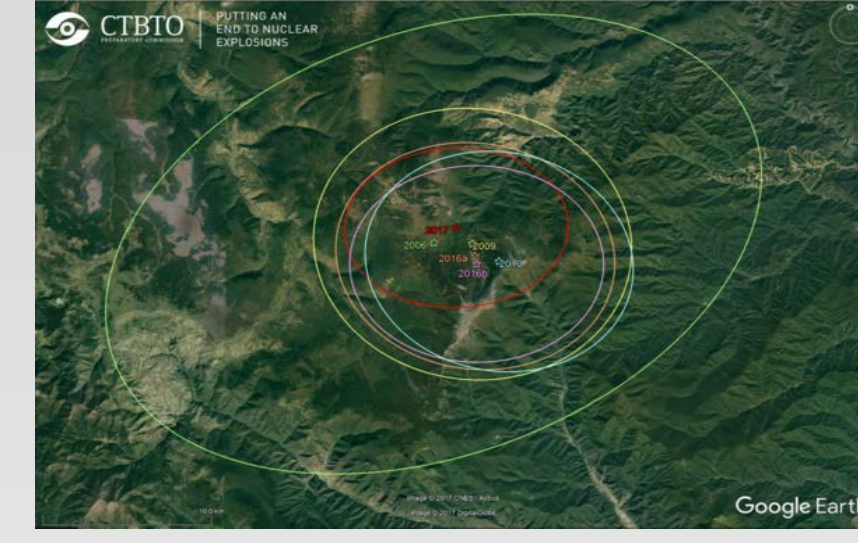
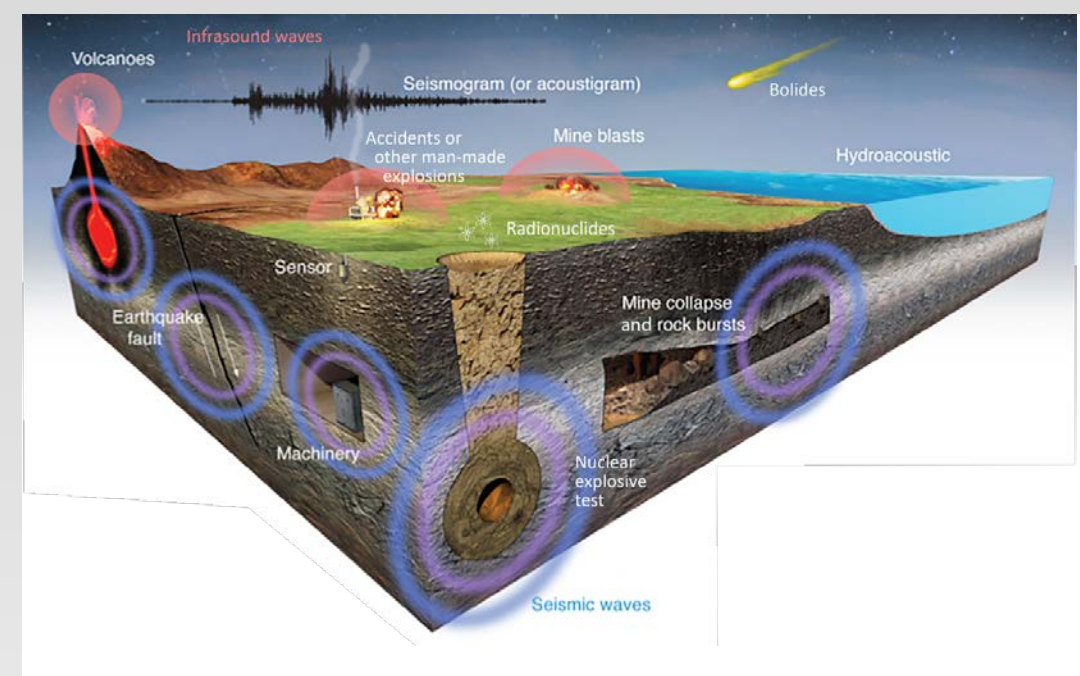




