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LAWRENCE LIVERMORE NATIONAL LABORATORY

Remote Reactor Monitoring

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REMOTE REACTOR MONITORING

LL13-WATCHMAN-PD2Lb and
SL13-WATCHMAN-PD2Lb

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University Contributors: THE WATCHMAN COLLABORATION

1. INTRODUCTION

The overall goal of the WATCHMAN project is to experimentally demonstrate the potential of water Cerenkov antineutrino detectors as a tool for remote monitoring of nuclear reactors. In particular, the project seeks to field a large prototype gadolinium-doped, water-based antineutrino detector to demonstrate sensitivity to a power reactor at ~10 kilometer standoff using a kiloton scale detector. The technology under development, when fully realized at large scale, could provide remote near-real-time information about reactor existence and operational status for small operating nuclear reactors out to distances of many hundreds of kilometers[1].

The current project is a design and experimental study in support of a possible decision by DNN and another sponsor (DOE-SC-HEP) to jointly support deployment of a kiloton-scale detector, known as WATCHMAN (WATer CHerenkov Monitor for ANtineutrinos) This project is a follow-on to the joint projects LL12 and SL12 -RxMon-PD02 (FY12-13). These projects identified a suitable deployment location for the kiloton scale detector at the Morton Salt mine near Cleveland, OH, provided an initial detector design, and began measurements of backgrounds relevant to the large underground detectors at the Kimballton Underground Research Facility (KURF) near Blacksburg, VA. The current project completed the measurement campaign, provided a use-case analysis, and refined the design and associated simulations for the kiloton-scale detector.

2. PROJECT ORGANIZATION, MILESTONES AND DELIVERABLES

WATCHMAN relies on close collaboration between national labs with expertise in neutrino detection and nuclear security, and eight academic groups that bring world-class expertise in both neutrino detection and large-scale water detector development. The project and collaboration are led by LLNL. SNL has major hardware, simulations and other project responsibilities. The University groups contribute design, simulations and other expertise that are essential to the realization of the full-scale detector. The project makes effective use of the ongoing DNN-funded Nuclear Science and Security Consortium. Three of the University collaborators (UCB,UCD, and UCI) supported a significant fraction of their contributor's effort using funds from the NSSC grant.

In FY14, the Lifecycle Plan for the project (final version, dated April 18 2014) contained three Tasks:

1. Use benchmarked simulations to optimize kiloton-scale detector design
2. Complete preliminary design and detailed cost estimate
3. Perform a systems analysis of the possible uses of a large Gd-WCD reactor monitor for remote detection of a small reactor

All tasks were completed. Two deliverables were provided in separate reports:

Task 2 deliverable: provide a preliminary design and detailed cost estimate: SNL and LLNL will jointly provide a Conceptual Design Report for Kiloton Scale detector, including information from a background measurement campaign, with inputs from all University collaborators, the Site Selection process, and detailed information on the Total Project Cost.

Task 3 deliverable: Perform a systems analysis of the possible uses of a large Gd-WCD reactor monitor for remote detection of a small reactor. SNL and LLNL will jointly provide a report describing possible end use scenarios for remote reactor monitoring with large scale antineutrino detectors

Roles and responsibilities

Lawrence Livermore National Laboratory had overall responsibility for all deliverables and tasks from Lab and University collaborators on WATCHMAN. LLNL also led the WATCHBOY detector deployment and analysis, completed a comprehensive and detailed cost and schedule estimates for the WATCHMAN deployment, created a requirements document for the detector, and performed extensive simulations of WATCHMAN response to the reactor signal.
Sandia National Laboratories completed measurements of fast neutron backgrounds (>~50 MeV) underground at two depths using the Multiplicity and Recoil Spectrometer (MARS), created a preliminary engineering design of the kiloton WATCHMAN prototype detector in consultation with WATCHMAN Laboratory and University collaborators, and wrote a preliminary use case study to examine the potential nonproliferation applications of antineutrino detectors.
University collaborators' contributions were indispensable to the successful completion of all tasks. Students and post-docs performed much of the simulations work for the main WATCHMAN detector, provided a preliminary design for the Gadolinium water recirculation system, and provided support for the KURF deployments and analyses.

