Antineutrino Monitoring of Reactors for Nuclear Nonproliferation

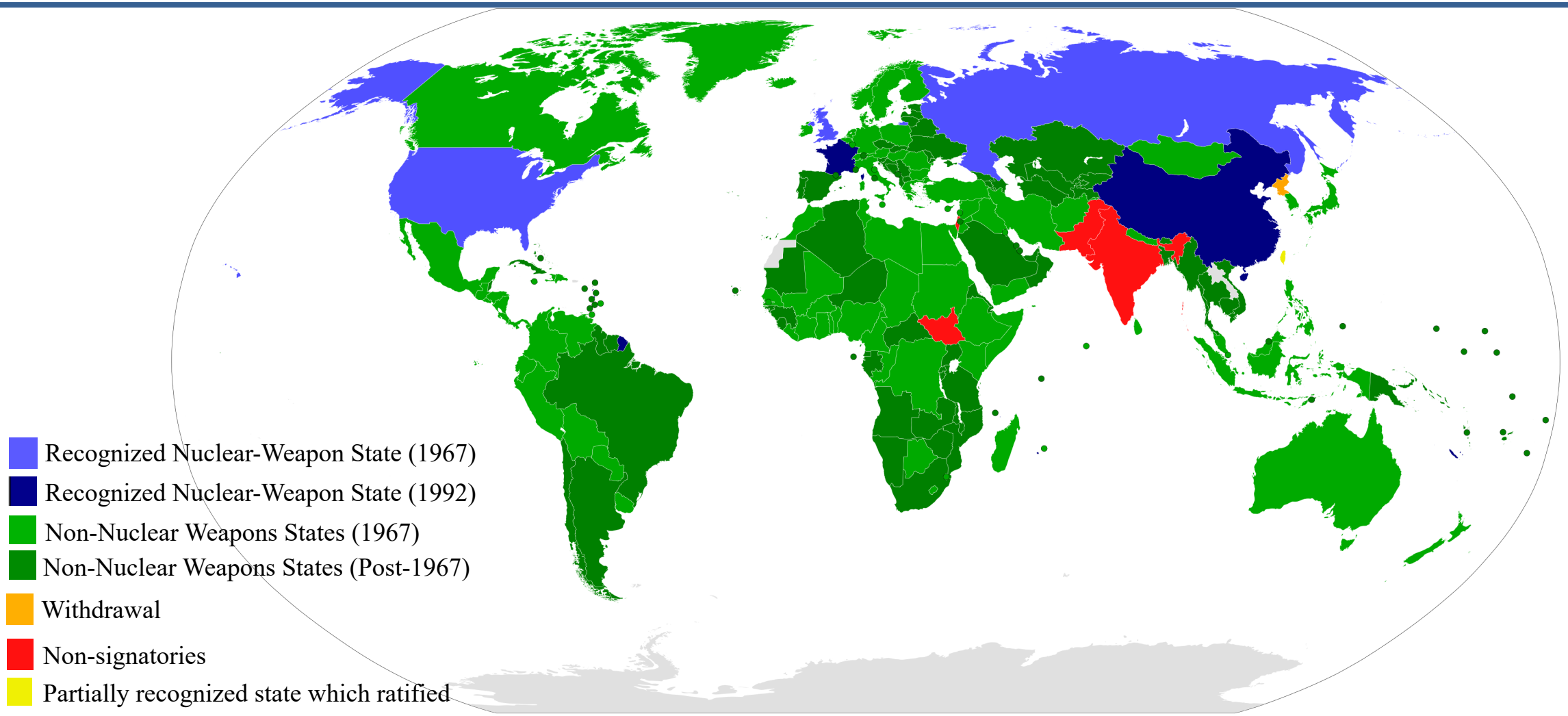
Tomi Akindele
Rare Event Detection Group

Neutrino2020
June 25, 2020

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

The Non-Proliferation Treaty (NPT)



Current IAEA Safeguards Practices

Reactor
(1-1.5 years)

- Check declarations
- **Item accountancy**
- Containment and surveillance

Onsite Fuel Storage
(months to years)

- Gross defect detection
- **Item accountancy**
- Containment and surveillance

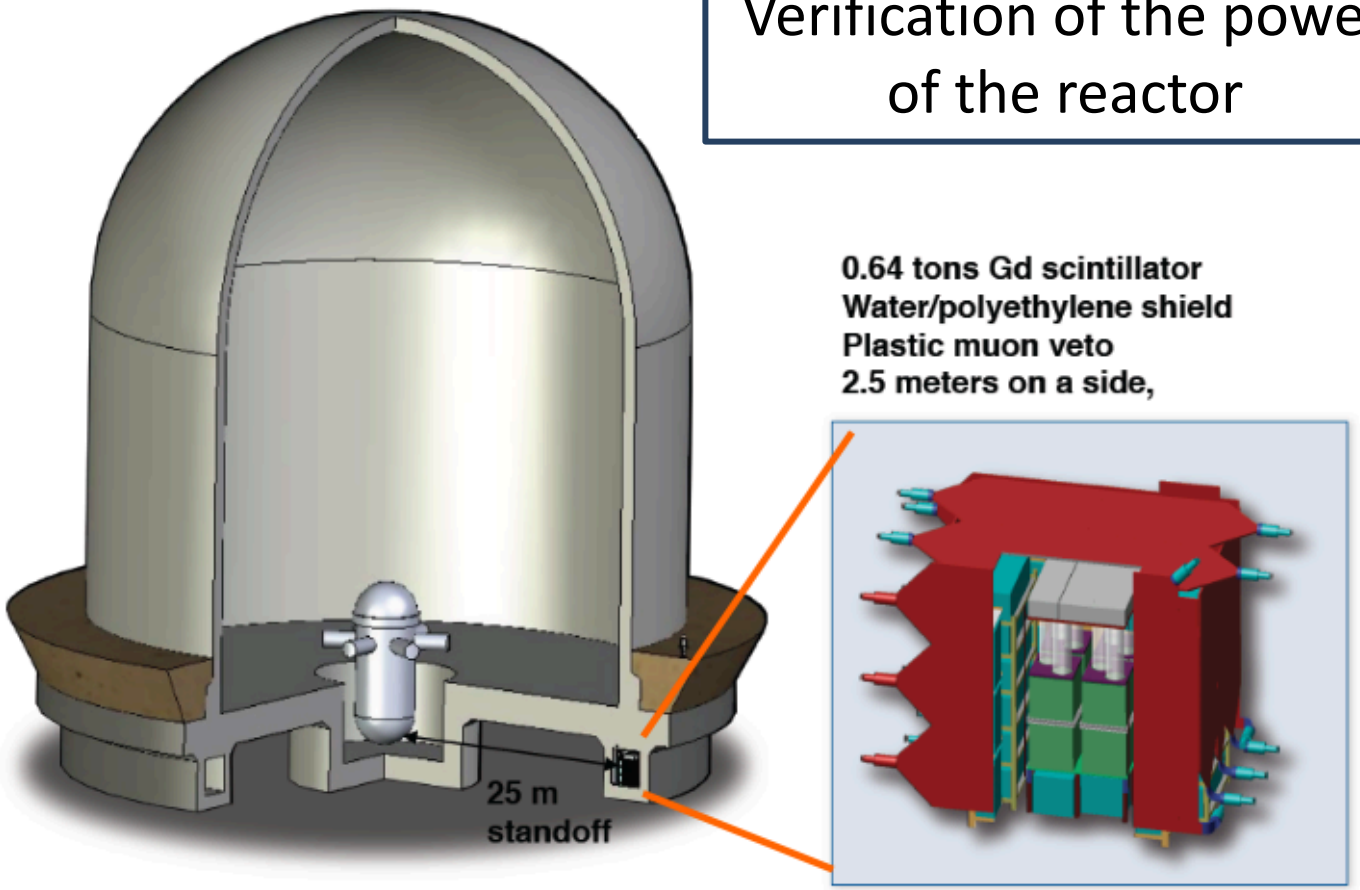
Reprocessing
(months)

