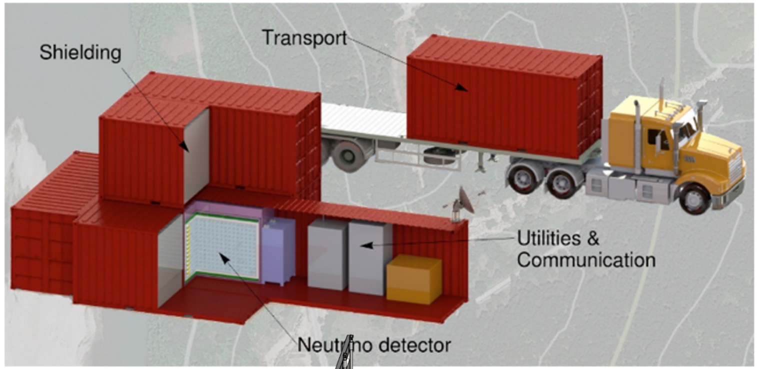
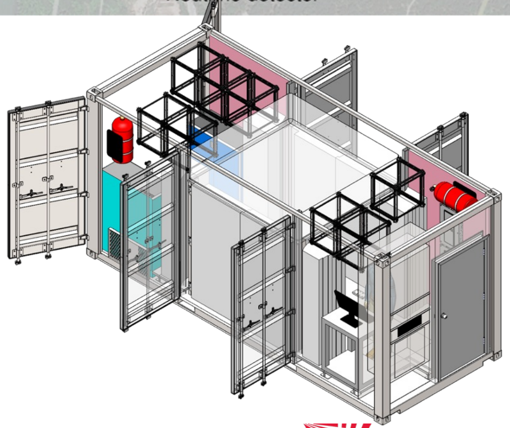
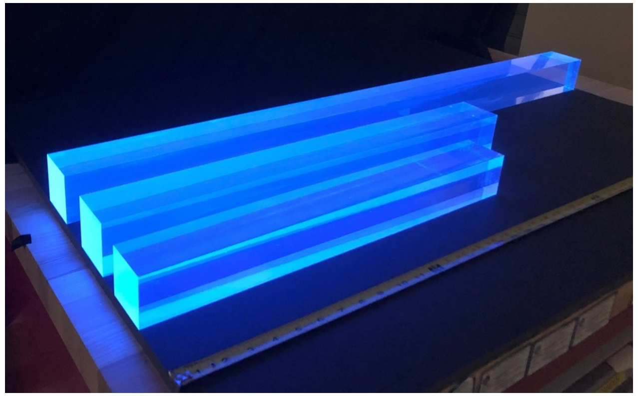
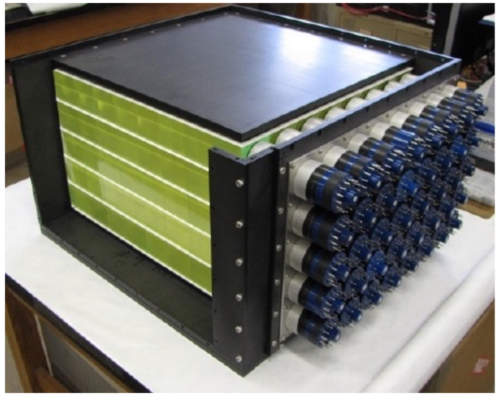
The Mobile Antineutrino Demonstrator Project

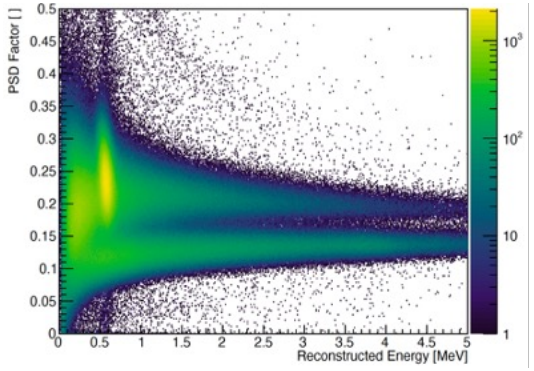
Nathaniel Bowden *for the Mobile Antineutrino Demonstrator Project*
Lawrence Livermore National Laboratory
Applied Antineutrino Physics 2023

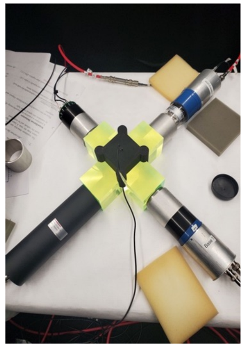












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LLNL-PRES-854342
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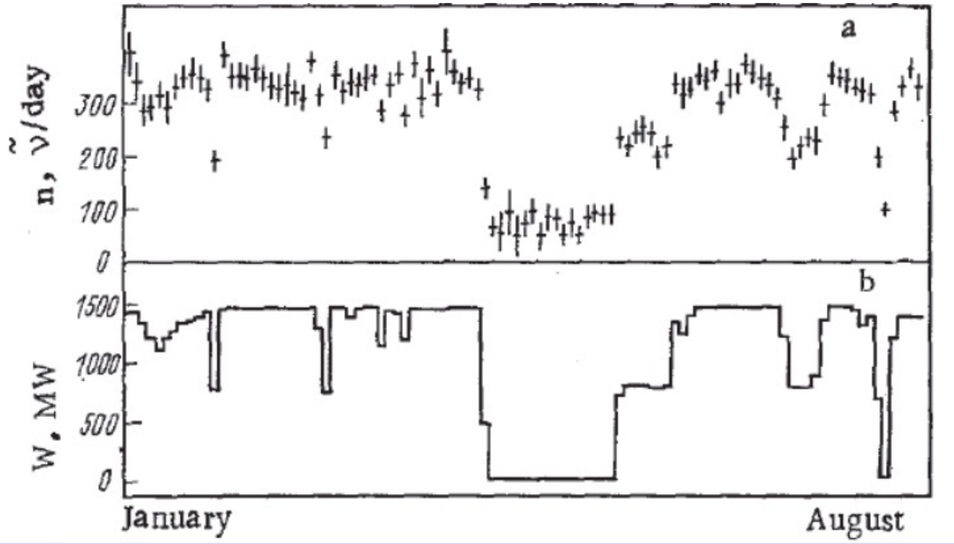
Potential for neutrinos in nuclear energy and security