3. TASK 1 ACTIVITIES (SIMULATIONS AND DETECTOR DESIGN)

Significant advances were made in the detail and scope of our simulations in FY14. In addition, near the end of the year, the collaboration moved to a new and more flexible simulations platform for its ongoing simulations task.
The major advances in FY14 were:

1. detailed simulations of the WATCHBOY and MARS detectors. These simulations are described in detail in the updated Task 2 Deliverable, attached with the FY14 Q4 quarterly report.
2. Updated simulations of the WATCHMAN response to ambient and muogenic backgrounds, and to the reactor signal, including the detection efficiency for reactor antineutrinos, and an improved estimate of the radionuclide backgrounds (though still pre-WATCHBOY). The latest summary is found in our Q3 quarterly report.

4. TASK 2: FAST NEUTRON BACKGROUND MEASUREMENTS USING MARS

Sandia National Laboratories (SNL) was responsible for the design, construction, and deployment of a fast neutron spectrometer to measure the muon induced fast neutron background as a function of depth. In FY12-FY13, the Multiplicity and Recoil Spectrometer (MARS) was designed, constructed, installed into a mobile platform (20 ft trailer), and deployed to KURF. Details of the physics and design of MARS are provided in the Detector Design Report, but briefly, the spectrometer illustrated in Figure 1 (left) determines the energy of incident neutrons by counting the number of low energy neutrons that escape out of 3,500 pounds of lead after being produced by high energy (n,kn) reactions on lead nuclei. Knowledge of the energy spectrum of these neutrons is essential to designing the appropriate shielding and other features of the reactor monitoring kiloton-scale WATCHMAN detector.

A description of this signature, the creation of a detector response matrix, and the process of the spectral unfolding algorithms are outlined in the FY14 fast neutron measurements report, which is submitted as part of our Q4 report. In late FY13 and throughout FY14, MARS acquired ~6 months of data at both ~380 m.w.e and ~600 m.w.e and has been stationed at the KURF facility at 1480 m.w.e for the last 6 months. This depth was not originally anticipated to be one of the measurement locations; however it was felt that this depth will better tie these measurements to published data that extend up to this depth. Unfolded spectra from the first two locations are shown in Figure 1 (right).

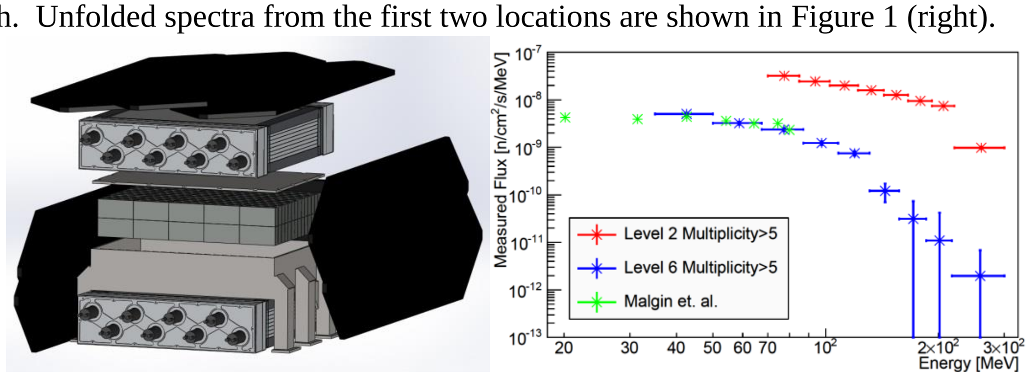

Figure 1 – (Left) Illustration of MARS including the muon veto system. (Right) Unfolded spectra from 380 m.w.e and 600 m.w.e. at KURF compared to a previous measurement at made by Malgin et al at 550 mwe

Preliminary results from the MARS detector are very encouraging. The depth at KURF is very similar to that at the Morton Salt Mine and will therefore have relevance both for future shallow detector deployments and the WATCHMAN demonstration detector if this project were to move forward.

5. TASK 2: RADIONUCLIDE MEASUREMENTS USING WATCHBOY

Lawrence Livermore National Laboratory (LLNL) was responsible for the design, construction, and deployment of the WATCHBOY radionuclide detector, and for the analysis of data from the detector. A detailed summary of results from WATCHBOY have been included in our Q4 report.