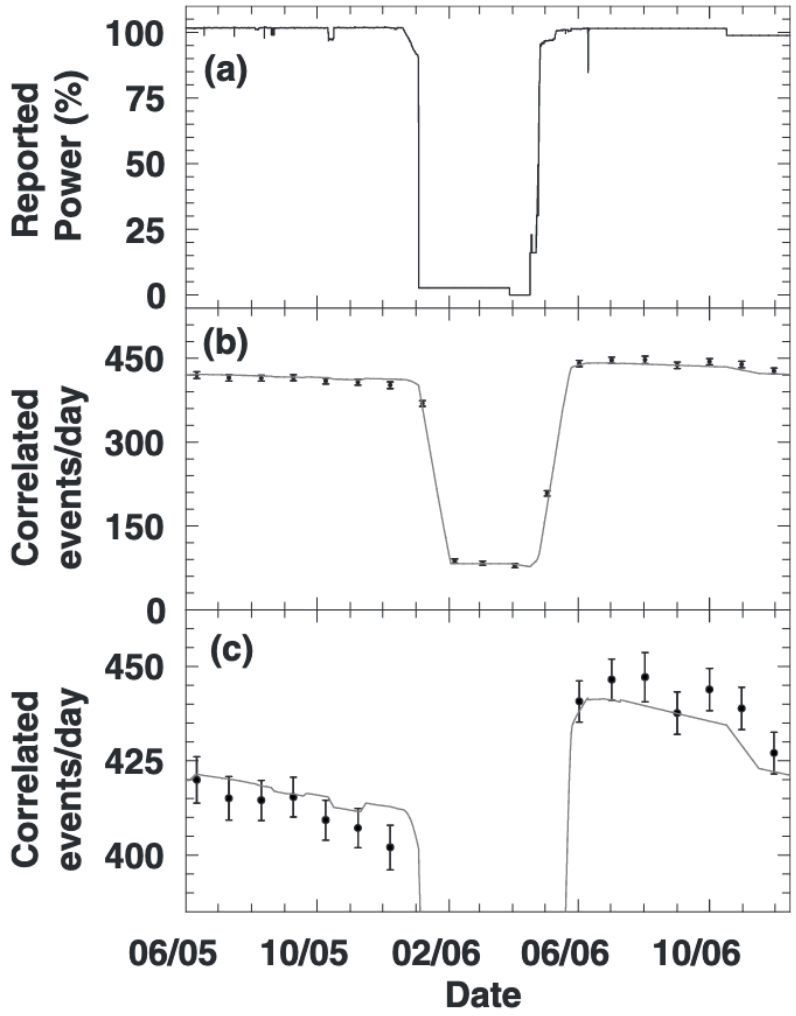
Waste Repository
(forever)

- Check declarations
- Bulk accountancy

Demonstrations of Power Monitoring

Verification of the power of the reactor

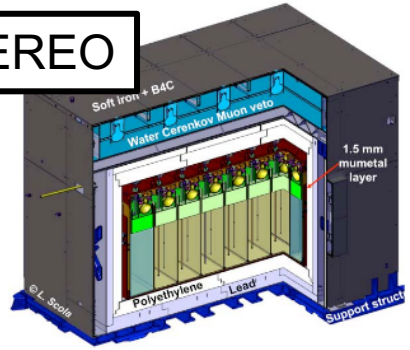




Bowden, N. S., Bernstein, A., Dazeley, et. Al. (2009 *Journal of Applied Physics*, *105*(6), 064902.

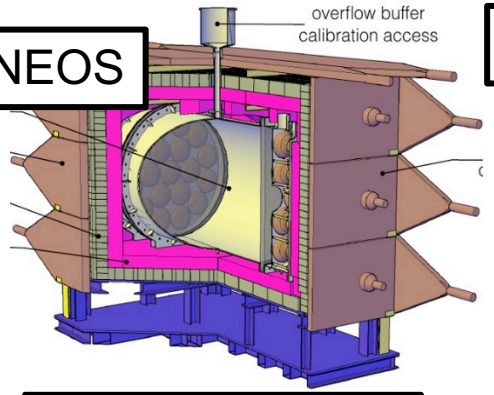
…Many more followed

STEREO



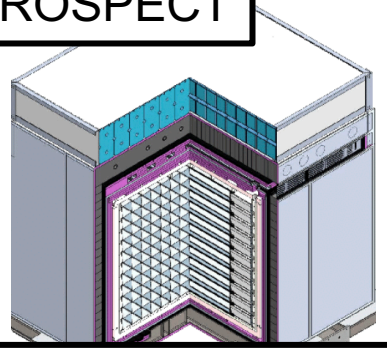
S. Schoppmann Poster #78
D. Lhuillier Poster #104
R. Rogly Poster #140
H. Almazan Poster #142

NEOS



J. Kim Poster #299
Y. Ko Poster #433

PROSPECT



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J. Gallo Poster #408
B. Foust Poster #516
X. Zhang Poster #527
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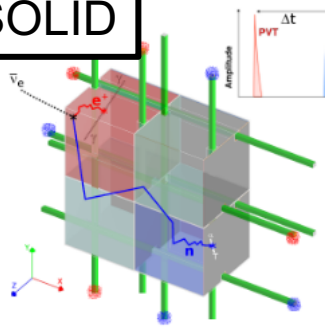
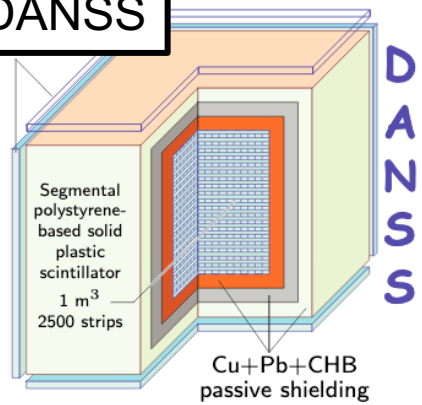
J. Gaison Poster #556