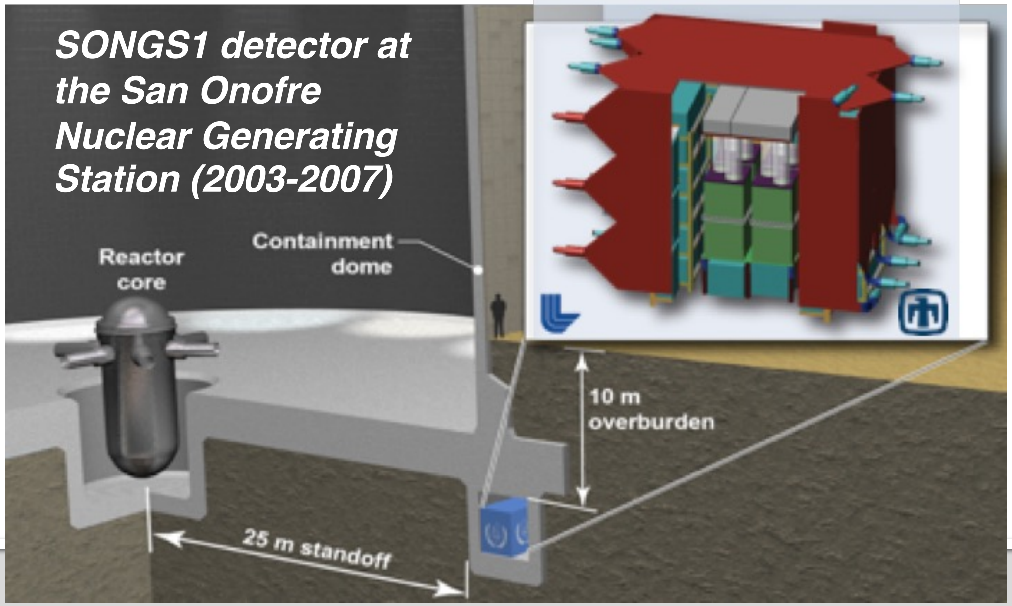
Detection techniques from neutrino physics have enabled **near-field reactor monitoring demonstrations:**

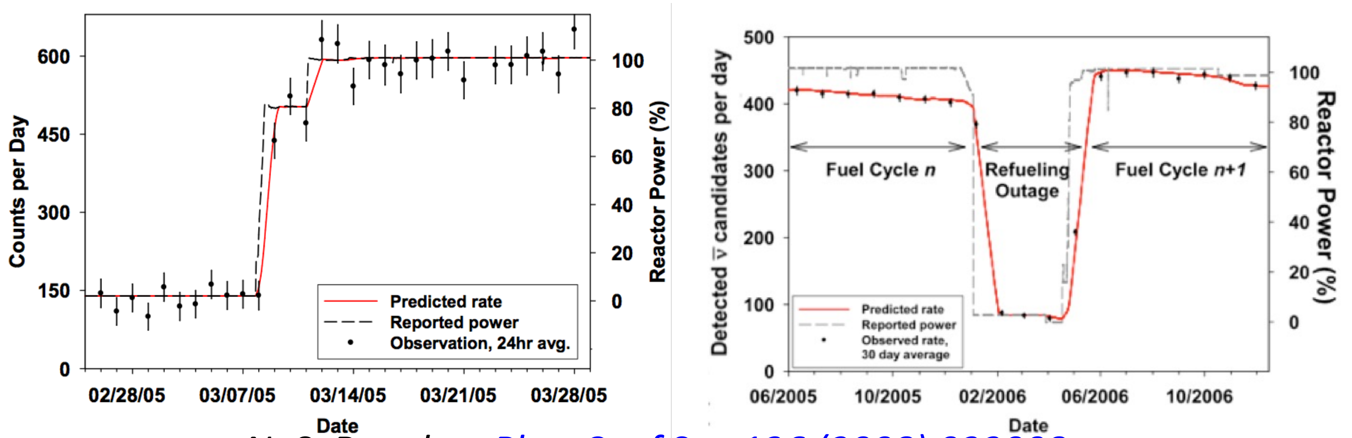
- Proposed in 1970's
- First demonstrated at Rovno (USSR) in 1980's
- U.S. demonstration at SONGS, early 2000s

Provides **non-intrusive** measurement capability for **reactor power** and **Pu production**



V.A. Korovkin et al., [Atomic Energy, 65, 712-718 (1988)]





N. S. Bowden, [Phys.Conf.Ser. 136 (2008) 022008]

Examples of Potential End User Feedback on Early Demonstrations

2008 Focused Workshop on Antineutrino Detection for Safeguards Applications

6.2. Medium Term:

inspector needs in some specific areas of reactor safeguards. To further expand the utility of antineutrino detectors, several useful medium term (5-8 year timeframe) R&D and safeguards analysis goals are proposed.

1. Above ground deployment. Above ground deployment will enable a wider set of operational concepts for IAEA and reactor operators, and will likely expand the base of reactors to which this technology can be applied;

antineutrino detectors. .In this regard, a possible deployment scenario is envisaged where the component parts of the detector, shielding and all associated electronics are contained within a standard 12 metre ISO container, facilitating ease of movement and providing physical protection to the

2011 Ad-Hoc Working Group on Safeguards Applications of Antineutrino Detectors

4. Conclusions:

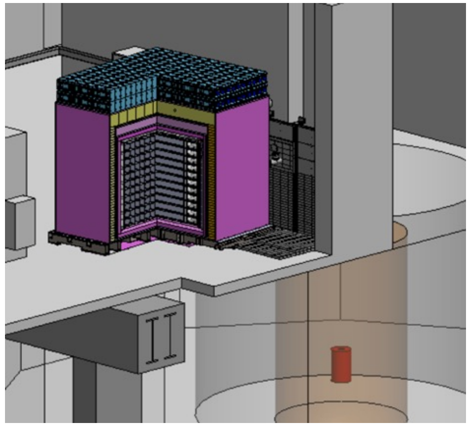
It was generally agreed that the meeting of the *ad hoc* working group of antineutrino experts and IAEA staff had been beneficial, providing the experts with a deeper understanding of how safeguards approaches are developed, their purpose, and how they typically incorporate several contributing elements that enable the IAEA to draw independent safeguard conclusions.