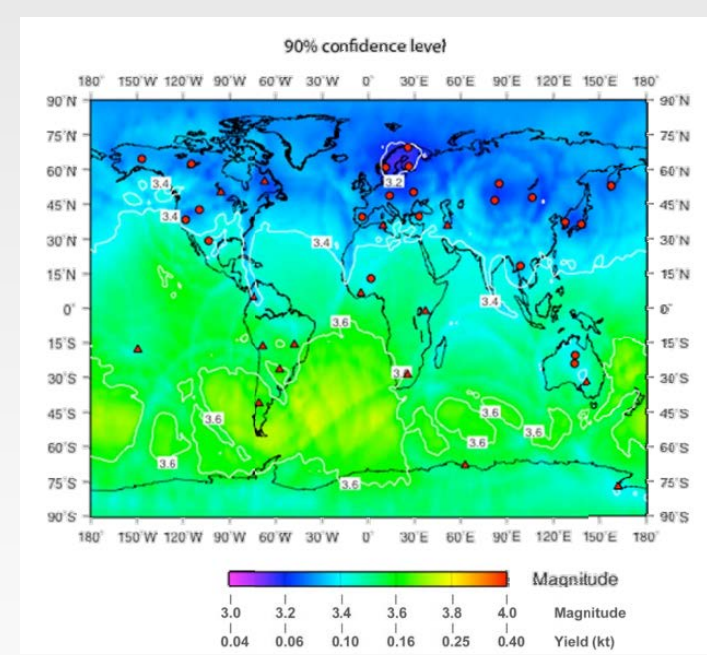
## Nuclear Explosion Monitoring Overview

Nuclear explosion monitoring utilizes a mix of monitoring phenomenologies to detect explosions and verify if they are nuclear in nature

- Seismic sensors (land)
- Hydroacoustic (water)
- Infrasond (air)
- Radionuclide
  - Particulate
  - Noble Gas



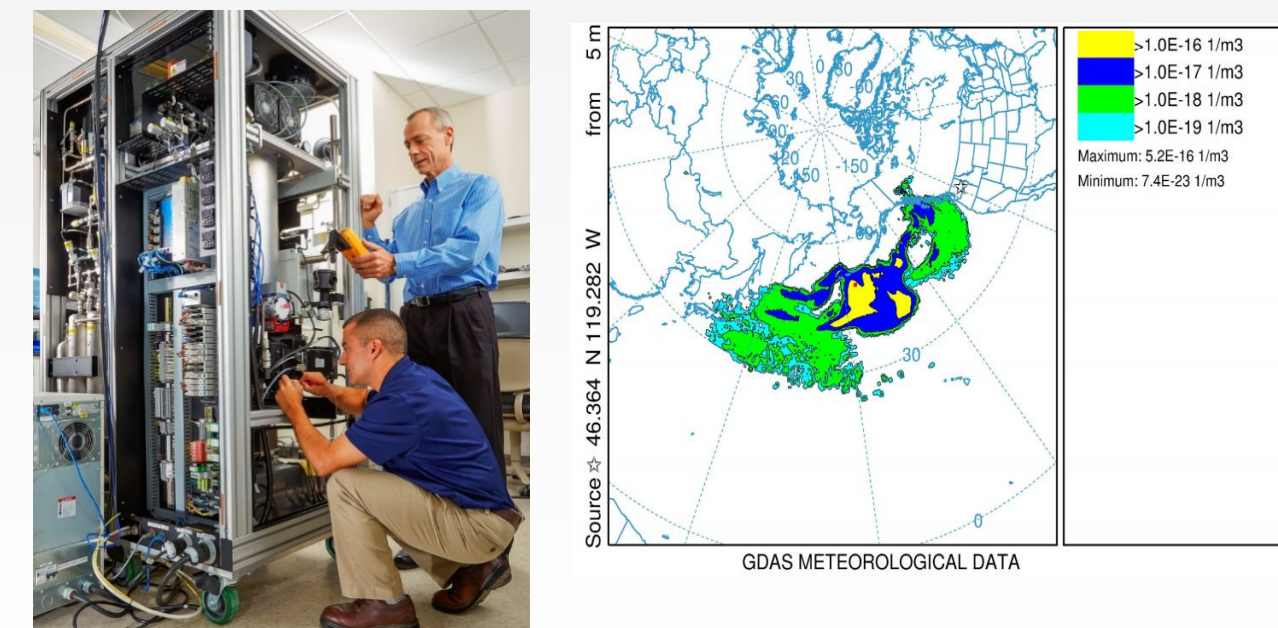
The error ellipse (red) has shrunk to +/- 6.7 km or 109 km<sup>2</sup> [2]



Radionuclide detectors continuously monitor for radioactive byproducts of a nuclear explosion. In combination with atmospheric transport modeling, the source location and activity release can be estimated [1]



Seismic sensors provide the ability to determine the location and yield of an explosion (or earthquake).