SOLID

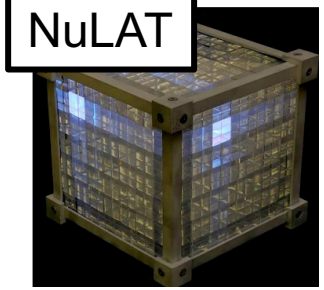


I. Bolognino Poster #497
V. Buridon Poster #522
M. Verstraeten Poster #530

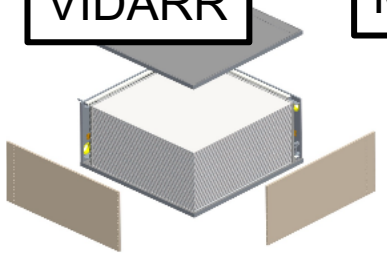
DANSS



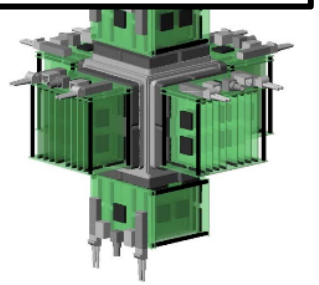
NuLAT



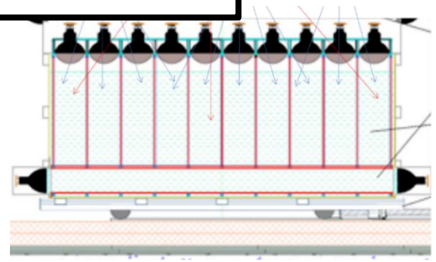
VIDARR



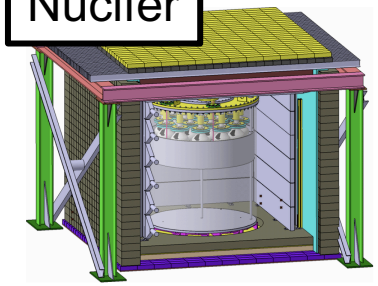
Mini-Time-Cube



Neutrino-4



Nucifer



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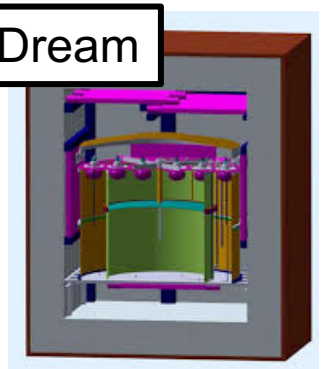
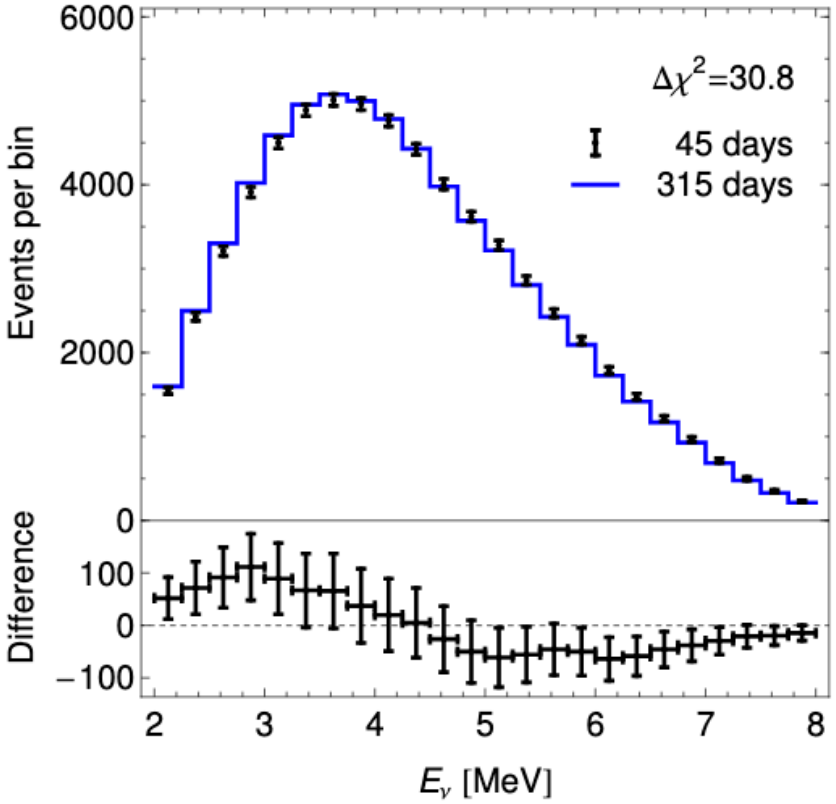
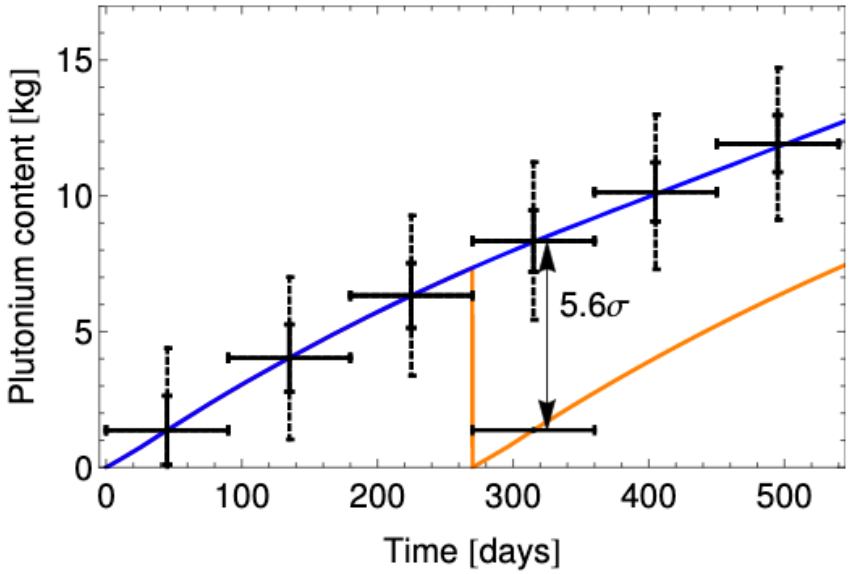


Case Studies of Applications

Satellite image of the heavy water reactor at Arak, Iran, May 2012. Image credit Digital Globe and Google Earth

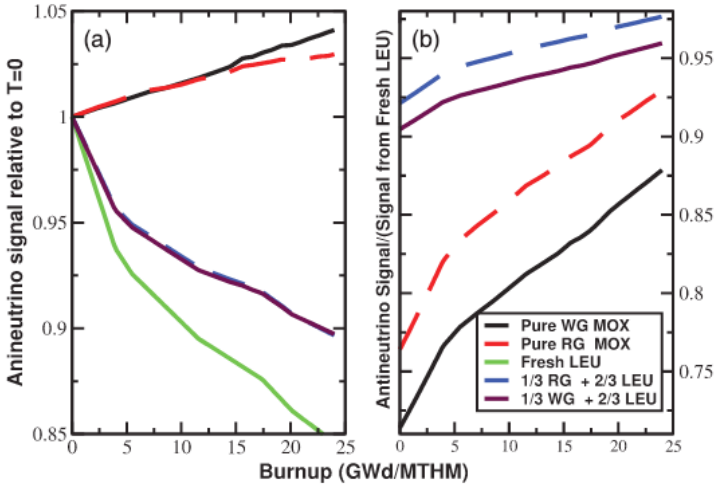




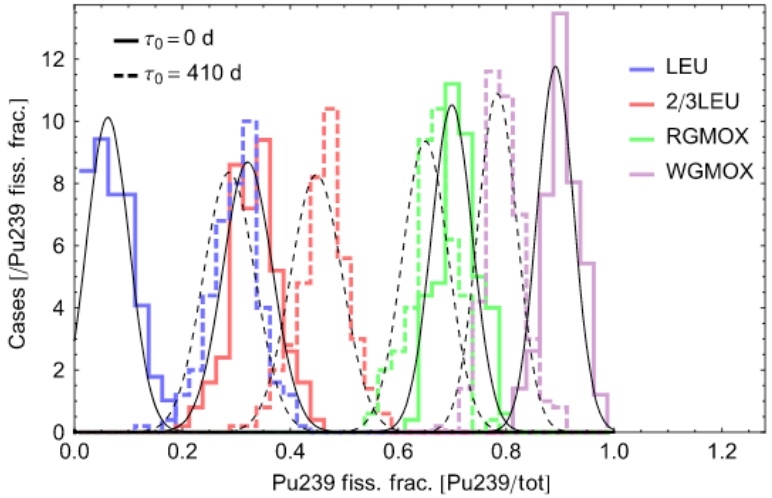
Verification of Pu Content

Huber et al.:arxiv:1403.7065

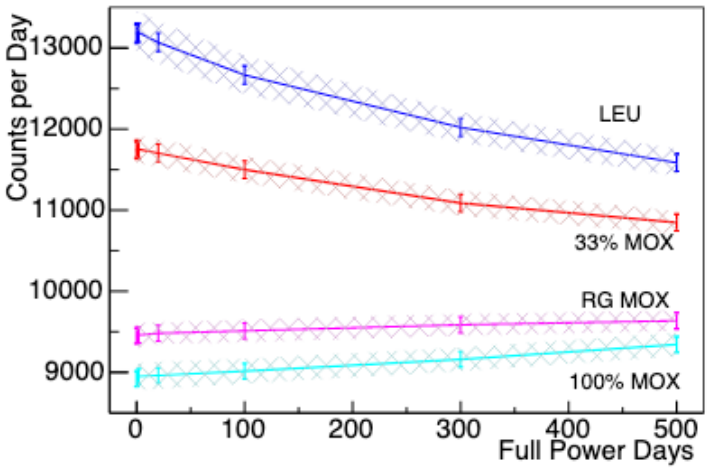
Case Studies of Applications



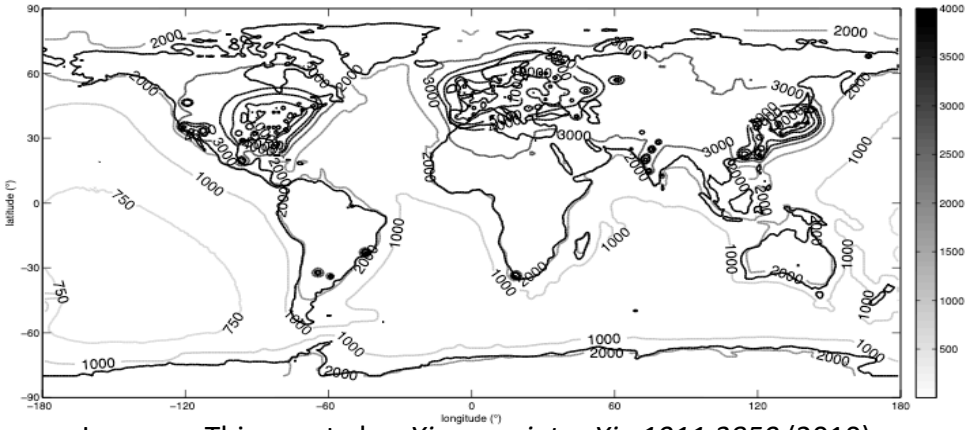
Hayes, A. C., et al *Physical Review C* 85.2 (2012): 024617.