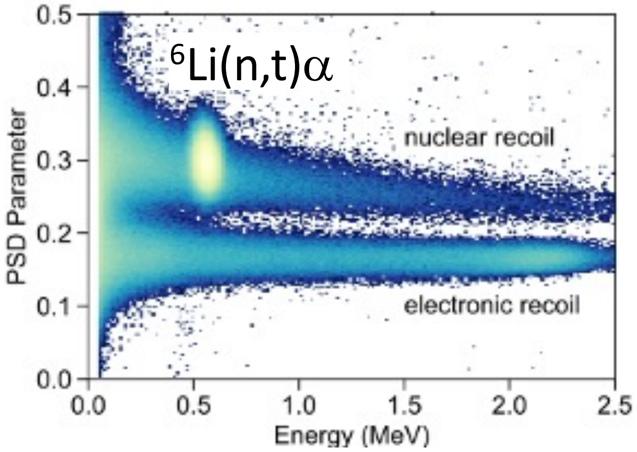
While the IAEA does not, at this time, foresee the use of antineutrino technology in support of current safeguards, it remains interested in possible useful developments in this scientific area. The IAEA is also grateful to several Member States for their individual initiatives in supporting antineutrino R&D in their own countries, while continuing to inform the Agency about their respective efforts. And,

Neutrino applications required technical advances and improved utility understanding

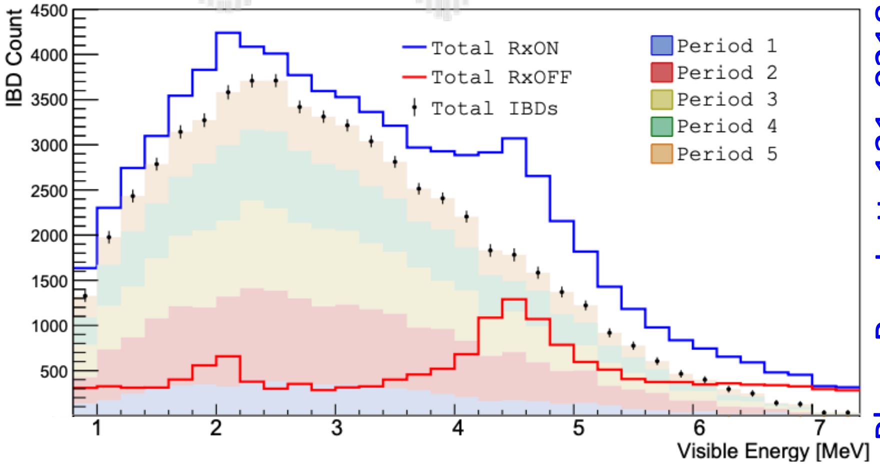
Technical advance in 2018:
Aboveground reactor antineutrino detection

- PROSPECT demonstrated high sensitivity aboveground detection at HFIR using Li-6 doped PSD liquid scintillator





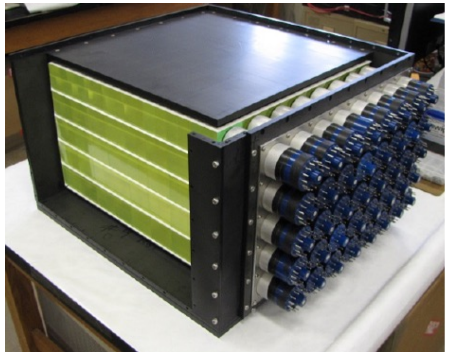
PROSPECT

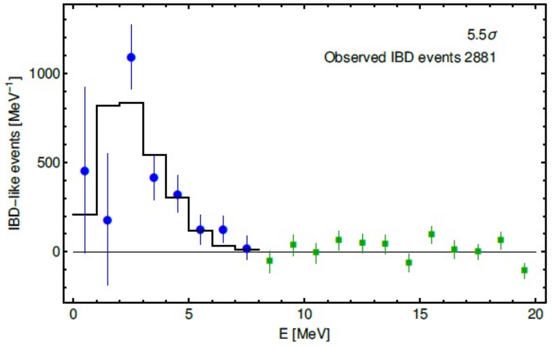


Phys. Rev. Lett. 131, 021802

- MiniCHANDLER prototype performed aboveground detection in mobile format

A. Haghighat et al., Phys. Rev. Applied 13, 034028 (2020)



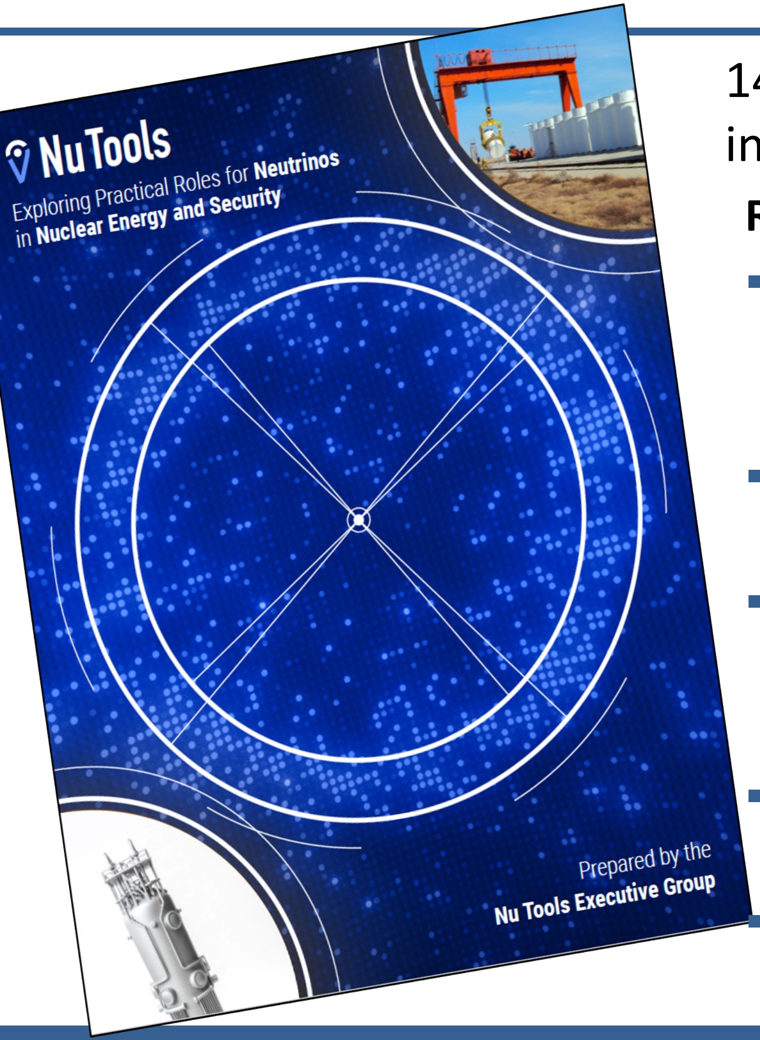


Enables broader range of deployment scenarios without need for fortuitous overburden or civil construction

https://nutools.ornl.gov/

The Nu Tools Study (2019-2021)