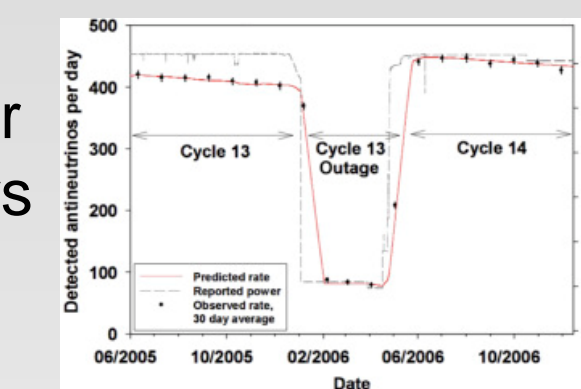


- As no technology is a single silver bullet, a proposed monitoring criteria for evaluating new technologies within this context is given as:
- Detection threshold of order 0.5 kT is required (Seismic thresholds of 0.09 to 0.56 kT from Table 2-2 in [3])
  - Potential stand-off of ~1000 km is required (see RN spacing)

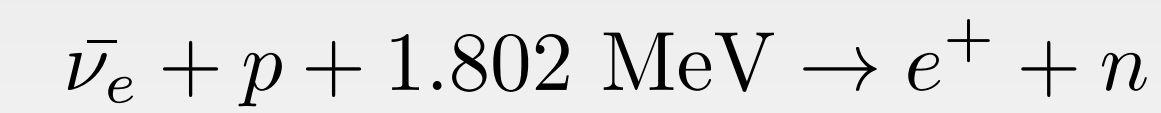
## Antineutrino Production and Detection

- Antineutrinos are produced as a result of the fission of uranium and plutonium. After a fission occurs, the subsequent beta decays result in the emission of 5-6 antineutrinos.
- Antineutrinos are emitted in large quantities from nuclear reactors, allowing the capability for antineutrino detectors to see the change in antineutrino emission rates as the fuels changes from uranium to plutonium [4].

Isotope	Average # of $\bar{\nu}_e$
<sup>235</sup> U	5.51
<sup>238</sup> U	6.28
<sup>239</sup> Pu	4.83
<sup>241</sup> Pu	5.63



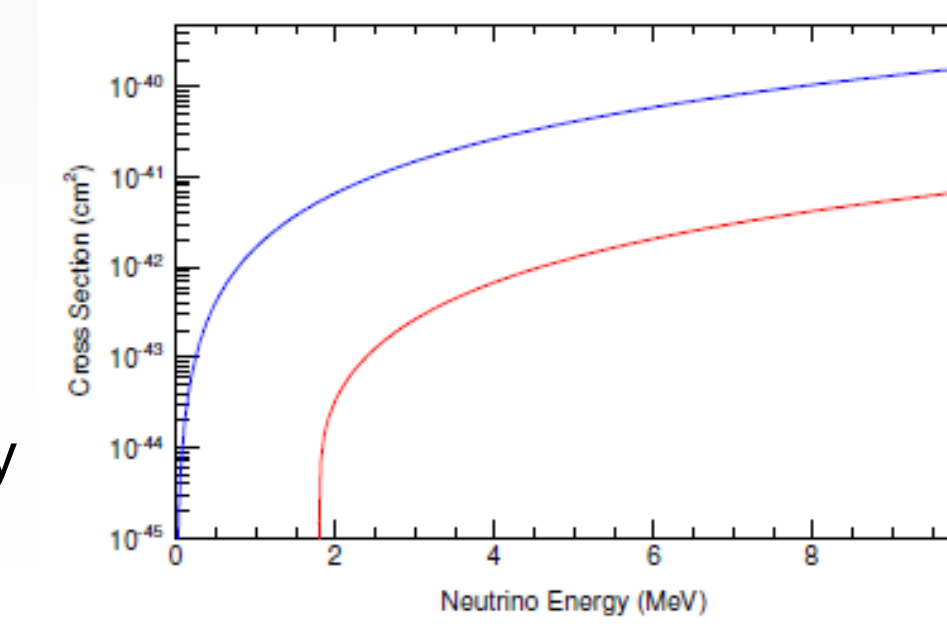
- Inverse beta decay (IBD) is used in the detection of antineutrinos, but the cross section is extremely low.



