The Mobile Antineutrino Demonstrator Project

Nathaniel Bowden[1], *for the Mobile Antineutrino Demonstrator Project* *

[1] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

Abstract

The Mobile Antineutrino Demonstrator project aims to construct a realistically deployable antineutrino detection system that can operate at essentially any reactor facility with no infrastructure support beyond electrical power. Through engagement with potential end-users and host facilities, this effort will advance the technical readiness of neutrino-based reactor monitoring concepts by enabling operationally relevant demonstrations. The project is motivated by recent technology development that enables antineutrino detectors to operate at the earth's surface and the results of the Nu Tools study which provided new insight into the utility of antineutrino measurements for current and foreseen nuclear security problems. Specifically, a mobile demonstrator system has relevance to the most promising use cases identified in that study, Advanced Reactors and Future Nuclear Deals, and will incorporate recommendations regarding End-User Engagement and Technical Readiness in the system development process. In this presentation we will describe the mobile system design process, antineutrino detector technology options under development, and operational concepts for the mobile system.

1 Introduction

For more than 50 years, physicists have used antineutrinos from nuclear reactors to advance basic science. Such work has led to concepts for the application of antineutrino detection to nuclear security problems. Recent work enabling antineutrino detectors to operate at the earth's surface and in understanding the utility of antineutrino measurements for current practical problems motivate development of a next-generation application-focused demonstration system. Specifically, a readily mobile detection system that can demonstrate a reactor antineutrino measurement capability in the near-field with limited infrastructure support at multiple locations now appears technically feasible and responsive to potential end-user needs.

The Mobile Antineutrino Demonstrator (MAD) project is designing and constructing such a system. Following the lead of a recent utility study, system requirements will be developed that incorporate end-user input. At the completion of this project, a flexible mobile system will be available for delivery by road to reactor site(s) for demonstration measurements with the goal that these should require little more than site access and electrical power. By providing the capability to perform a full-scale system prototype demonstration in an operationally relevant environment, this project will advance the technical readiness of near-field antineutrino monitoring concepts.

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2 Antineutrino Detection and Near-Field Monitoring Applications

Antineutrinos generated in nuclear reactors can be detected by their infrequent interactions in hydrogenous materials via the Inverse Beta Decay (IBD) reaction: $\nu + p \rightarrow e^{+} + n$. An incident antineutrino with energy above the 1.8 MeV IBD threshold interacts with a quasi-free proton in the detection medium, producing a final state positron and neutron. Powerful background rejection is provided by detecting both final state particles in close temporal and spatial coincidence (typically a few tens of microseconds and a few tens of centimeters). Detectors that use the IBD channel therefore often contain a neutron-capture agent, such as Gd or ^{6}Li, to increase the neutron detection efficiency and tighten these correlations between the two final state particles. The kinematics of the IBD interaction ensure that the final state positron energy is closely correlated with the incident antineutrino energy, providing a spectral measurement capability.

Numerous experiments have demonstrated technology relevant to reactor antineutrino measurements using IBD, especially in the context of 'near-field' measurements within 10s of meters of a reactor core. Reference [1] provides a comprehensive review of experiments relevant to reactor monitoring in general, while references [2–12] are examples with specific relevance to the near-field monitoring regime. Historically, reactor antineutrino measurements have been conducted under at least 10 meters of material providing 'overburden' to attenuate background causing cosmic rays. This overburden has typically taken the form of convenient locations within existing facility structures or nearby underground facilities (e.g. mines) which are not generally guaranteed to exist, and/or being provided by dedicated civil construction.

Neutrino physics experiments seeking to resolve the "Reactor Antineutrino Anomaly" have over the last several years demonstrated important new capabilities including aboveground detection with good signal-to-background [9], high-resolution energy spectral measurements in ton-scale detectors [8, 11, 13], and prototype mobile aboveground systems [6, 10, 12]. Of most importance to reactor monitoring applications is aboveground detection without significant overburden, which enables an important Concept of Operations (CONOPS), namely the self-contained mobile system. This deployment modality gives tremendous flexibility in developing use-cases since existing locations at a facility can be considered without the need for extensive civil works or negotiating access within facility structures. The key enabling technologies for aboveground detection are use of segmentation, ^{6}Li as a neutron capture agent, and Pulse Shape Discrimination (PSD) to identify ^{6}Li neutron captures and ideally fast neutrons [14]. Combinations of these capabilities allow IBD interactions to be preferentially selected from cosmogenic backgrounds.

There are several approaches for constructing IBD detectors that include ^{6}Li-bearing material. ^{6}Li-loaded liquid scintillators (LiLS) have demonstrated the best background rejection and energy resolution performance to date [9], but require careful engineering and documentation. Liquids also carry a negative perception among end-users [15]. Accordingly, the MAD project will not consider LiLS implementations, but existing work serves as an important performance benchmark and provides considerable insight into background processes that can be used for design and assessment of other approaches.