An effort to evaluate practical uses for neutrinos via broad input on needs and constraints



14-member Nu Tools study group engaged experts from the nuclear energy industry, regulatory, safeguards researcher and practitioner communities

Relevant Findings:

- **End User Engagement:** *".. neutrino technology R&D community is only beginning to engage attentively with end users … further coordinated exchange is necessary"*
- **Technical Readiness:** *"... novel system such as a neutrino detector requires a dedicated qualification exercise."*
- **Neutrino System Siting:** *"... requires a balance between intrusiveness concerns and technical considerations, where the latter favor a siting as close as possible"*
- **Advanced Reactors:** *"… present novel safeguards challenges which represent possible use cases for neutrino monitoring"*
- **Future Nuclear Deals:** *"… interest within the policy community in neutrino detection as a possible element of future nuclear deals*

Nu Tools provides motivation & guiding principles for the Mobile Antineutrino Demonstrator Project

Mobile Antineutrino Demonstrator

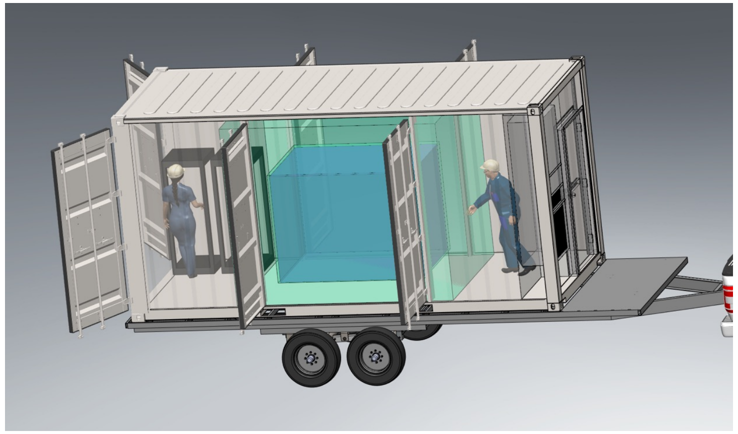
Goal: Develop & construct readily mobile ton-scale antineutrino detector system

The Mobile Antineutrino Demonstrator will:

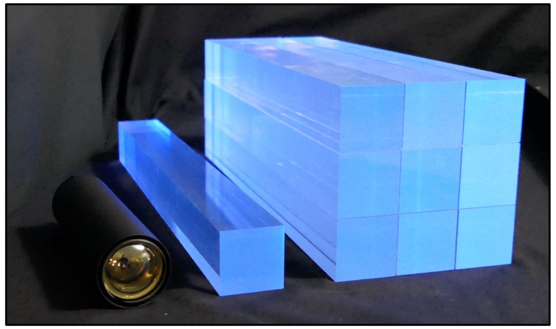
- require no infrastructure beyond power & deployment footprint
- operate aboveground with ‘PROSPECT-like’ sensitivity
- incorporate potential end-user input
- advance “Technical Readiness” of neutrino applications by performing capability demonstration in operationally relevant environments

Timeline:

- 2022-2023: Detector concept R&D, potential host and end-user engagement
- 2023-2024: Technology selection, system design, construction & commissioning

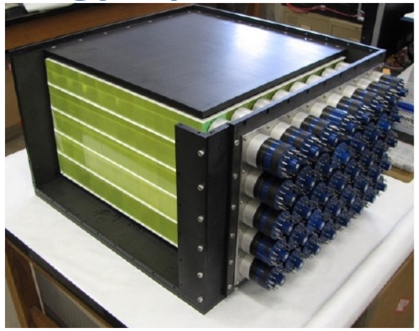


Solid-State Detector Technology Options



2D segmentation with ^{6}Li-doped PSD plastic scintillator

- *Novel Material*
- *Mature PROSPECT-like analysis*



3D segmentation with ^{6}LiZnS & WLS plastic scintillator (CHANDLER)

- *Mature Material*
- *Novel 3D reco & topological analysis*

Mobile Antineutrino Demonstrator Activities

- Near-field Use Case Sensitivity Framework
- Reactor Host & Developer Engagement
- End User Engagement
- Mobile Enclosure Engineering

Mobile Antineutrino Demonstrator

- Near-field Detector Simulation Framework
- Aboveground Background Prediction Capability
- Aboveground Detector R&D
- Prototype Detector Measurement Campaigns

Comprehensive effort that will provide foundational technology & knowledge for any near-field use case

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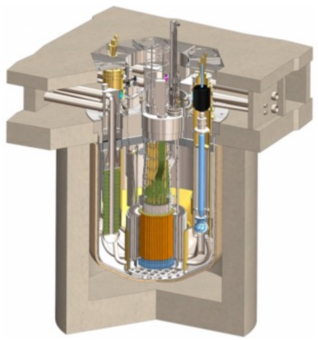
Prepared by LLNL under Contract DE-AC52-07NA27344.