- Coherent Neutrino-Nuclear Scattering (CNNS) was recently discovered and could allow for a reduction in the size of detectors of approximately 100x, but the threshold needed for fission antineutrinos has yet to be demonstrated [5].

Detection methods under consideration:

- IBD: Scintillator
  - Pro: Good detection efficiency
  - Con: Expensive at large scale
- IBD: Gd-H<sub>2</sub>O
  - Pro: Great for large volumes
  - Con: Generally lower detection efficiency
- Coherent scattering
  - Pro: Potential for smaller detectors
  - Con: Not yet a proven detection technology



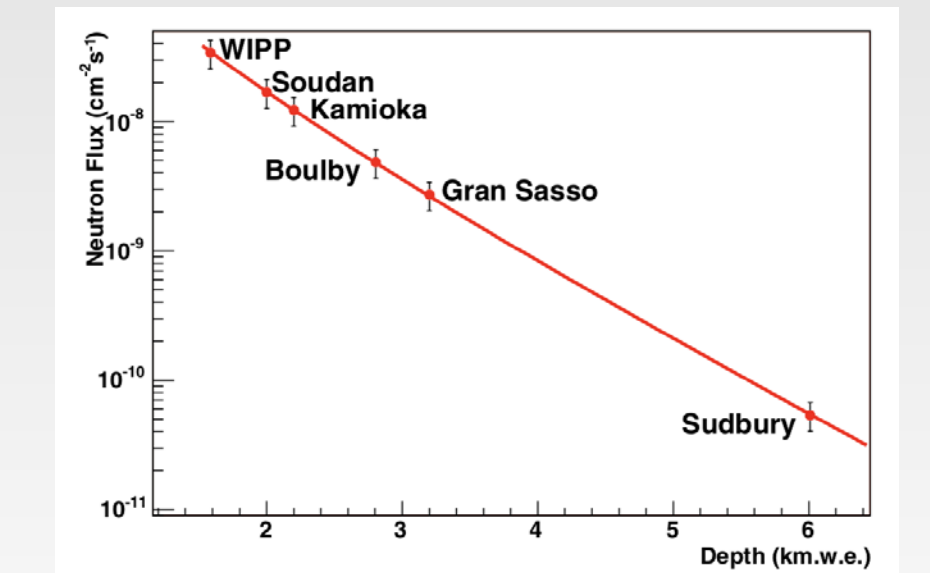
## Antineutrino Backgrounds

Anticipated backgrounds for all detector types include:

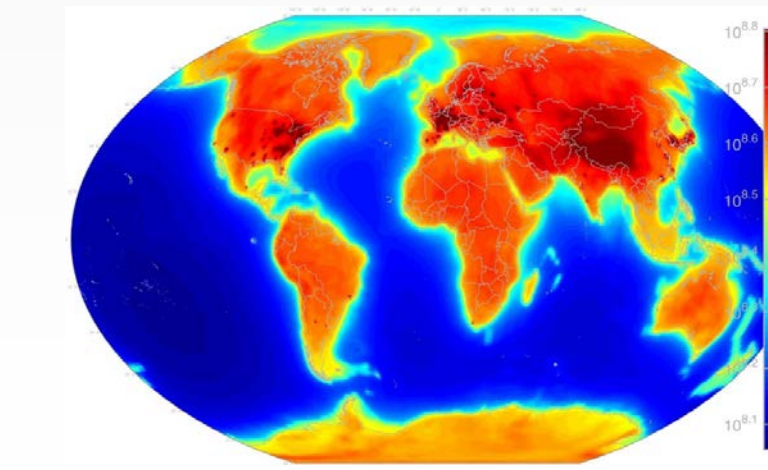
- False antineutrino events (i.e. fast neutrons)
- Terrestrial antineutrinos (i.e. geo-neutrinos from Uranium fission in the earth)
- Anthropogenic antineutrinos (i.e. nuclear reactor antineutrinos)
- Solar neutrinos (when not performing IBD)

False antineutrino events can be minimized with detector shielding and overburden. Antineutrino backgrounds cannot be shielded and are a location-dependence, irreducible background.