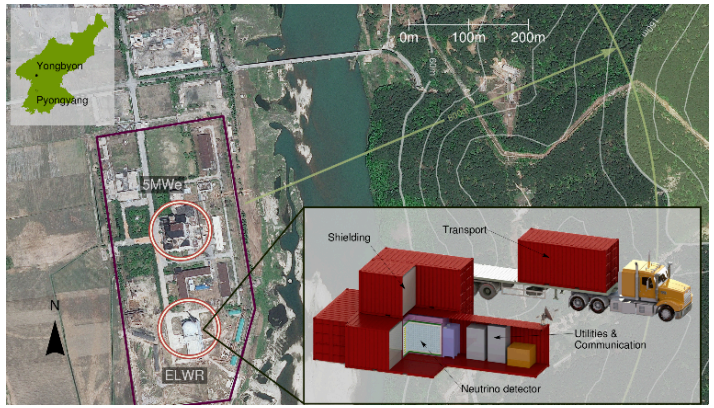
Jaffke, Patrick, and Patrick Huber. *Physical Review Applied* 8.3 (2017): 034005.



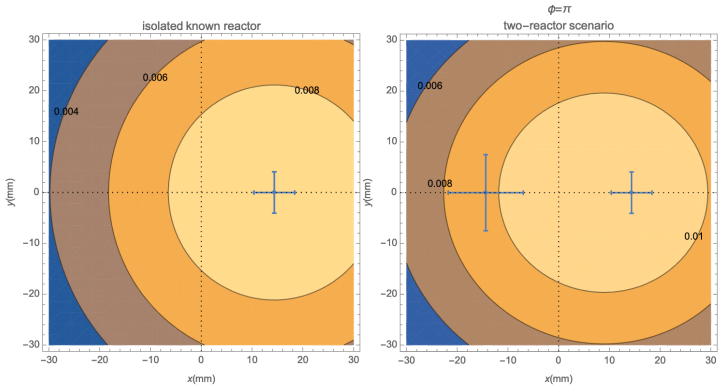
Bernstein, Adam, Nathaniel S. Bowden, and Anna S. Erickson. *Physical Review Applied* 9.1 (2018): 014003.



Lasserre, Thierry, et al. *arXiv preprint arXiv:1011.3850* (2010).



Carr, Rachel, et al. *Science & Global Security* 27.1 (2019): 15-28.



D. Danielson *arXiv:1909.05374 (2019)* Poster #96

Why hasn’t antineutrino monitoring been adopted by an end user?

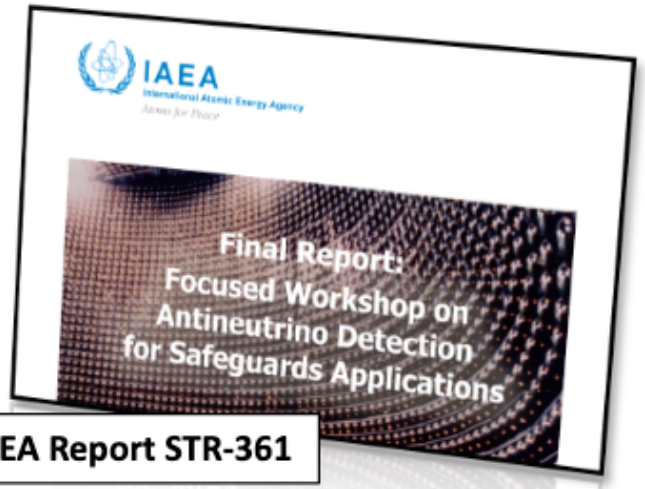
Required Considerations by the IAEA

Aboveground operation and **packaging/mobility** are among the utility considerations raised by potential end-users.

IAEA Report STR-361

Above Ground Reactor Antineutrino Monitoring

Aboveground operation and packaging/mobility are among the utility considerations raised by potential end-users



IAEA Report STR-361

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J. Gallo Poster #408
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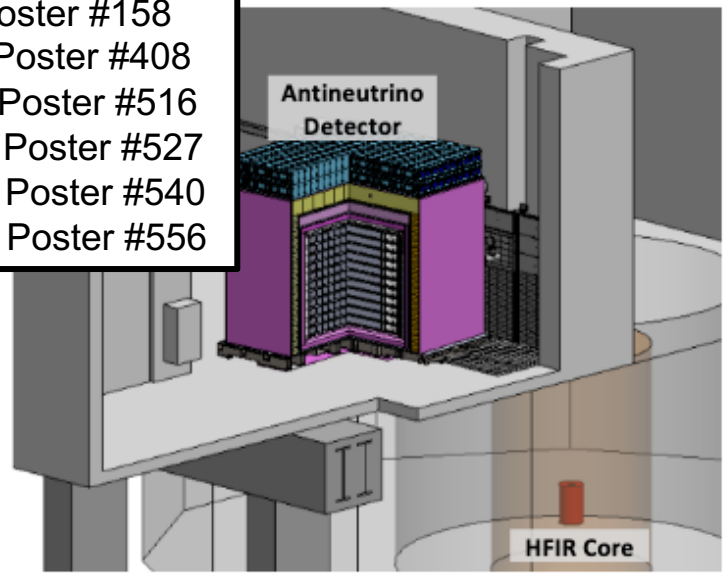
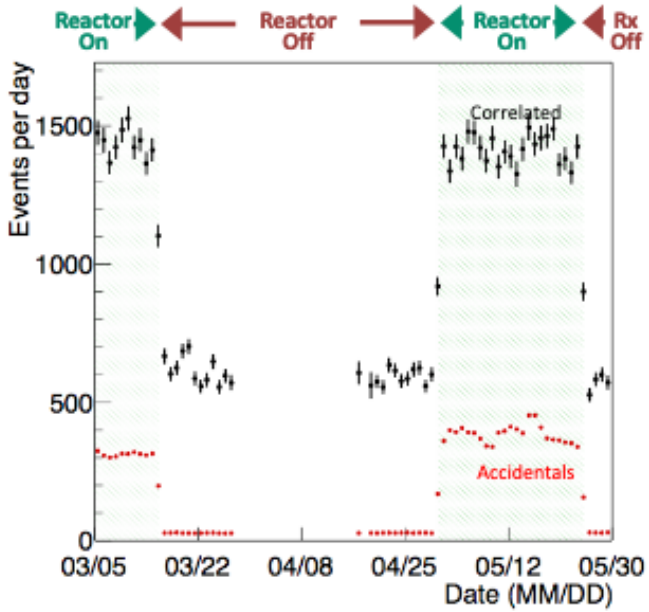


*Schematic diagram of **PROSPECT** experiment at High Flux Isotope Reactor (HFIR), **with almost no overburden***

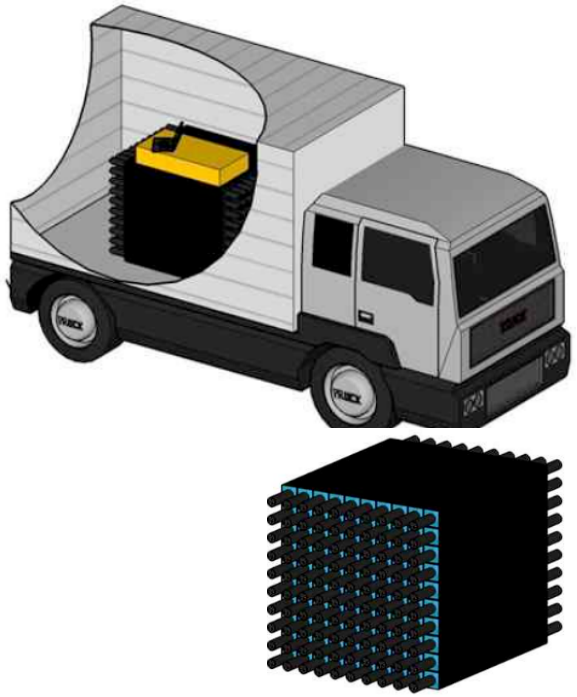


***PROSPECT** measurement of the HFIR antineutrino flux with >1:1 S:B on the earth's surface*

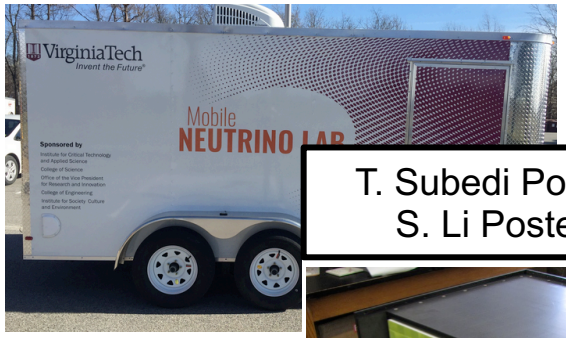
Above Ground Reactor Antineutrino Monitoring