Potential Mobile System/Near-field Use Cases

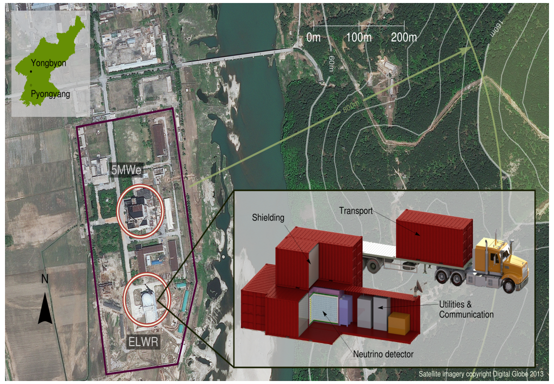
Advanced Reactor Safeguards

- Monitoring reactors with bulk fuel or opaque coolants, where conventional techniques may not apply
- Monitoring multiple small modular reactors on a site
- Reducing in-person inspections



Future Nuclear Deals

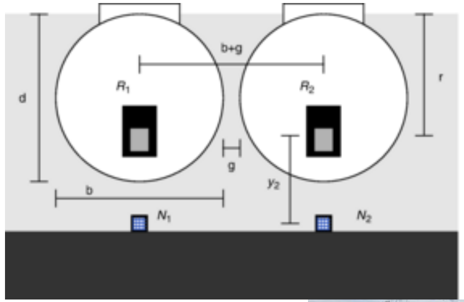
- Verifying a reactor shutdown from outside the building
- Verifying operations consistent with a civilian fuel cycle in a potentially dual-use reactor
- Creating opportunities for scientific engagement



Carr, et al, [Science & Global Security (2019)]

Naval Reactor Verification

- Using underwater variation of MAD-like technology to verify presence/enrichment level of nuclear reactor in a non-nuclear weapon state's submarine



Cogswell & Huber, [PRL 128 241803 (2022)]

Use cases characterized for specific international agreements; studies in progress for advanced reactor safeguards

Engagement with Potential End-Users

Important topics:

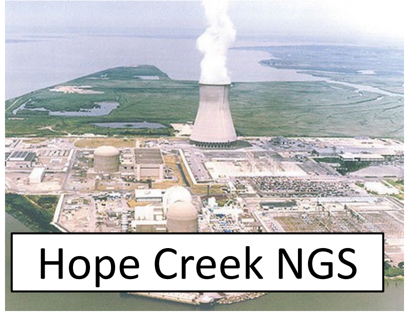
- Reliability
  "Predictability, reliability – these are absolutely key for getting something certified"
- Demonstration fidelity vs. sensitivity
  "It's not necessary to have a fully engineered system for a demonstration, but if self-contained is a selling point, the demonstrator needs to be self-contained and simple to operate."
- Value of communicating use cases
  "Beyond showing that the technology works, it is just as important to be able to tell leadership what the unique capabilities and advantages are. Why is this technology valuable, compared to other technologies? ... With a novel signal, it is very important to manage expectations. Don't oversell the technology. Express the current state of technology and realistic future performance."

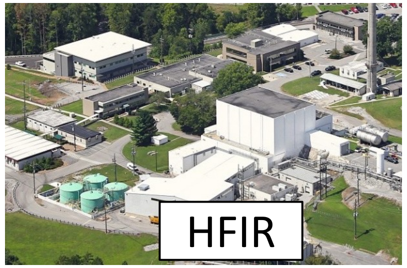
Engagement with Reactor Sites & Other Mobile Projects

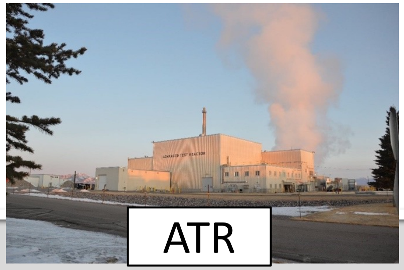
Important topics:

- Security inspection for PA access
- Fire Suppression
- Environmental Control
- Safety & Mechanical Assessment
- Physical Site & System Access
- Emplacement
- Communications
- Electrical Power


