What can neutrino detectors do for nonproliferation, arms control, and safeguards: Results of the Nu Tools study

Michael Foxe on behalf of the Nu Tools Team

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Why Nu Tools?

Originally focused on neutrino technology assessment, but:

- DNN R&D leadership recognized a piece was missing: **What are practical end uses for this technology? What are the real needs and constraints?**

Laboratory & academic participants worked to develop a study charge:

> *"...to facilitate broad engagement with interested communities on the topic of antineutrino-based monitoring of nuclear reactors and associated post-irradiation fuel cycle activities. The particular focus... should be on the **potential utility** of antineutrino detection technologies… in the context of existing or potential policy needs."*

Nu Tools is a unique effort that has **evaluated a range of possible uses for neutrino technology, with input from all stakeholders.**

Nu Tools Executive Group

Tomi Akindele, *LLNL*
Nathaniel Bowden, *LLNL*
Rachel Carr, *MIT, USNA*
Andrew Conant, *ORNL*
Milind Diwan, *BNL*
Anna Erickson, *Georgia Tech*
Michael Foxe, *PNNL*

Bethany Goldblum, *LBNL*
Patrick Huber, *Virginia Tech*
Jason Newby, *ORNL*
Igor Jovanovic, *Michigan*
Jon Link, *Virginia Tech*
Bryce Littlejohn, *IIT*
Pieter Mumm, *NIST*

Steering Group: M. Foxe (PI), N. Bowden, R. Carr, P. Huber, J. Newby

Engagement with Expert Communities

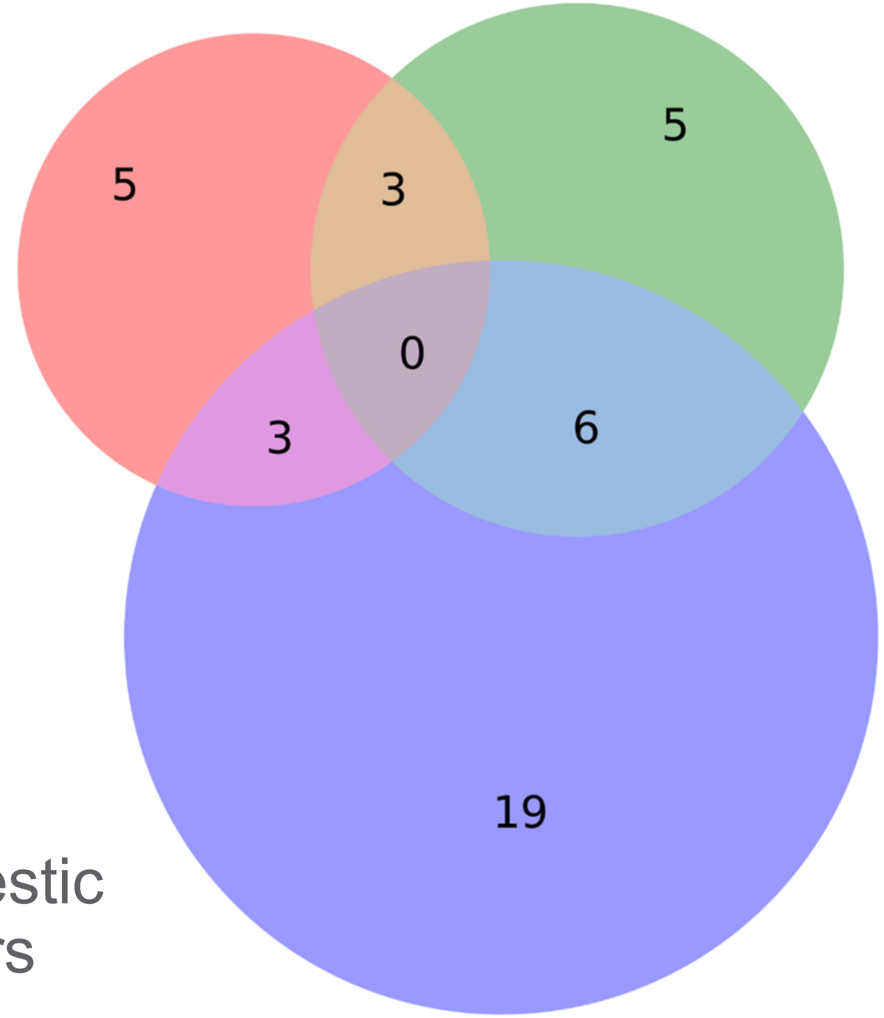
- To collect expert views, the Nu Tools study prioritized broad engagement with relevant communities via semi-structured interviews and a mini-workshop