Aboveground operation and **packaging/mobility** are among the utility considerations raised by potential end-users

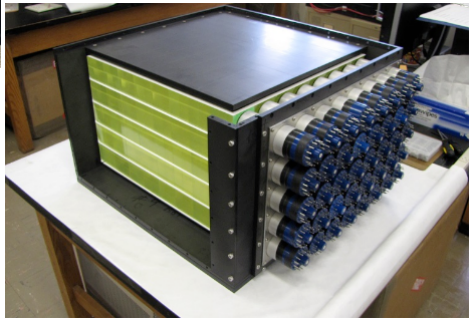
PANDA



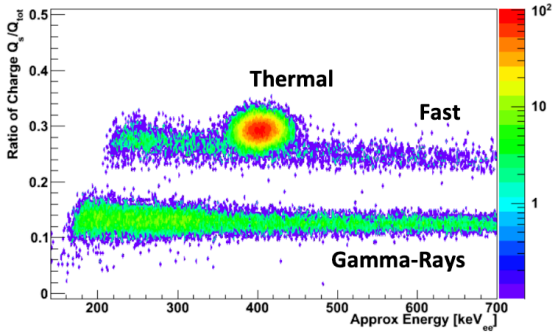
MiniCHANDLER

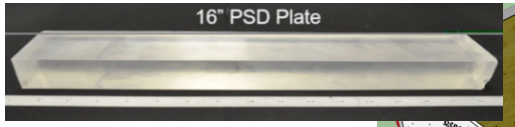


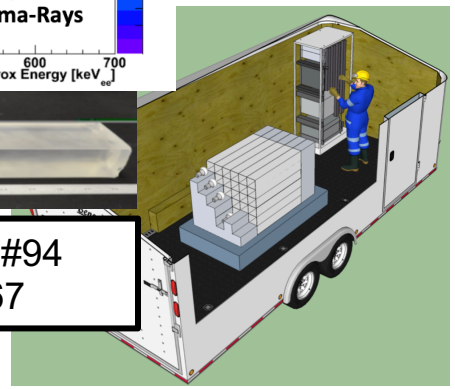
T. Subedi Poster #493
S. Li Poster #500



LLNL R&D







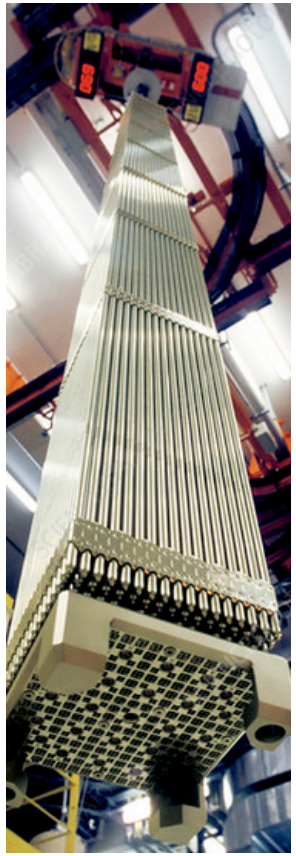
F. Sutanto Poster #94
V. Li Poster #267

Current IAEA Safeguards Practices (revisited)

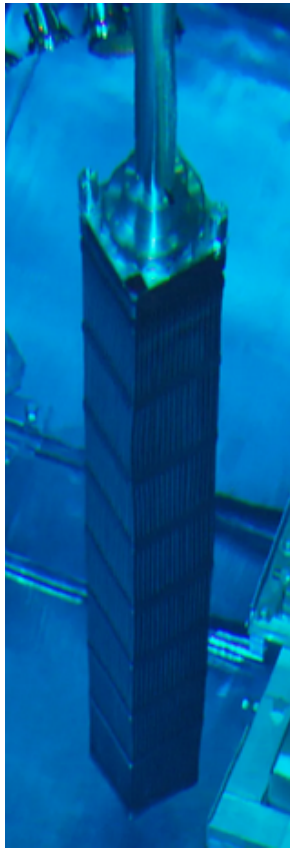
Reactor

(1-1.5 years)

- Check declarations
- **Item accountancy**
- Containment and surveillance



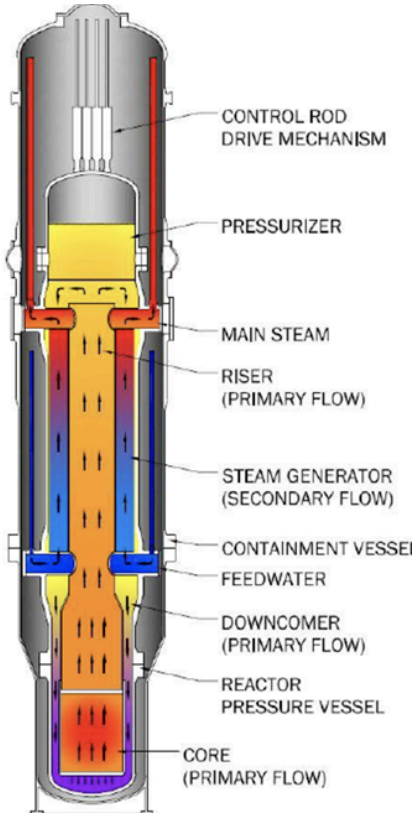
Number of fuel pins and assemblies entering the reactor