Pt. Lepreau GS


Hope Creek NGS


HFIR

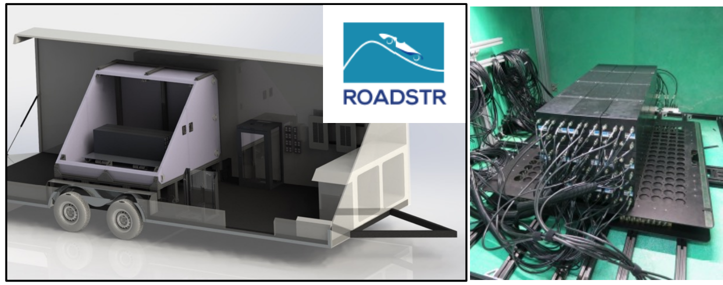

ATR


SONGS


PANDA


VIDAAR

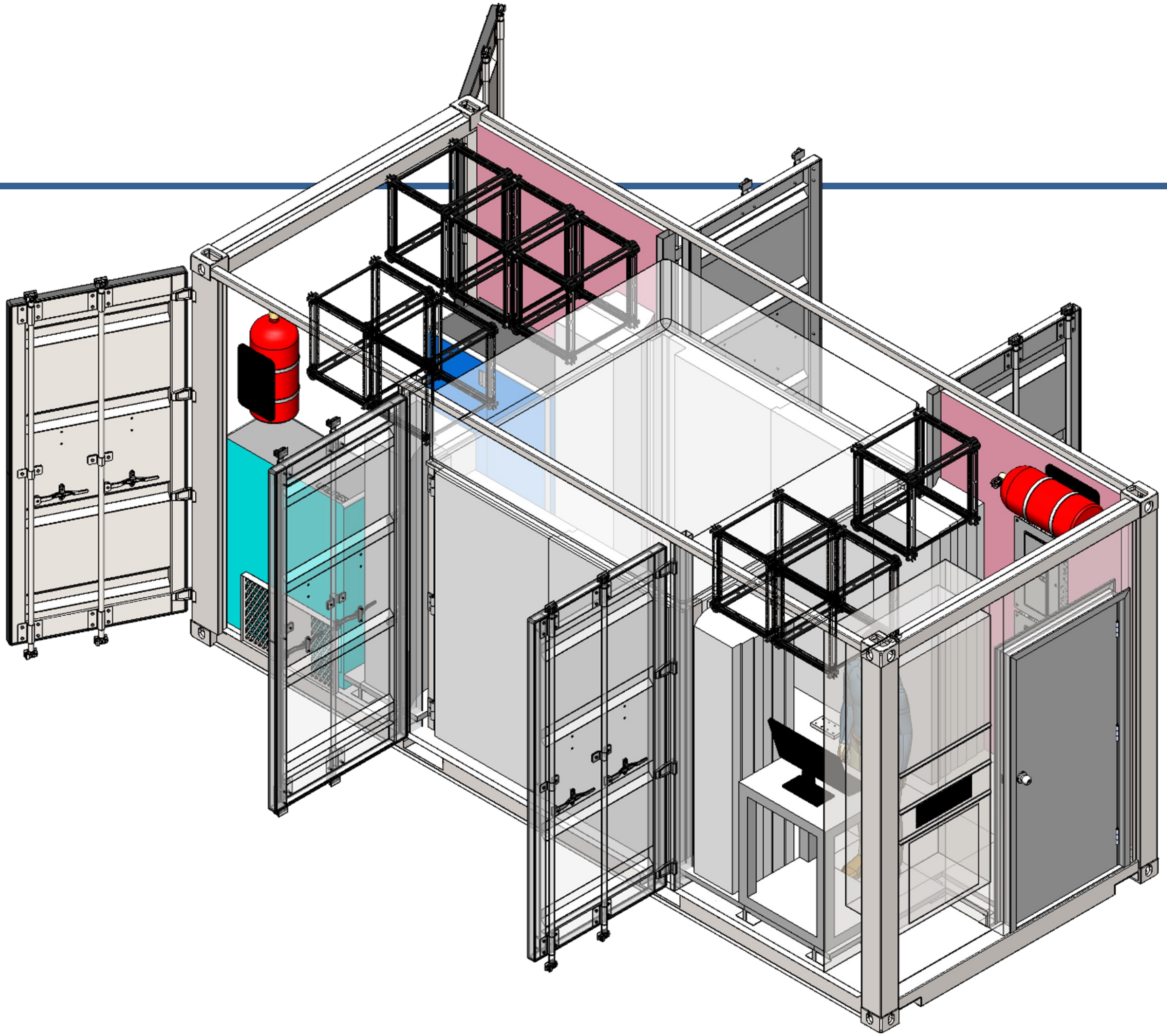
miniCHANDLER



Mobile Enclosure

Provides:

- compliance with host requirements for safety, security, and inspections
- environmental control, power distribution, and connectivity
- modest detector shielding
- safe detector transport

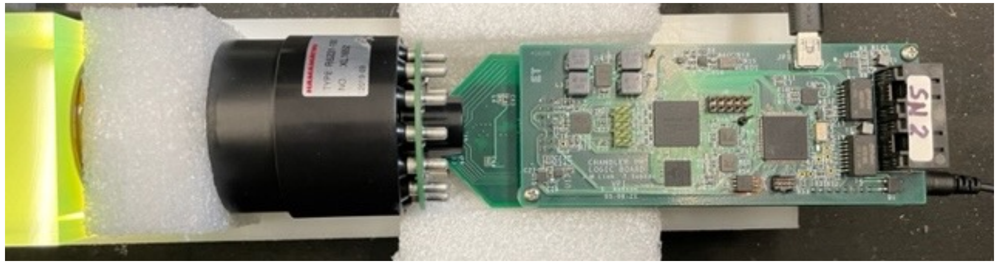


Aboveground Detector R&D

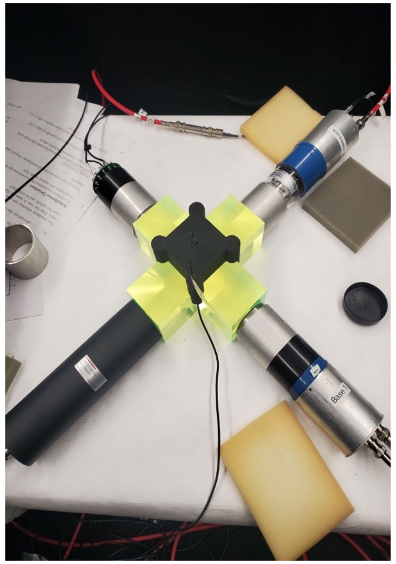
See: PSD Plastics talk (C. Roca)
ROADSTR talk (C. Bravo)
CHANDLER talk (K. Walkup)

- Advance maturity of 2D and 3D detector concepts:
  - — Materials characterization and packaging
  - — Detector mechanical design
  - — PMTs and readout
  - — IBD Selection and Background studies