- Interviewees were selected with an emphasis on expertise outside the physics research community, including:
    - international and domestic safeguards practitioners
    - nuclear reactor vendors and operators, and
    - nuclear policy experts with experience in government agencies and NGOs

Expert interviews: May 2020-Feb. 2021 (41 individuals)

Neutrino Physics & Technology

Physicists specializing in neutrino application concepts



Reactor Design & Engineering

Nuclear reactor vendors, operators, and researchers

Nuclear Security & Safeguards

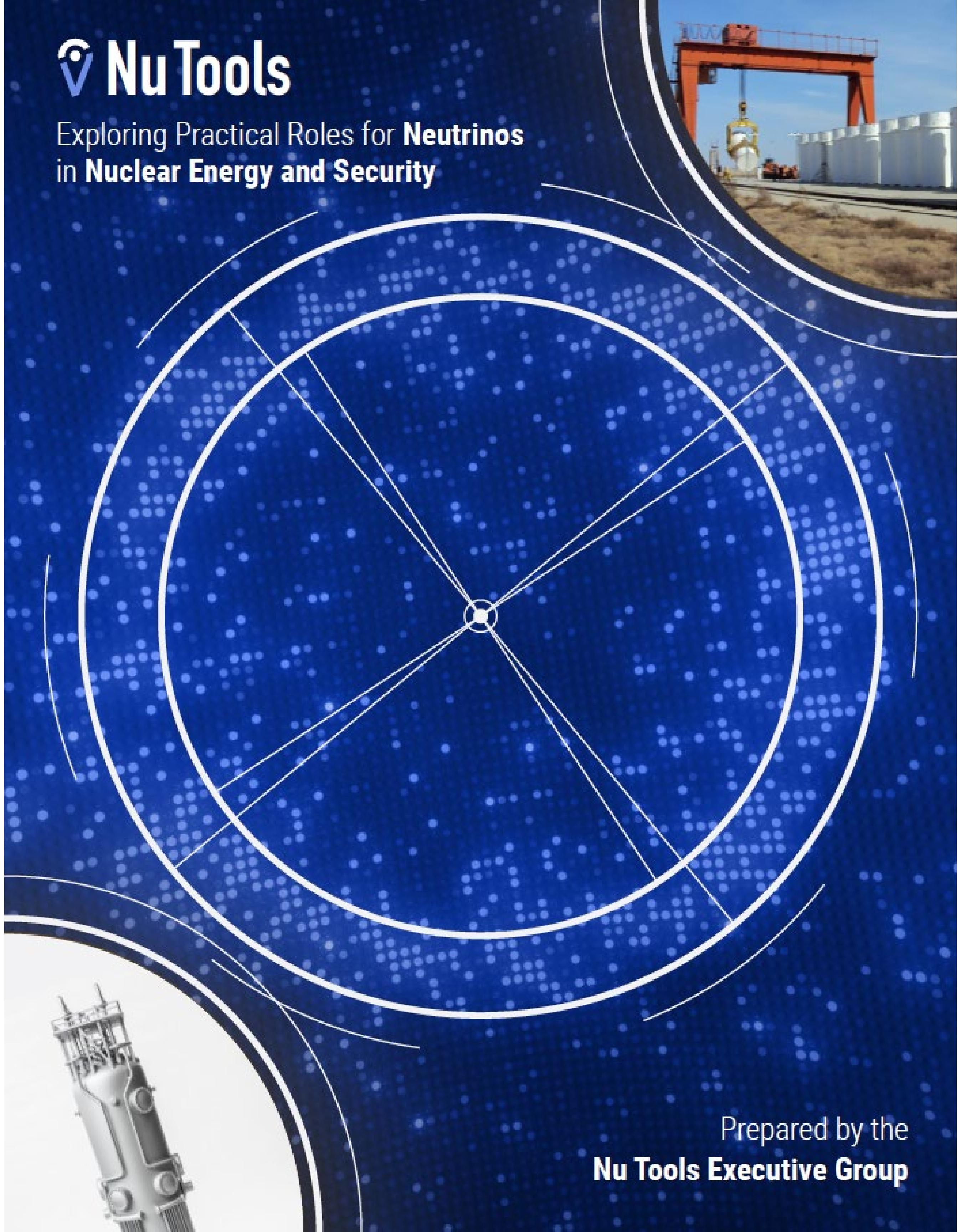
- International and domestic safeguards practitioners
- Nuclear policy experts from government agencies and NGOs