Number of fuel pins and assemblies leaving the reactor

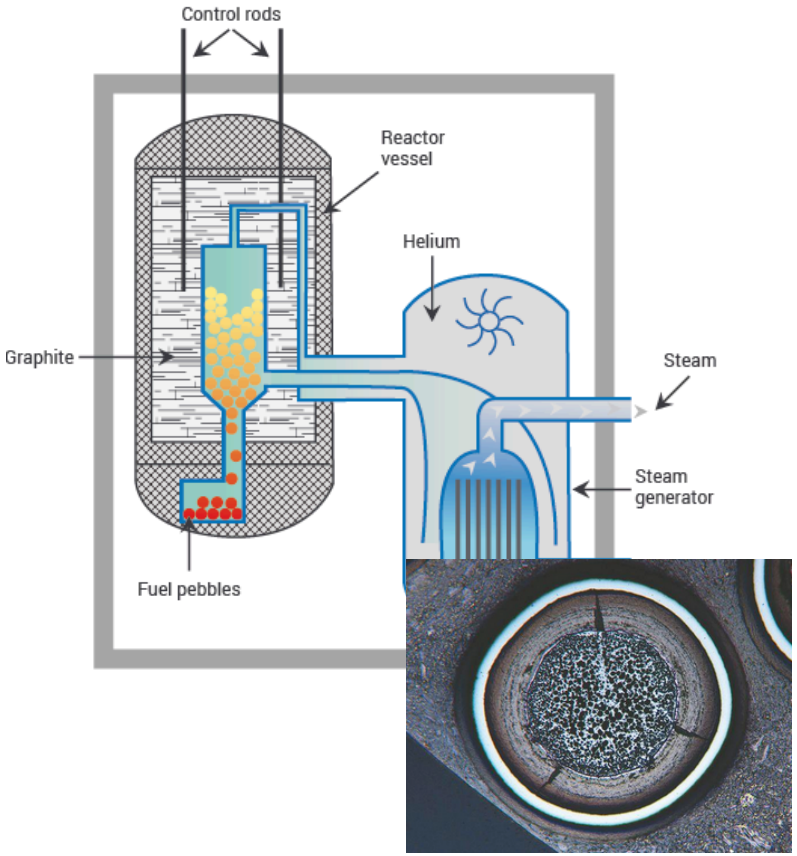
The Nuclear Fuel Cycle is Changing…

Small Modular Reactors



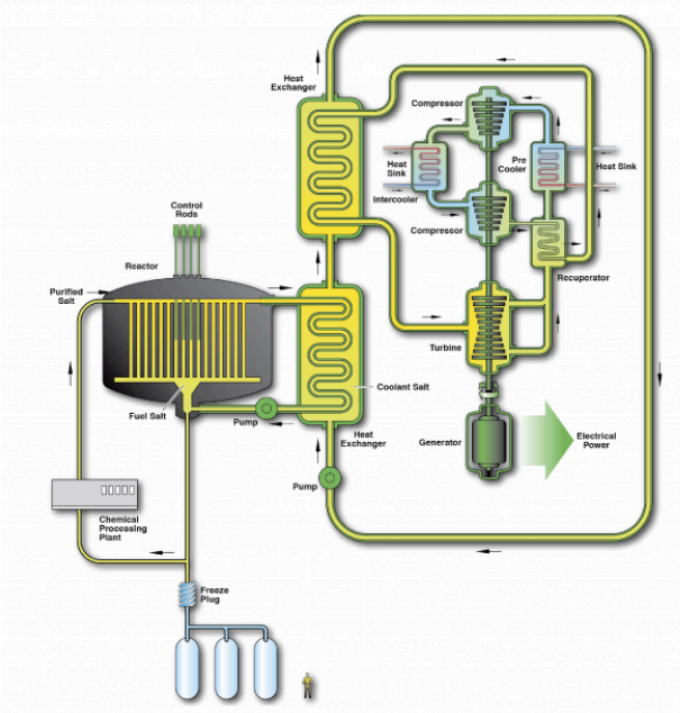
NuScale Design

Pebble Bed Reactors



TRISO FUELS: 3mm Diameter

Molten Fuel Reactors



Concerns about Cost

Physics ABOUT BROWSE PRESS COLLECTIONS

FEATURE

Neutrino Detectors for National Security

March 12, 2020 • *Physics* 13, 36

Detecting neutrinos offers a new way to monitor the potential bomb materials inside a nuclear reactor, but the technology's practicality remains uncertain.

Lukas Bischoff/iStock/Getty Images

Neutrino detectors can continuously measure the plutonium content of a nuclear reactor, such as this one in Iran, providing a tool for monitoring this potentially deadly material.

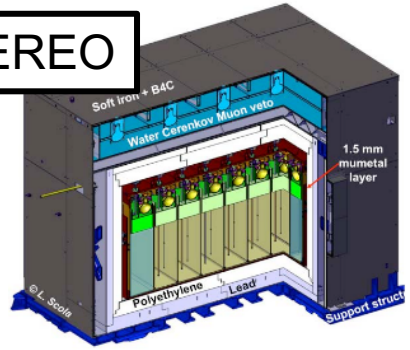
"The cost of these detectors also presents a significant implementation barrier, since building and operating even one detector could potentially require a large fraction of the annual nuclear verification budget (about $170 million) of the International Atomic Energy Agency (IAEA)"

"The cost of [building] many detectors is just so high that it's not practical within a real-world context,"

"[B]uilding a detector is just one part of the budget—there are personnel costs for operating the device and analyzing the data. Factor in that there are 450 reactors in 30 countries, and the costs could quickly become unmanageable".

Near Field Neutrino Experiments (Revisited)

STEREO



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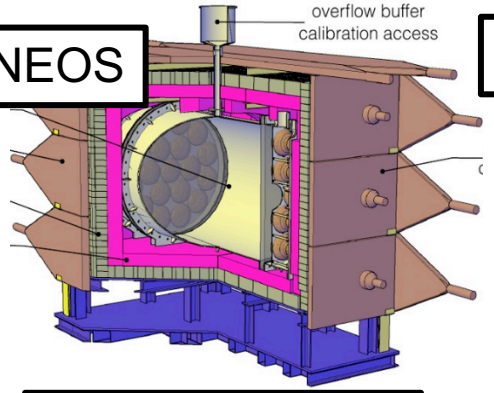
NEOS



J. Kim Poster #299
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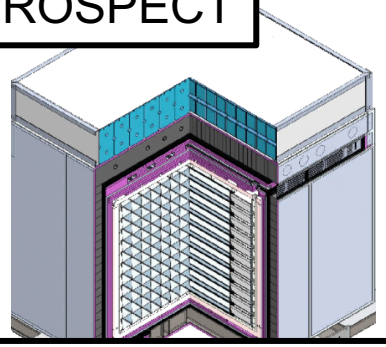
PROSPECT



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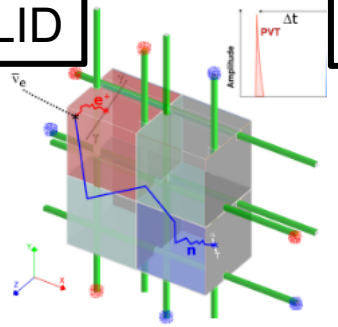

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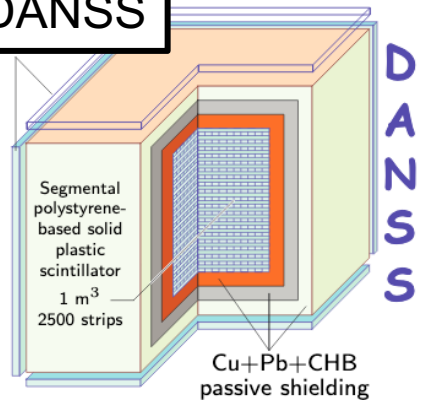

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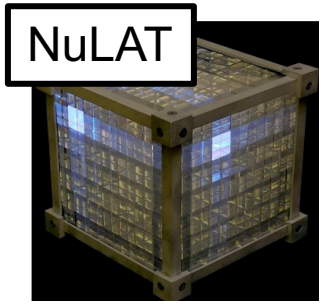
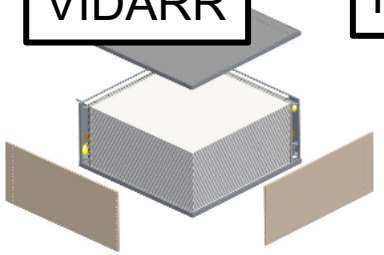


VIDARR



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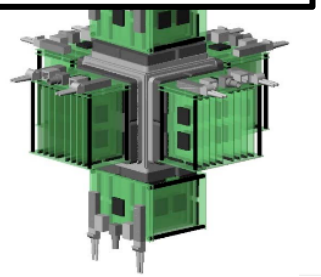
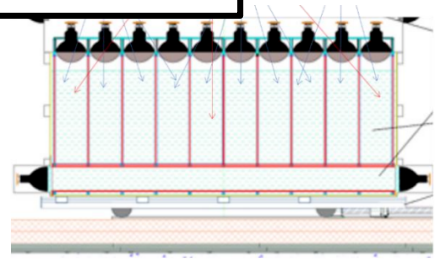
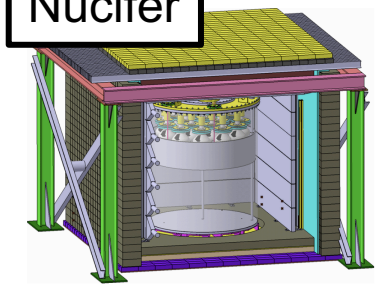


Neutrino-4



Nucifer



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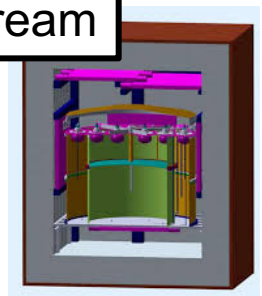
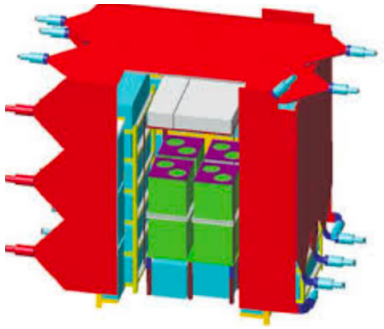
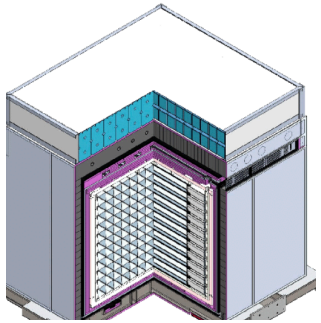


An Engineer's Solution: Safeguards by Design

- Cost of a nuclear reactor: $6-$9 Billion for 1 GWth
- Inclusion of antineutrino detectors as part of the construction of the facility: Safeguards by design

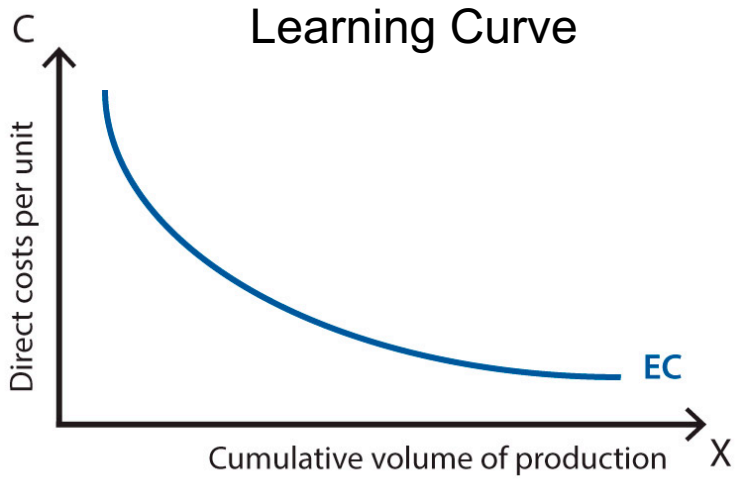


SONGS 2002



PROSPECT 2015

- "Modest" improvement in design: segmentation and Li-doping
- Revolutionary results: Energy resolution, above ground capabilities, etc.