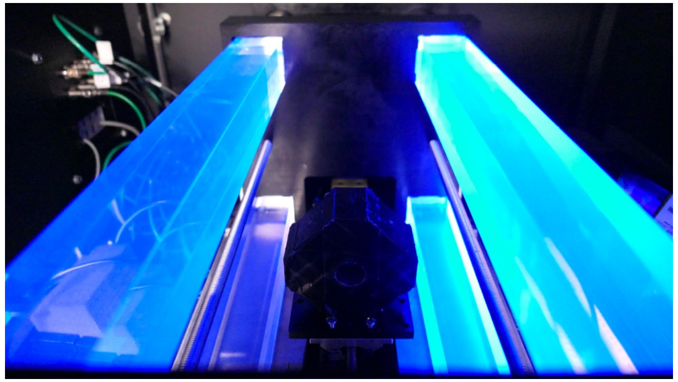
Readout and low-power HV



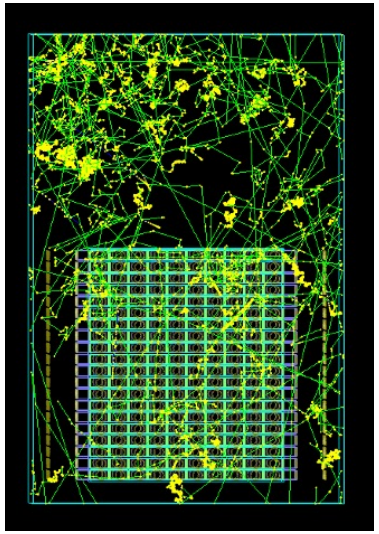
PMT Selection

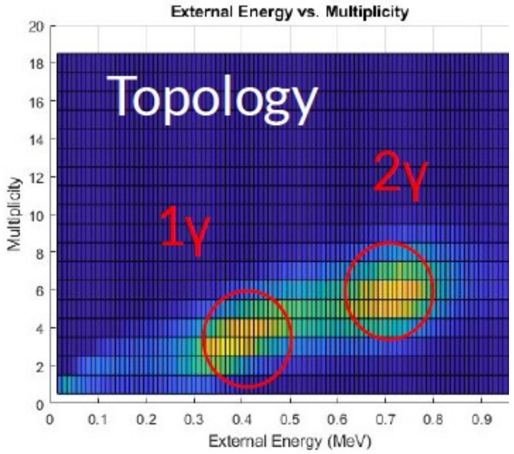


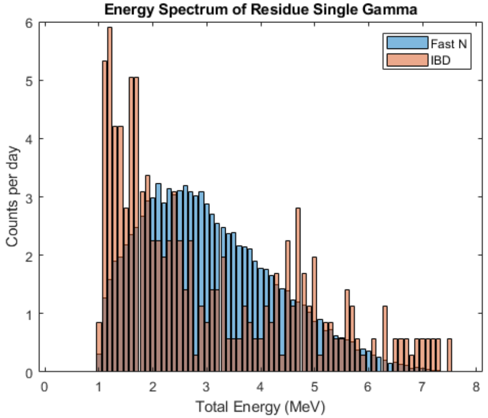
Materials Characterization



Background simulation and IBD event selection sim







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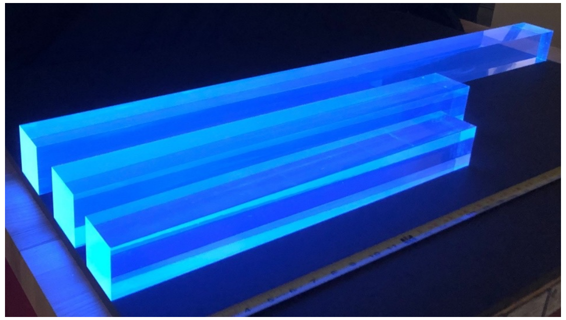
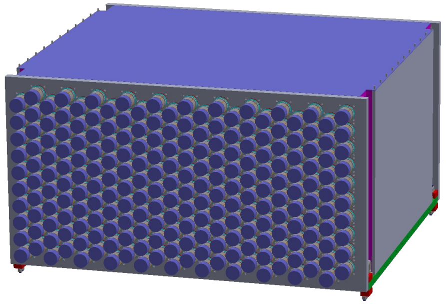
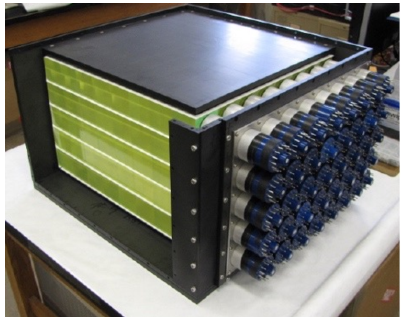
MAD R&D Phase established two concepts with good performance potential

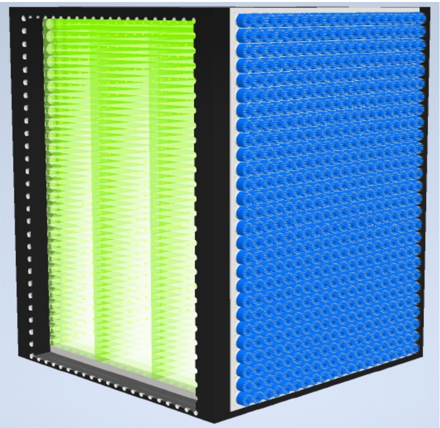
2D segmentation with ^{6}Li-doped PSD plastic





3D segmentation with ^{6}LiZnS & WLS plastic (CHANDLER)





Concept	x	y	z	Volume	Elements	PMTs	"Eff. Counts" (*)
2D	14 bars 84.0 cm	14 bars 84.0 cm	- 100 cm	0.71 m^3	196	392	130 day^{-1}
3D	16 cubes 92.8 cm	16 cubes 92.8 cm	41 ½-cubes 116.9 cm	1.01 m^3	10,496	1,344	131 day^{-1}

@ 2MW/m^2 flux, e.g.
39m from 3GW reactor

- Technical risk: plastic stability not fully qualified on multi-year time scale; standup of new material production
- Technical risk: implementation of 3D event reconstruction & topological observables at scale

Residual technical risks for both concepts most effectively resolved through build out at larger scale

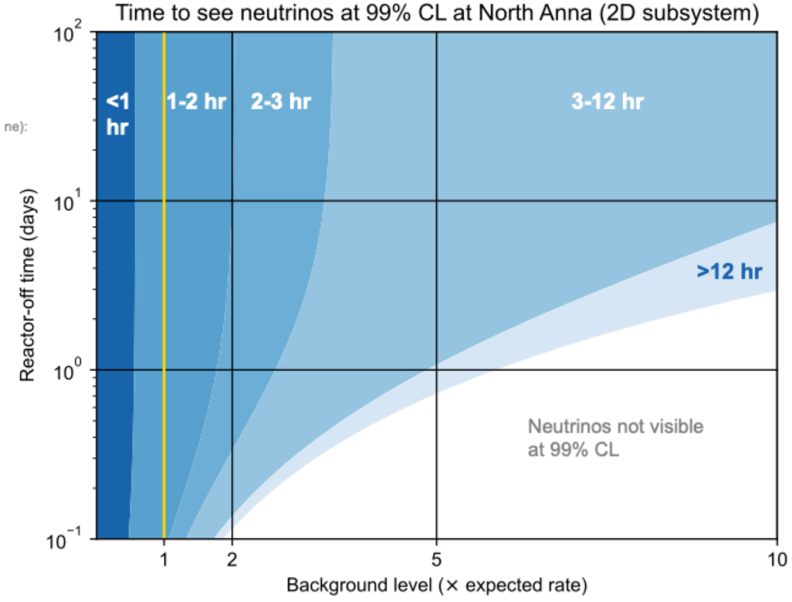
Neither relative performance nor technical considerations provided a strong preference for either concept