Beyond these 41 individuals:

Mini-Workshop with the neutrino community:

- 21 presenters
- >100 more attendees

nutools.ornl.gov



Cross Cutting Findings:

End User Engagement: The neutrino technology R&D community is only beginning to engage attentively with end users, and further coordinated exchange is necessary to explore and develop potential use cases.

Neutrino System Siting: Siting of a neutrino-based system requires a balance between intrusiveness concerns and technical considerations, where the latter favor a siting as close as possible.

Technical readiness: The incorporation of new technologies into the safeguards or verification toolbox is a methodical process, and a novel system such as a neutrino detector requires a dedicated qualification exercise.

Cross Cutting Finding: End-User Engagement

The neutrino technology R&D community is only beginning to engage attentively with end-users, and further coordinated exchange is necessary to explore and develop potential use cases.

- Although potential is seen in neutrino technologies, there is not a compelling use case that justifies adoption at this time
- To date, potential use cases have mostly been developed in the technical community with a focus on signals and detection, an approach that has not established enduring end-user connection or credibility
- Systematic and sustained two-way exchange is necessary to develop mutual understanding and identify use cases responsive to user needs

Cross Cutting Finding: Technical Readiness

The incorporation of new technologies into the nuclear energy or security toolbox is a methodical process, requiring a novel system such as a neutrino detector to demonstrate sufficient technical readiness.

- Technical Readiness Level (TRL) requirements will vary by use, but will generally be higher than currently demonstrated systems
- Safeguards end-users will generally expect demonstration at TRL 7-8, i.e., full-scale demo in operational relevant environment.
  - important for readiness and user familiarity
- As a neutrino technology proceeds through successively higher TRLs, end-user input should be an integral part of the process

Cross Cutting Finding: Neutrino System Siting

Siting of a neutrino-based system requires a balance between intrusiveness concerns and technical considerations, where the latter favor a siting as close as possible.

- Non-intrusiveness is viewed as a key advantage of neutrino-based monitoring approaches
- Neutrino-based monitoring can assuage intrusiveness concerns, since no connection to facility process components is required to access a neutrino signal.
- A very strong impetus to negotiate the closest possible deployment site derives from implementation constraints related to neutrino detector size, cost, and construction timeline.

Nu Tools approach to utility

During expert engagement, common themes emerged which have been synthesized into the Nu Tools Utility Framework

A promising use case for neutrino technology fulfills *all* four criteria:

	Determined by...
Need for a new or improved capability	*… End user*
Existence of a neutrino signal	*… Tech development community*
Availability of a neutrino detection technology	*… Tech development community*
Compatibility with implementation constraints	*… End user*

Since expertise on capability need and implementation constraints resides in the nuclear security and nuclear engineering communities, expert engagement provides perspective on these criteria in the Nu Tools report.

Criteria 1: Need for a new or improved capability

- Need expressed by the *user community* for specific monitoring capabilities, which either are entirely missing or not as effective as sought.