While plastic scintillator (PS) is preferable for a mobile system, it trades off some capability at present and has higher material costs than liquid. Most readily available is ^{6}LiZnS plus wavelength shifting (WLS) PS using 'Commercial-off-the-Shelf' (COTS) materials [5, 10]. Since this combination does not have the ability to reject fast neutrons via PSD, this approach relies on topological selection of events that resemble the IBD positron energy deposition and how distinct these are from background processes like neutron-correlated gamma-rays and fast neutron recoils. PSD plastic scintillators (PSD-PS) combined with 6Li-doping or ^{6}LiZnS provide similar particle identification (PID) parameters to those demonstrated with ^{6}Li-doped liquids, but material performance and material cost at the cubic-meter scale are questions that need further examination. To summarize, demonstrated aboveground antineutrino detection concepts exist but these necessarily involve compromises between performance, cost, deployability, and complexity. The MAD project is performing R&D to advance promising PS-based concepts and assess their associated trade-offs.

3 Utility of Antineutrino Monitoring

Until recently, technical development and evaluation of utility for antineutrino monitoring were largely disconnected. To give an example, no specific application has been identified that has resulted in the generation of a detailed set of technical requirements to inform system design. To state this in a different way, the capability advances described in prior sections have been made in the context of neutrino physics measurements or general detection R&D. The recent Nu Tools study represents the first systematic attempt to engage potential Nuclear Energy and Security end users. The Nu Tools report [15] therefore provides important guidance and context for MAD.

The Nu Tools report contains several findings that motivate and are relevant to the Mobile Antineutrino Demonstrator:

- The End-User Engagement Finding emphasizes the importance of being attentive to user needs and constraints and incorporating these into the technical R&D process. By performing a requirements definition exercise at the outset of the project, this work adopts and addresses this finding.

- The Technical Readiness Finding points out that incorporation of novel technologies into end-user 'tool boxes' is a methodical and long process, in which demonstrations that advance technical readiness and user familiarity are essential. This project is developing a system specifically with this demonstration and familiarization process in mind.

- The Neutrino System Siting Finding describes how a balance of intrusiveness concerns and technical considerations must be struck when determining the deployment site of a monitoring system. The mobile deployment modality explicitly supports this tradeoff process through flexibility and will allow siting as close to a reactor as non-technical considerations allow, thereby collecting as much information and limiting required detector size as much as possible.

- The Advanced Reactors Finding describes how these forthcoming systems present novel safeguards challenges which represent possible use cases for neutrino monitoring. To collect relevant information, near-field deployment is likely to be required to address potential needs. Advanced reactor developers, safeguards experts, and forthcoming pilot facilities will be considered during the development of the mobile antineutrino demonstrator. Opportunities for actual demonstration measurements using the developed system will also be sought.

- The Future Nuclear Deals Finding describes how there is interest in the policy community in the capabilities that neutrino detection could provide for cooperative reactor monitoring or verifying the absence of reactor operations in the context of agreements between nations. Similar to the prior finding, relevant experts will be consulted in the requirements definition phase of this project and relevant demonstration opportunities sought that involve potential end users.

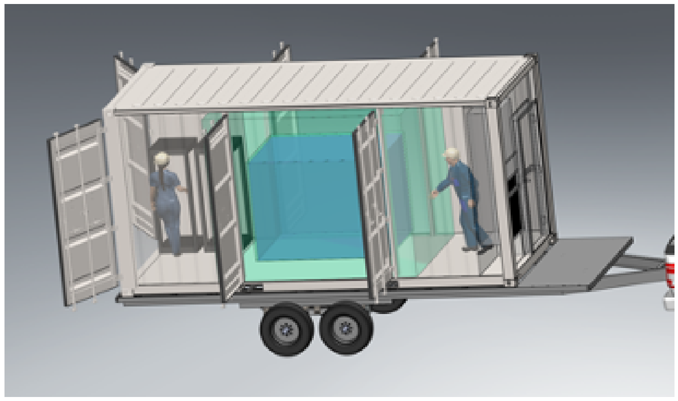

Figure 1: Conceptual rendering of the Mobile Antineutrino Demonstrator. A ton-scale antineutrino detector system is housed within a mobile enclosure that provides supporting infrastructure.

4 Mobile Antineutrino Demonstrator Activities

A conceptual rendering of the planned Mobile Antineutrino Demonstrator system is shown in Fig. 1. The MAD project is undertaking multiple activities that support design, construction, and demonstration of the mobile detector system. These include:

- Aboveground detector system R&D, design, and construction: two aboveground antineutrino detection concepts are being be advanced: two-dimensional segmentation using PSD capable ^{6}Li-doped plastic [16] and the CHANDLER concept based on three-dimensional segmentation, well established COTS materials, and topological event selection [10]. Based on this work, a ton-scale detector will be designed and constructed. The R&D questions to be addressed vary between detection concepts. That based on PSD plastic materials, work underway refine the production process, improve long-term material stability either through material chemistry or mechanical packaging, and to better define material optical performance at meter-scale lengths and cost at cubic meter-scale volumes. Additionally, event reconstruction and particle ID performance is being measured using a 60 kg prototype detector ("ROADSTR") to provide validation and input to a simulation framework. For the CHANDLER concepts based on non-PSD COTS materials, work is underway to develop and demonstrate event reconstruction techniques using the 80kg MiniCHANDLER prototype. Additionally, event identification algorithms must be developed and refined to preferentially select IBD signal and reject background. These will serve as inputs to a simulation framework to predict achievable performance at the cubic-meter scale.