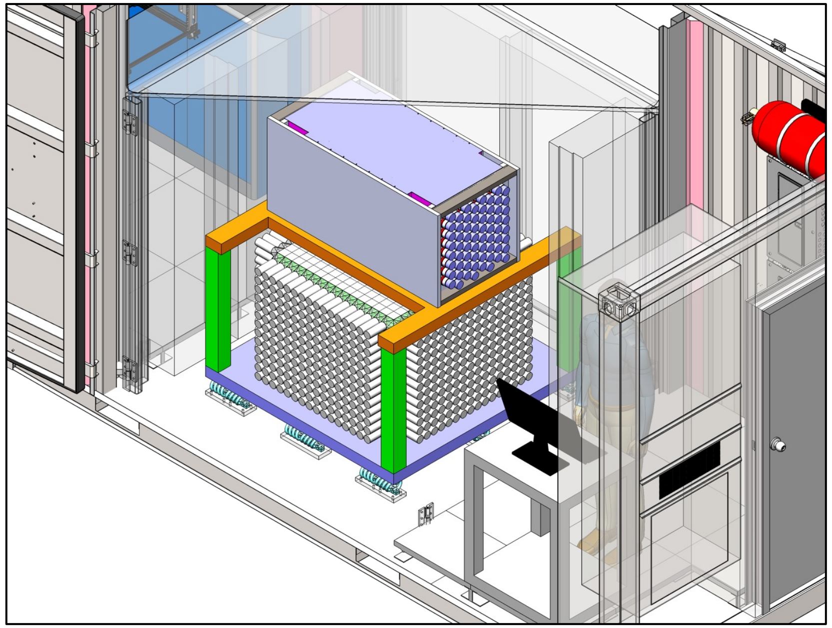
(*) "effective counts" = $S^2/(S+2B)$

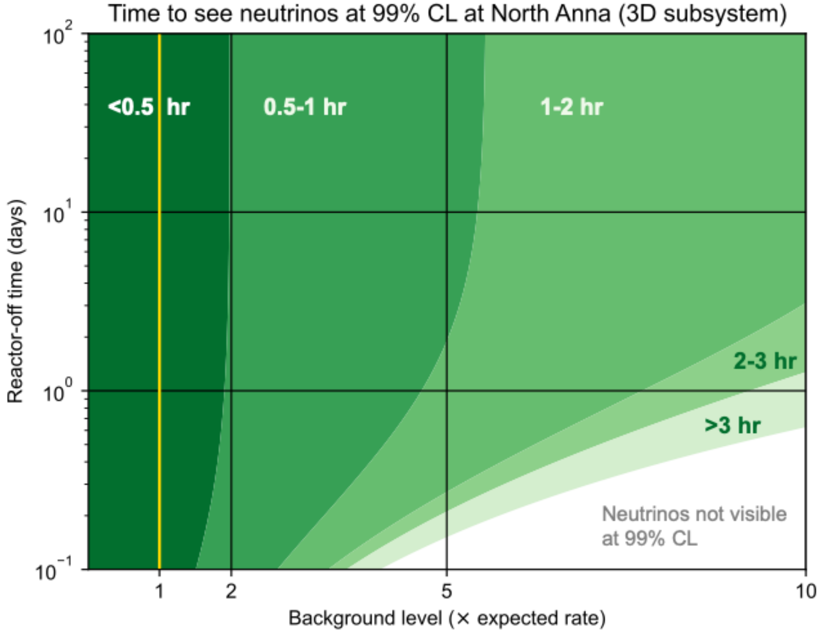
roughly, number of background-free counts with same 1/sqrt(N) statistical significance

MAD will proceed with 2 detector subsystems

Concept	x	y	z	Volume	PMTs
2D	8 bars 48.0 cm	8 bars 48.0 cm	- 100 cm	0.23 m^3	128
3D	16 cubes 92.8 cm	16 cubes 92.8 cm	25 ½-cubes 73 cm	0.61 m^3	832







Demonstrator with two subsystems will perform capability demonstrations and advance both technology concepts

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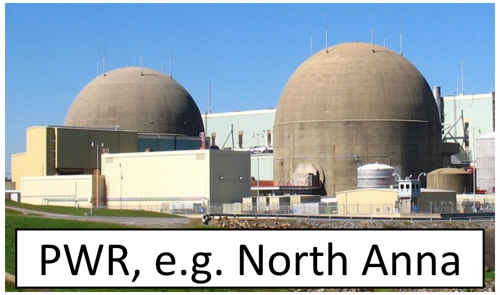
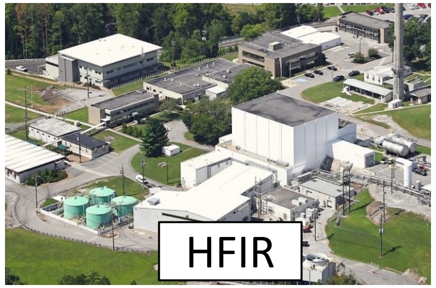
MAD Demonstration Goals and Options

- Technology Goals:
  - *Well characterized, sensitive, aboveground detector*
  - *Validated background prediction capability*
- Utility Goals:
  - *Capability to access relevant environments*
  - *Monitoring at multiple sites with minimal infrastructure, setup/teardown (hours timescale)*
  - *Reliable, unattended operation in relevant environments (multi-month timescale)*
  - *Monitoring capabilities:*
    - *Operational status (minutes to days)*
    - *Power (hours to weeks)*
    - *Burnup (weeks to months)*
- Nuclear Data Goals:
  - *Benchmark measurements of flux and spectrum at multiple, unique reactor cores*

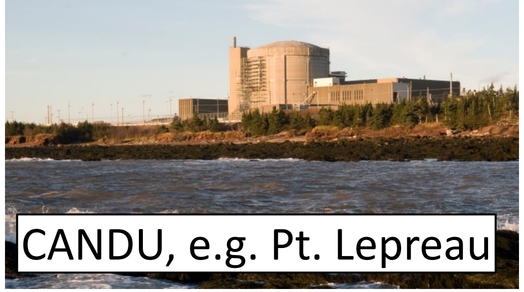
- Potential Sites:



- Demonstrate Protected Area access
- “High” flux technology demonstration
- Operational status, power, and burnup monitoring capability demonstrations
- Benchmark LEU core



- Research Reactor with frequent cycles
- “Low” flux technology demonstration
- Co-location with other monitoring projects
- Unique HEU core



- Unique online refueled CANDU core
- Analogue to some Advanced Reactors
- Under International Safeguards
- International partnership & cross border transport demonstration

Mobile system will be able to demonstrate technology & utility, plus collect benchmarks, at broad facility range

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Conclusion

- There have been advances in technology and understanding of neutrino utility that motivate this new effort to develop a readily-mobile detection system
- The MAD project takes guidance from Nu Tools by incorporating potential user and host feedback into system design
- A simulation framework is being developed for detector performance prediction, design guidance, and validated background prediction
- Two plastic-based detection concepts with complementary characteristics and good performance potential have been established
  - MAD will incorporate subsystems based on both concepts to further advance these technologies
- MAD will provide a Mobile Demonstrator system *and* foundational technology and knowledge for a broad range of Near-field Use cases

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Thank you for your attention

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