- For a given use case, different stakeholders may have different needs

- Consideration of a capability is often tied to the cost and effort associated with it. For some capabilities there is:
  - a cost beyond which they are no longer perceived as needed
  - no associated value even at very small cost.

- Implementation constraints therefore play an important role in user considerations (4th criteria)

Criteria 2: Existence of a neutrino signal

- The neutrino technology community makes this determination

- This assessment is based on:
  - Well-known principles of reactor operation, nuclear physics, and neutrino physics
  - An understanding of the use case, i.e. what information is required to address a capability need - may be approximate

- Considering some specific examples:
  - Operating reactors produce large numbers of neutrinos and there are reactions in target media that support detection, e.g. Inverse Beta Decay
  - Uranium enrichment produces no neutrino signatures, and therefore neutrino-detection supports no use cases

Criteria 3: Availability of a neutrino detection technology

- The neutrino technology community makes this determination, assessing
  - whether a detector sensitive enough to detect the neutrino signature can be built, and
  - whether backgrounds can be sufficiently suppressed.
- In assessing technology availability, a wide range of maturity is considered adequate to meet this criterion:
  - *Considered satisfied* if a foreseeable R&D path supported by fundamental physics has been articulated
  - *Not considered satisfied* if major, unforeseeable breakthroughs in technology or new discoveries in neutrino physics are required

Criteria 4: Compatibility with implementation constraints

- Implementation constraints that are expressed by the user community.

- Examples of implementation constraints mentioned during expert engagements include:
  - cost, including system acquisition and ongoing operation and maintenance obligations
  - workforce requirements, including size and training
  - measurement timeliness
  - deployment lead time and complexity
  - general logistical constraints, e.g. infrastructure support for a system
  - intrusiveness

- Consideration of this criterion includes a weighing of the urgency of a capability need versus constraints of these types

Current IAEA Safeguards

For the vast majority of reactors under current IAEA safeguards, the safeguards community is satisfied with the existing toolset and does not see a specific role for neutrinos

- Capability need
  - IAEA has a well-established toolset and operational experience
  - Item accountancy is sufficient for current reactors (seals, cameras, etc.)
  - Few research reactors have powers in ~10 MWs
  - Real-time measurement of power or fuel burnup could be of value
- Neutrino signal
  - Proportional to power and fissioning isotope
- Detection technology
  - Requires deployment ~10s of meters from core for increased resolution
- Implementation constraints
  - New technology integration is not a priority absent a strong capability need
  - Changes in conceptual approach carry training and implementation burden
  - Cost and size concerns are significant
  - Continuous monitoring via neutrinos could reduce onsite inspection resources

Reactor Operations

Utility of neutrino detectors as a component of instrumentation and control systems at existing reactors would be limited

- Capability need
  - Current in- and ex-core radiation and thermal-hydraulic sensors are sufficient
  - No specific scenario related to neutrinos was identified
- Neutrino signal
  - Would take ~10s of minutes to respond to change in reactor conditions
  - Integration time of months to years could give power measurement or calibration
- Detection technology
  - Slow response time is too limiting
- Implementation constraints
  - Cost is concerning, unless it can provide economic benefits to operators
  - Combustible organic scintillators are used, but mitigation techniques suffice to date
  - Must adapt to existing facility design and layout

Post-Accident Response

Determining the status of core assemblies and spent fuel is a capability need for post-accident response, but the applicability of neutrino detectors to these applications requires further study

- Capability need
  - If core has melted, we need to know: location, quantity, and configuration
  - Flare-ups detected by instrumentation posed an issue
  - High radiation environments rendered key instrumentation inoperable
- Neutrino signal
  - Shifting of bulk material (shielding) has no impact on neutrino propagation
  - Unclear how low emissions will be, but spent fuel levels may be comparable
- Detection technology
  - Harsh radiation environment is likely troublesome for IBD detectors
- Implementation constraints
  - Compact, transportable, and robust technology
  - Alternatively, could locate detector permanently on site
  - Lack of power could be an issue
  - Unclear who would pay for R&D