WATCHBOY was designed to measure the rate of radionuclide production in water created via muon spallation. The three primary nuclei of interest, ^{11}Li, ^{8}He and ^{9}Li, can mimic an antineutrino induced inverse beta decay, via coincident high-energy beta decay and neutron emission. The rate of production, however, has not been measured, and could contribute significantly to the background in WATCHMAN. WATCHBOY was constructed between April and July 2013 at the Kimballton Underground Research Facility (KURF) in Virginia. "First light" was late in July 2013. Figure 2 shows the design of the detector hardware (not including the outer tank supporting the water). There are 16 inner target 10-inch PMTs instrumenting a volume of approximately 2 cubic meters, and 36 veto PMTs for the remaining 40 cubic meter veto volume. The veto is a volume of pure DI water surrounding the target averaging 1.4 meters thick. It serves two purposes, to indicate the passage of cosmic ray muons nearby, and to prevent fast neutrons and high-energy gamma rays from the rock reaching the target. Figure 1 shows some of the installed PMTs in the outer veto and the completed inner target (left) and the bottom veto region under the target (right).

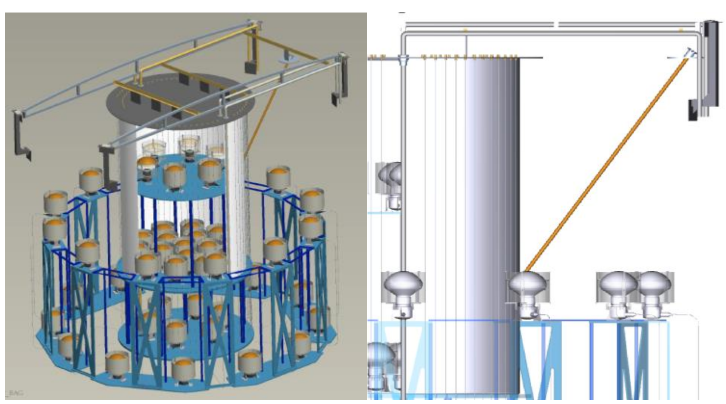

Figure 2: The Watchboy detector design inside the steel detector tank. The target gadolinium doped region containing 16 tightly packed upward facing PMTs is shown at the center of the detector (left). To the right the bag that supports the target region and the calibration source tube are shown. The source tube allows deployment of sources at the edge of the target volume.

Figure 2 shows the key preliminary result from the WATCHBOY detector. We plot the number of correlated event pairs following a muon as a function of the elapsed time since the last muon. The selection criteria were assuming the sub-events were consistent with neutrons. Our final selection criteria will be adjusted so that the first of the two events is the prompt beta distribution from the relevant radionuclides. At this stage there appears to be no evidence for the presence of any shorter exponential component that would indicate the presence of radionuclide decay pairs in WATCHBOY. This preliminary result is encouraging, since it appears to show that the radionuclide rates are so low that they do not affect the WATCHBOY signal.

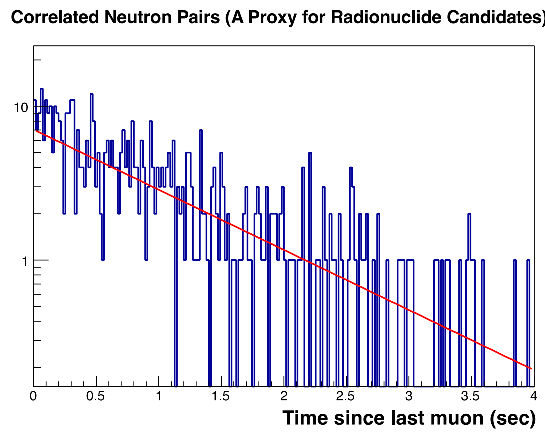

Figure 3: After 221 live days, 536 correlated neutron pairs have been detected in the target. Plotted here, for each of these pairs, is the distribution of times to the previous muon through the target. The red line is an exponential fit with the time constant fixed at the measured muon rate through the target *(slope = 0.9, exponential fit = $Ae^{-0.9t}$*)