- A large overburden of either land or water is generally required to sufficiently reduce the neutron and muon flux. The overburden requirement further limits the available locations that can be used for the detector [6].



The antineutrino survey suggests that a detector in the water would have the most desirable background levels [7].



2015 survey of antineutrinos around the world [8]

- Antineutrino hotspots can be seen at the locations of nuclear reactors with general elevation due to uranium/thorium content in the crust and mantle.
- There is a need to validate global antineutrino flux models to support this measurement methodology.

$$\text{Global antineutrino background} \sim 10^6 \frac{\bar{\nu}}{\text{cm}^2 \cdot \text{s}} \text{ with } E > 1.802 \text{ MeV}$$

## Use Case: International Monitoring

$$\text{Explosion Yield} = \mathcal{O} 0.5 \text{ kT} \approx 1 \text{ kT}$$

$$\text{Monitoring Distance} = 1000 \text{ km}$$

- In a 1 kT nuclear explosion, there are approximately  $8.7 \times 10^{23}$  antineutrinos produced.
- Of those antineutrinos, approximately 10% are above the 1.802 MeV threshold for inverse beta decay in the first 10 second [9] following the fission (required to correlate the antineutrino events)

$$\text{Available Antineutrinos} = \text{Yield} \cdot \frac{\text{Antineutrinos}}{1 \text{ kT}} \cdot \text{Fraction emitted in 10 seconds} \cdot \text{Fraction Above 1.802 MeV}$$

$$\text{Antineutrino Flux at Detector} = \frac{\text{Antineutrino Flux}}{\text{Distance from explosion}^2} = \frac{7.25 \times 10^{22} \text{ Antineutrinos}}{(1000 \text{ km})^2} = 7250000 \frac{\bar{\nu}}{\text{cm}^2}$$

For inverse beta decay, the average cross section of interaction is  $10^{-44} \text{ cm}^2$  (compared to a neutron fission cross section of  $\sim 10^{-24} \text{ cm}^2$ )

$$\text{Antineutrino interaction rate} = 7250000 \frac{\bar{\nu}}{\text{cm}^2} \cdot 10^{-44} \text{ cm}^2 \cdot 3.3 \times 10^{23} \frac{1}{\text{g}} = 2.4 \times 10^{-14} \frac{\bar{\nu} \text{ events}}{\text{g}}$$

Based on the background rates, a burst of 5 events is required to correlate the antineutrinos to the same source.

$$\text{Detector size} = \frac{\text{Burst size}}{\text{Antineutrino interaction rate}} = \frac{5 \text{ events}}{2.4 \times 10^{-14} \frac{\bar{\nu} \text{ events}}{\text{g}}} = 2.06 \times 10^{14} \text{ g} = 200 \text{ MTonnes} = 200,000,000 \text{ m}^3$$

At an average cost of \$100M for a 50 kTonne detector (Super-K), the calculated antineutrino detector would cost ~\$400B.



One antineutrino detector for the global nuclear explosion monitoring network would be ~200x the size of the Empire State building and cost ~400 billion dollars. Compared to a total network cost of 1 billion dollars.

## Use Case: Test Site Transparency

An alternative use case for antineutrino detectors is the co-operative scenario where an antineutrino detector is deployed as part of a Test Site Transparency agreement.

- 1 kT nuclear explosion threshold
- 50 km stand-off (based on Nevada Test Site dimensions)

$$\text{Antineutrino interaction rate} = 2.9 \times 10^9 \frac{\bar{\nu}}{\text{cm}^2} \cdot 10^{-44} \text{ cm}^2 \cdot 3.3 \times 10^{23} \frac{1}{\text{g}} = 9.7 \times 10^{-12} \frac{\bar{\nu} \text{ events}}{\text{g}}$$

$$\text{Detector size} = \frac{5 \text{ events}}{9.7 \times 10^{-12} \frac{\bar{\nu} \text{ events}}{\text{g}}} = 500 \text{ kTonnes}$$

$$\text{Detector size} = 500 \text{ kTonnes} = 500,000 \text{ m}^3$$

$$\text{Detector cost} = \$1 \text{ billion}$$



It should be noted that in this instance, there would need to be an agreement with the country to be monitored. It would be possible to move a test-site in the amount of time it takes to build and deploy an antineutrino detector of this magnitude.