- Mobile Deployment Enclosure design and construction: an enclosure that provides mechanical housing, environmental control, and utilities to the detection system will be designed and constructed. This must be engineered for the safe road-transport of the detection system and for maintaining a suitable operating environment once deployed. The goal is for minimal on-site setup. It should accommodate any detection concept under development and support incremental additions to detector volume, plus the addition of modest amounts of shielding material to increase measurement sensitivity.

- Simulation framework development for performance assessment of aboveground antineutrino detection concepts: building on prior work by PROSPECT, ROADSTR, and CHANDLER

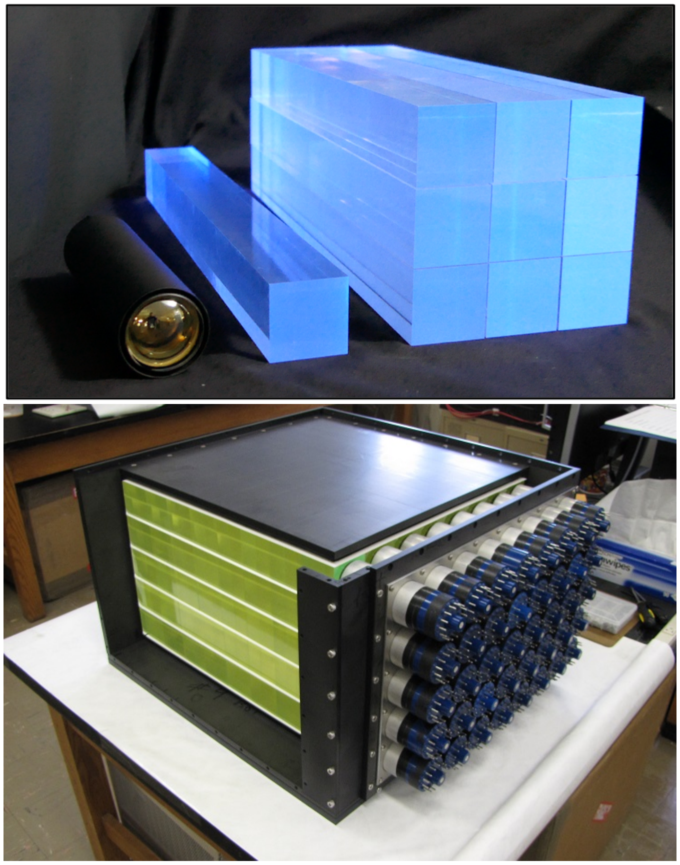

Figure 2: The two solid-state detector technology options under consideration: (top) two-dimensional segmentation using PSD capable ^{6}Li-doped plastic and (bottom) the CHANDLER concept based on three-dimensional segmentation, well established COTS materials, and topological event selection (MiniCHANDLER prototype shown).

develop a framework, validated by detector system R&D, that can compare and predict concept performance under a wide variety of conditions and use cases. This framework will provide essential input to detector concept selection, detector design, and use case development. Work is underway to develop a flexible code base that can readily accommodate multiple concepts, includes accurate representation of signal and background, and that can accurately reproduce the response of the detection concepts.

- Use case and requirements development: building on prior work by Nu Tools and team members, ensure that requirements for the Mobile Antineutrino Demonstrator incorporate end user needs and constraints. In the context of the most promising Nu Tools findings, engagement is underway to collect end-user input on practical needs and constraints related to the mobile deployment enclosure (e.g. delivery, security inspection, on-site emplacement, fire protection, foot print, surface load limits, and utility access) and the detection system (e.g. combustible inventory). Similarly, representative use cases will be generated from the findings to provide guidance on detection sensitivity and standoff requirements.

5 Conclusion

There have been advances in technology and understanding of neutrino utility that motivate this new effort to develop a readily-mobile detection, specifically the demonstration of aboveground reactor antineutrino detection and the improved understanding of antineutrino detection utility provided by the Nu Tools study. The MAD project takes strong guidance from findings of Nu Tools by incorporating potential user and host feedback into system design and considering system capabilities in the context of potential use cases. Major activities include the development of a simulation framework for detector performance prediction, design guidance, and for providing a validated background prediction for use in demonstrations. Two plastic-based detection concepts with complementary characteristics are being developed and assessed, with a ton-scale detector being planned. It should also be noted that in addition to a mobile demonstrator system, the MAD project will provide foundational technology and knowledge for a broad range of Near-field Use cases.

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