.[3], Tafoya, J.[4], Tagoe, M.[5], Taguba, C.[2], Tarnecki, L.[3], Tatge, R.[5], Teich-McGoldrick, S.[4], Terry, B.[6], Thompson, R.[5], Townsend, M.[5], Tubbs, G.[3], Turley, R.[5], Valdez, N.[4], Van Morris, A.[2], Vergara, S.[5], Vigil, J.[3], Villanueva, J.[5], Vorobiev, O.[1], Wallace, D.[3], Walrath, T.[3], Wharton, S.[1], White, R.[5], White, H.[6], Whitehill, A.[2], Williams, M.[4], Wilson, J.[4], Wood, L.[2], Wright, C.[3], Wright, A.[4], Xu, G.[4], Yang, X.[1], Yost, R.[3], Zeiler, C.[5]

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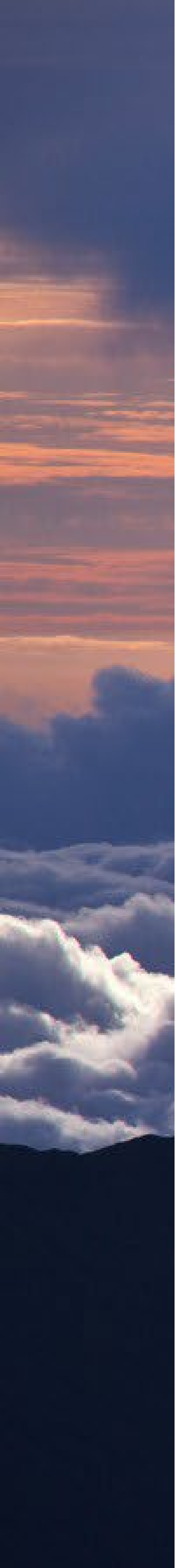

Thank you