- With community involvement we need to understand the minimum need.
- With two or three solutions we can drive down the costs of these detectors and develop generic analytical tools for analyzing data.

NU TOOLS: EXPLORING PRACTICAL ROLES FOR NEUTRINOS IN NUCLEAR ENERGY AND SECURITY

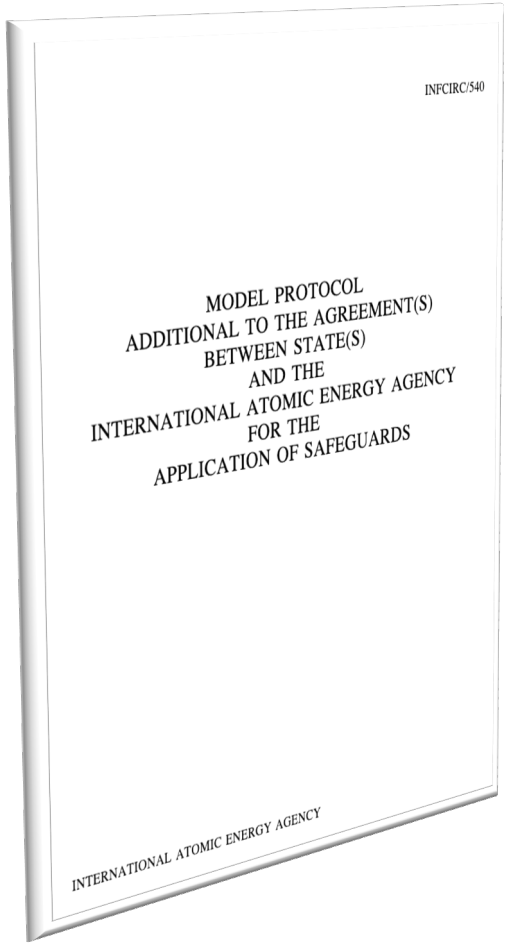
A COMMUNITY STUDY, INCLUDING INDIVIDUAL ENGAGEMENT AND ONLINE WORKSHOPS

WHEN
Summer 2020

WHERE
All Meetings Virtual

https://nutools.ornl.gov/

Additional Protocol: Motivation for Far-Field Reactor Monitoring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MODEL PROTOCOL
ADDITIONAL TO THE AGREEMENT(S)
BETWEEN STATE(S)
AND THE
INTERNATIONAL ATOMIC ENERGY AGENCY
FOR THE
APPLICATION OF SAFEGUARDS

INTERNATIONAL ATOMIC ENERGY AGENCY

Existing treaty language emphasizes minimizing intrusiveness and burden to the state being monitored:

- "avoid hampering economic and technological development"
- "avoid undue interference"
- "take every precaution to protect commercial and industrial secrets and other confidential information coming to its knowledge and implementation of the Agreement"

(C. Jabarri, Center for Nonproliferation Studies, Monterey, CA)

WATCHMAN: WATer CHerenkov Monitor of ANtineutrinos

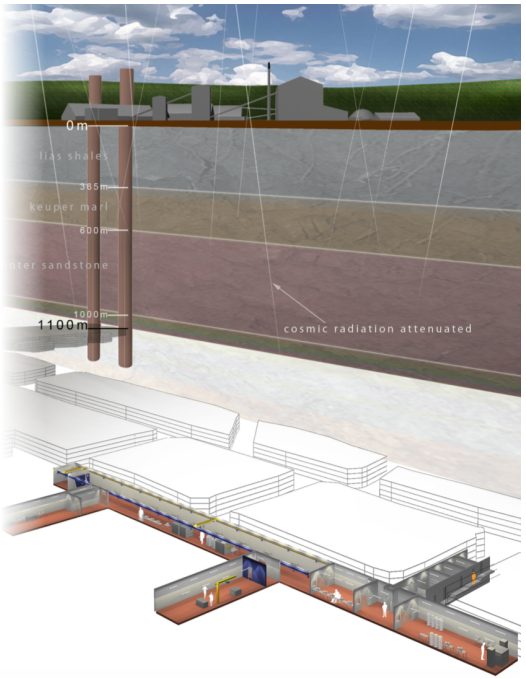
D. Danielson #96
P. Kunkle Poster #252
T. Akindele Poster #315

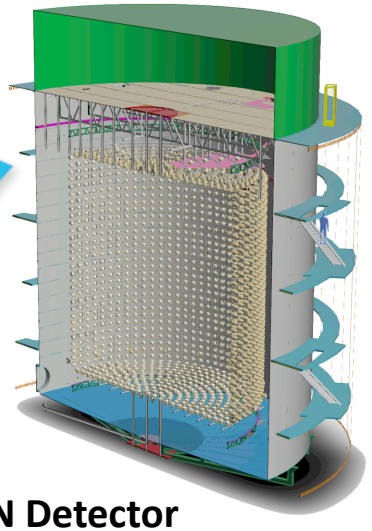
Hartlepool Reactors

- 2 cores
- 1570 MWt per core
- 25 km standoff

- Selected detector site: Boulby Underground Laboratory
- Operated by UK-STFC located 1100m underground
- Part of an operating potash/polyhalite mine

Boulby Underground Laboratory



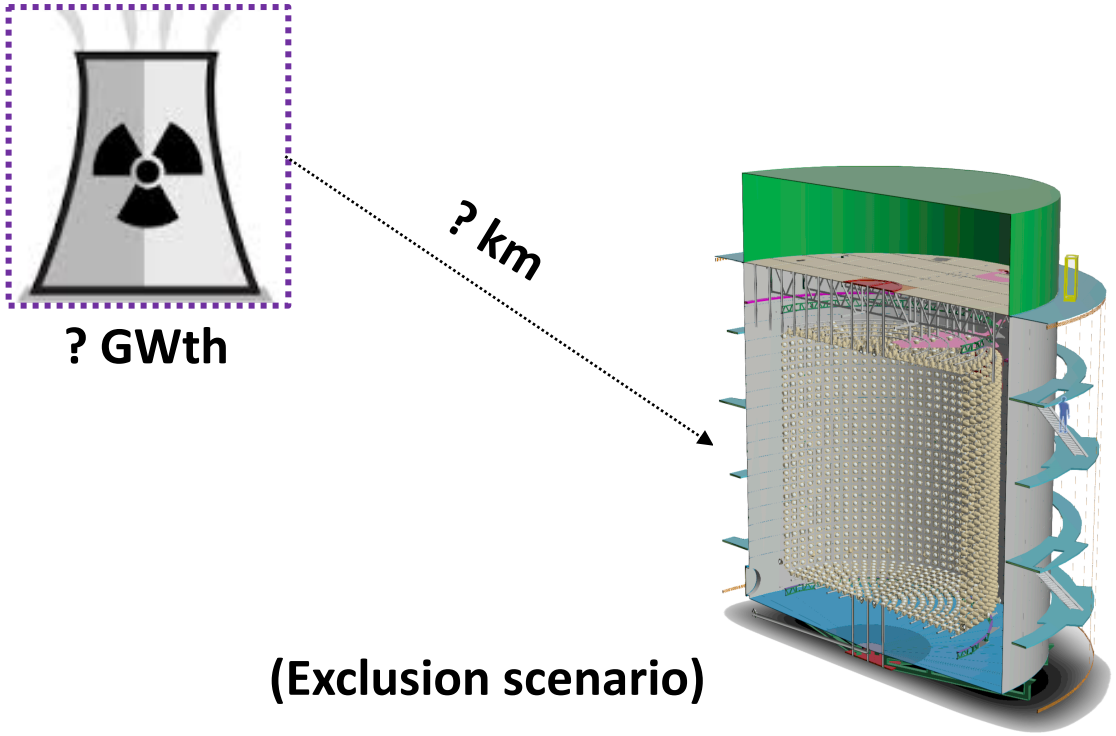


WATCHMAN Detector

- Either Gd-doped water or water-based liquid scintillator.
- 20-meter by 20-meter cylindrical tank.
- 20% photocoverage with 10’’ low radioactivity pmts.

