Antineutrino Monitoring of Reactors for Nuclear Nonproliferation

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Rare Event Detection Group

Neutrino2020
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The Non-Proliferation Treaty (NPT)

- Recognized Nuclear-Weapon State (1967)
- Non-Nuclear Weapons States (1967)
- Non-Nuclear Weapons States (Post-1967)
- Withdrawal
- Non-signatories
- Partially recognized state which ratified
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)
  - Check declarations
  - **Item accountancy**
  - Containment and surveillance

- **Waste Repository** (forever)
  - Check declarations
  - Bulk accountancy
Demonstrations of Power Monitoring

Verification of the power of the reactor

...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**: X. Lu Poster #158
  - J. Gallo Poster #408
  - B. Foust Poster #516
  - X. Zhang Poster #527
  - P. Mumm Poster #540
  - J. Gaison Poster #556

- **SOLID**: I. Bolognino Poster #497
  - V. Buridon Poster #522
  - M. Verstraeten Poster #530

- **DANSS**: Cu+Pb+CHB passive shielding
  - Segmental polystyrene-based solid plastic scintillator 1 m$^3$ 2500 strips

- **NuLAT**: VIDARR

- **Mini-Time-Cube**: Neutrino-4

- **Nucifer**: iDream
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


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.
Above Ground Reactor Antineutrino Monitoring

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

IAEA Report STR-361

X. Lu Poster #158
J. Gallo Poster #408
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Above Ground Reactor Antineutrino Monitoring

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

“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”.

Neutrino Detectors for National Security
March 12, 2020 • Physics 33, 36

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

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.
Near Field Neutrino Experiments (Revisited)

STEREO
S. Schoppmann Poster #78
D. Lhuillier Poster #104
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DANSS

NuLAT

VIDARR

Mini-Time-Cube

Neutrino-4

Nucifer

iDream
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

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

PROSPECT 2015

- 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

https://nutools.ornl.gov/
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

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

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

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

Reactor Power [MWth]

Standoff Distance [km]

90% C.L.

> 3σ

> 2σ

> 1σ
In the context of a cooperative verification regime, one can...

Exclude the existence of Pu production facilities

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Type</th>
<th>Power (MWe) (design/upgraded)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>once-through</td>
<td>1450/2000</td>
</tr>
<tr>
<td>ADE-1</td>
<td>once-through</td>
<td>1450/2000</td>
</tr>
<tr>
<td>ADE-2</td>
<td>closed-circuit</td>
<td>1450/1800</td>
</tr>
</tbody>
</table>

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

90% C.L.

- $> 3\sigma$
- $> 2\sigma$
- $> 1\sigma$
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?