Alternatively, if we assume that 0.1% of all of the radioxenon produced from a 1 kT explosion was released [10], we can calculate the level above the detection threshold of 0.15 mBq/m<sup>3</sup> (Xenon International threshold requirement [11-13]).

$$1 \text{ kT} \sim 10^{15} \text{ Bq of } ^{133}\text{Xe} \cdot 10^{-3} \text{ assumed release fraction}$$

$$10^{12} \text{ Bq of } ^{133}\text{Xe} \cdot \text{dilution of } 10^{10} \frac{1}{\text{m}^3} = 10^2 \frac{\text{Bq}}{\text{m}^3}$$

Thus, in the assumed test-site transparency scenario, a radioxenon detector could expect to see a  $\sim 1.5 \times 10^{-6}$  kT explosion.

An antineutrino detector for test site transparency would need to be 500 kTonnes and cost approximately 1 billion dollars. It is expected that a 1 million dollar radioxenon detector would have a detection threshold approximately 1 million times better than the antineutrino detector.

## Conclusions

- Very large detectors with limited deployment options would have costs greater than the entire existing monitoring network.
- The size can be reduced for test-site transparency, but in this instance the detection threshold would need to be reduced, a requirement that could be met with current radioxenon detection systems.
- Although not described, if CNNS could be utilized for the detection of fission antineutrinos, it may reduce the size of the detector to the 10 MTonne range. However, CNNS detectors only exist in the kg range at the current time.
- The geo-neutrino flux of  $\sim 10^6 \bar{\nu}/\text{cm}^2/\text{s}$  will serve as a signal-to-noise limitation as the distance from a nuclear explosion increases (observed in the international monitoring scenario). Solar neutrinos provide an additional background for CNNS detectors.

### References

- [1] Maceira, Monica, Blom, Philip Stephen, MacCarthy, Jonathan K., Marcoll, Omar Eduardo, Euler, Garrett Gene, Begnaud, Michael Lee, Ford, Sean R., Pasyanos, Michael E., Orris, Gregory J., Foxe, Michael P., Arrowsmith, Stephen J., Merchant, B. John, and Slinkard, Megan E. *Trends in Nuclear Explosion Monitoring Research & Development - A Physics Perspective*. United States: N. p., 2017. Web. doi:10.2172/1355758.
- [2] https://CTBTO.org
- [3] National Research Council. 2012. *The Comprehensive Nuclear Test Ban Treaty: Technical Issues for the United States*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/12849>.
- [4] N S Bowden 2008 J. Phys.: Conf. Ser. 136 022008
- [5] Foxe, Michael, *Low-Energy Ionization Yield in Liquid Argon for a Coherent Neutrino-Nucleus Scatter Detector*, Thesis: The Pennsylvania State University, 2013.
- [6] D.-M. Mei and A. Hime, Phys. Rev. D 73, 053004
- [7] Guillian, E.H. Earth Moon Planet (2006) 99: 309. <https://doi.org/10.1007/s11038-006-9110-x>
- [8] S.M. Usman, G.R. Jocher, S.T. Dye, W.F. McDonough & J.G. Learned, AGM2015: Antineutrino Global Map 2015, Scientific Reports volume 5, Article number: 13945 (2015)
- [9] Rachel Carr, Ferenc Dalnoki-Veress, and Adam Bernstein, Phys. Rev. Applied 10, 024014.
- [10] A. Ringbom, A. Axelsson, M. Aldener, M. Auer, T.W. Bowyer, T. Fritioff, I. Hoffman, K. Khruustalev, M. Nikkinen, V. Popov, Y. Popov, K. Ungar, G. Wotawa, *Radioxenon detections in the CTBT international monitoring system likely related to the announced nuclear test in North Korea on February 12, 2013*, Journal of Environmental Radioactivity, Volume 128, 2014, Pages 47-63. <https://doi.org/10.1016/j.jenvrad.2013.10.027>
- [11] Requirements for Xenon International: Revision 1, Pacific Northwest National Laboratory, PNNL-22227 (Rev. 1), doi:10.2172/1122330
- [12] <https://tbe.com/energy/xenon-international>
- [13] [https://www.pnnl.gov/main/publications/external/technical\\_reports/PNNL-23176.pdf](https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23176.pdf)

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