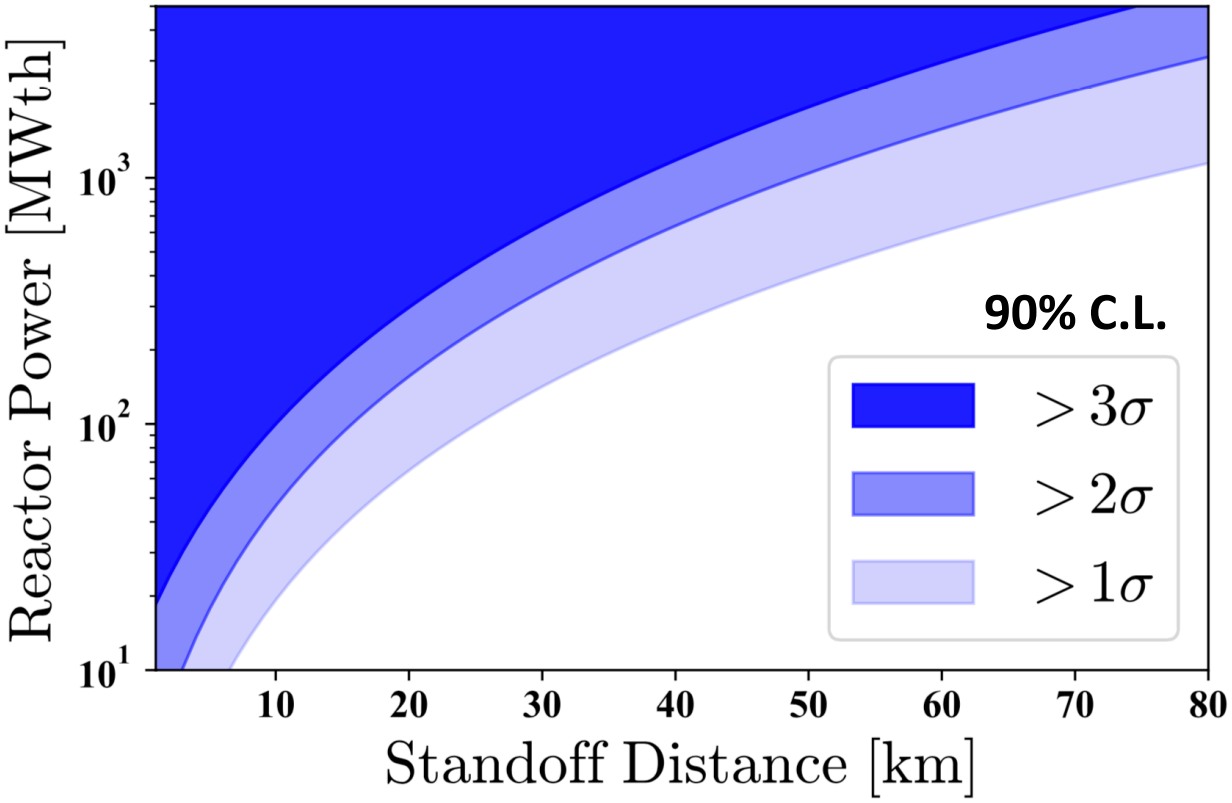
WATCHMAN Nonproliferation Goals

How well can WATCHMAN exclude the presence of a reactor?



(Exclusion scenario)

WATCHMAN Exclusion Contour: One-Year Dwell Time, Gd-Doped Water



In the context of a cooperative verification regime, one can…

Exclude the existence of Pu production facilities

Science & Global Security, 19:28–45, 2011

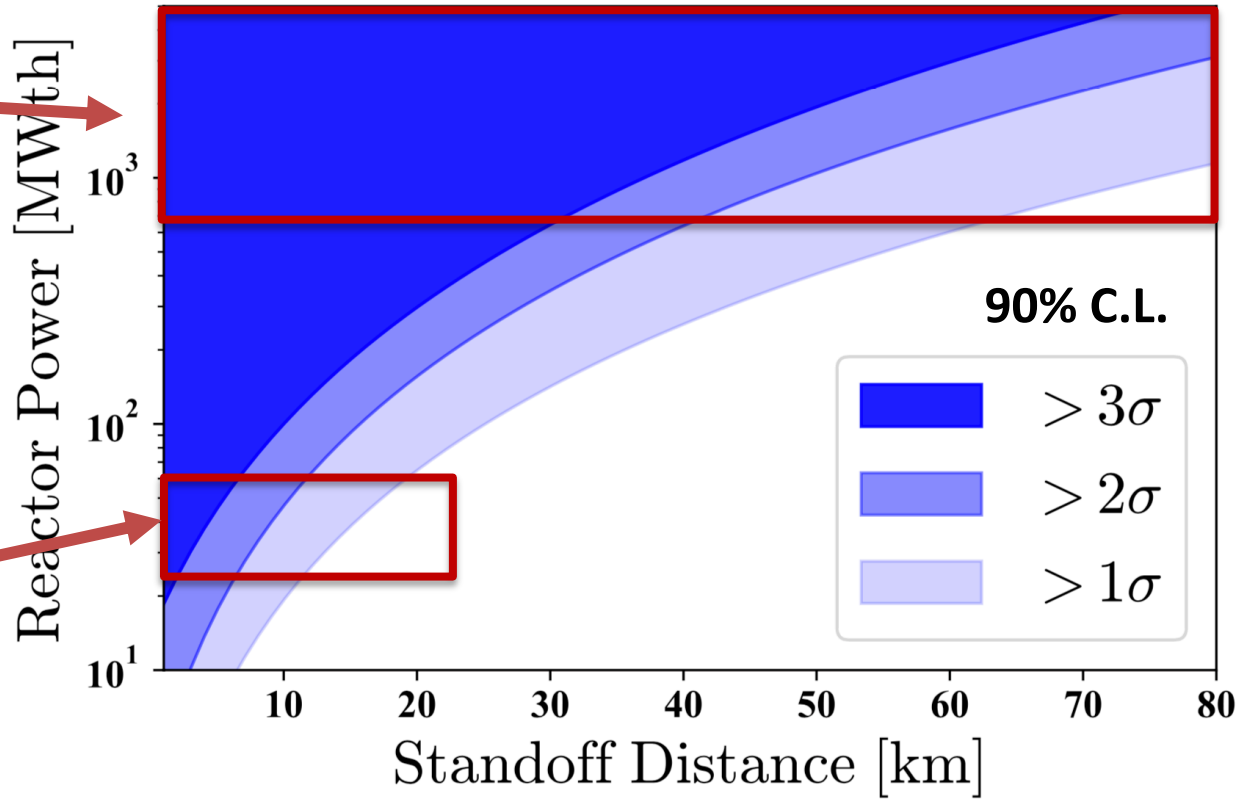
Reactor	Type	Power (MWt) (design/upgraded)
AD	once-through	1450/2000
ADE-1	once-through	1450/2000
ADE-2	closed-circuit	1450/1800

Krasnoyarsk plutonium production reactors.

Exclude the existence of research reactors

Satellite image of the heavy water reactor at Arak, Iran, May 2012. Image credit Digital Globe and Google Earth

WATCHMAN Exclusion Contour: One-Year Dwell Time, Gd-Doped Water



Conclusion

- Antineutrino monitoring has demonstrated the capability to measure useful quantities for reactor safeguards and nonproliferation.
- The measurement of oscillation parameters has been instrumental in developing detection media and techniques for this application.
- The evolving nuclear fuel cycle and a dedicated effort to address the needs of the nuclear community represents an opportunity to make applied antineutrino monitoring attractive to verification bodies.
- WATCHMAN will be the first demonstration of far-field reactor monitoring and can be applied to bilateral agreements and uses where the additional protocol is needed.

Questions?

Lawrence Livermore National Laboratory

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