Spent Nuclear Fuel

Non-destructive assay of dry casks (C) is a capability need which could potentially be met by neutrino technology, whereas long-term geological repositories (R) are unlikely to present a use case

- Capability need
  - (C) Currently tags and seals are used with visual inspections
  - (C) NDA techniques are being explored to verify cask contents and detect diversions
  - (R) No specific safeguards arrangements for repositories have been established
  - (R) Minimal maintenance and ability to operate on long time scales required
- Neutrino signal
  - 10^5 or less in magnitude as compared to operating reactor, only ^{90}Sr after years
- Detection technology
  - (C) Background issues from above-ground deployment are significant
  - (R) Statistical sensitivities to anomalies would be difficult
- Implementation constraints
  - (C) Sensitivity is largest issue, and changing procedure (moving casks) likely required
  - (R) Access for maintenance and experimental validation required
  - New technology and cost concerns, particularly for large detectors to achieve sensitivity

Advanced Reactors

Advanced reactors present novel safeguards challenges which represent possible use cases for neutrino monitoring

- Capability need
  - Novel reactor and fuel designs will require safeguards concepts
  - Non-LWR/traditional designs that deviate significantly may require bulk measurements
  - Molten fuel, spatial power variations, continuous feed/removal present challenges
- Neutrino signal
  - Yields and spectra for higher actinides (>= Pu) not well-known
  - Pu breeding would be difficult to detect (non-fission reactions)
- Detection technology
  - Highly agnostic to physical form of fuel
  - High sensitivity and low backgrounds required for fissile content determination
  - Various detection systems for different reactor types (e.g. SMRs versus MSRs)
- Implementation constraints
  - Current focus is on safety and licensing of designs
  - Safeguards-by-design approach can aid if considered early or integrated
  - Cost and size concerns are significant

Future Nuclear Deals

There is interest in the policy community in neutrino detection as a possible element of future nuclear deals

- Capability need
  - The U.S. will continue to seek agreements regarding nonproliferation and arms control
  - Increasing technical verification toolset for negotiators is desired
  - Capability to verify operation of reactor and exclude underground reactor presence
- Neutrino signal
  - Information gained depends on how close detector is to reactor
  - Easiest: verify operational status, hardest: estimation of fissile content
- Detection technology
  - Siting as close to reactor as possible decreases footprint
- Implementation constraints
  - High degree of field testing is needed to qualify levels of false positive rates
  - Technology development likely to be funded by nations themselves
  - Potentially low acceptability of technology due to novelty
  - Concerns on revealing information beyond the scope of the agreement

Non-Cooperative Reactor Monitoring

Implementation constraints related to required detector size, dwell time, distance, and backgrounds preclude consideration of neutrino detectors for non-cooperative monitoring

- Capability need
  - Observing nuclear facility operations without local facility cooperation is attractive
  - Other methods can provide information prior to an operational reactor
- Neutrino signal
  - Significant drop-off in signal with 100s of kilometers, plus backgrounds from other reactors
- Detection technology
  - Required to have underground kiloton detectors due to low signal + high backgrounds
  - Alternatively, close-range deployment requires < 100 m standoff
- Implementation constraints
  - Limited fraction of country’s area could be monitored
  - Large underground construction project could be counterproductive to the goal
  - Need cooperation of bordering country
  - Information needed on location of an undeclared facility
  - Most significant costs due to need for underground and kiloton scale detectors

Conclusions

- Expert engagement was central to this effort, and emphasized that useful application of neutrinos will require both:
  - advancing physics and technology
  - an understanding of the needs and constraints of potential end-users

- The Nu Tools Utility framework which emerged from end user engagement
  - this proved invaluable as a tool for assessing the utility of specific use cases
  - although formulated here in the context of neutrino-based methods, it could be adapted to other technologies

- The Nu Tools focus on utility adds practical context to the prior literature on neutrino applications. We hope it will:
  - inform the R&D efforts of scientists and engineers interested in neutrino applications
  - offer potential end-users a perspective on where neutrino technology could add practical value for them