6. WATCHMAN PRELIMINARY ENGINEERING DESIGN

Through early FY14 SNL conducted a series of detector design meetings that included many of the lead WATCHMAN collaborators; each with decades of experience in large detector design. Design components and lessons learned from detectors ranging from the Large Baseline Neutrino Experiment (LBNE) to Borexino to Super Kamiokande (Super-K) were incorporated into the WATCHMAN design. Between meetings Sandian engineers integrated suggestions and iterated on design components. LLNL created and maintained a detector requirements document, populated by experts in various detector components (PMT mounting, electronics, cleanliness, tanks, water filtration, etc.).

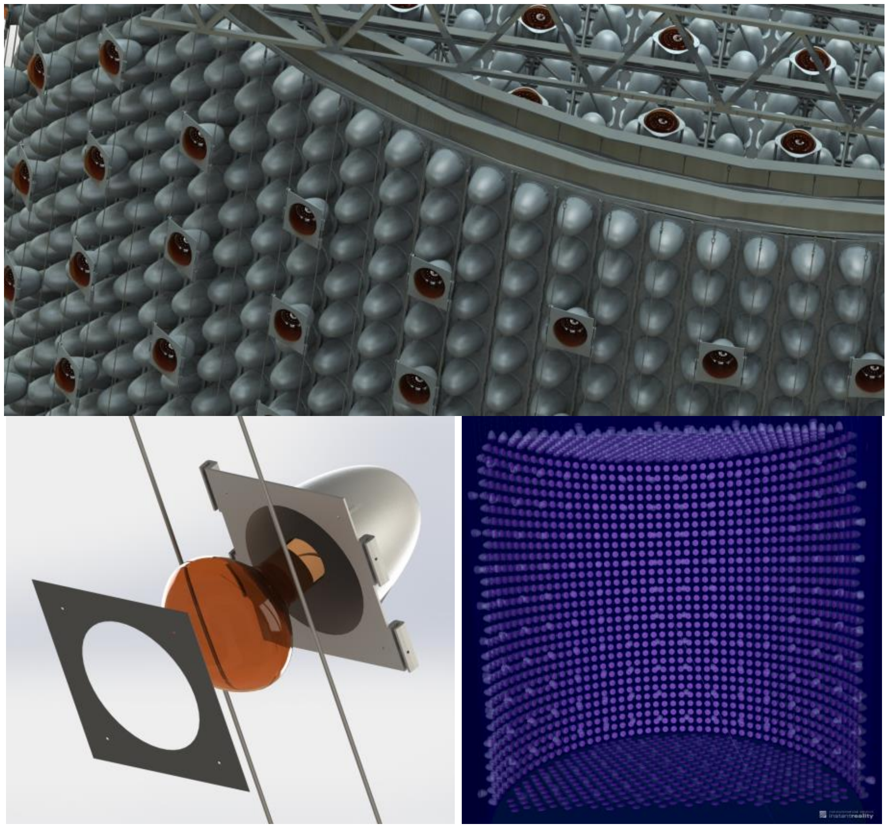

Figure 4 - WATCHMAN preliminary engineering design. (Top) CAD rendering of the backside of the PMT support structure. (Bottom left) CAD rendering of the PMT cable mounting system. (Bottom right) Visual of the Geant4 WATCHMAN detector used in simulation studies.

In parallel to the engineering design and requirements definition, a Monte Carlo simulation was developed. Designs were implemented in the BACCARAT Geant4 package both as a check against other code development (led by UC Davis) and as a means to quickly iterate between designs and predictions. Illustrations from the Monte Carlo as well as several engineered component renderings are shown in Figure 4.
The completion of preliminary engineering designs of the WATCHMAN detector has allowed us to reduce contingencies in budget estimates. For several major components such as the water tank and PMTs we were able to establish cost estimates from vendors.

7. USE CASE STUDY

In FY14, SNL and LLNL assembled a team to examine the potential nonproliferation applications of antineutrino detectors with a focus on kiloton- and megaton-scale detectors. The substantial nonproliferation expertise that exists at SNL and LLNL was leveraged by interviewing a variety of nonproliferation experts. Expert feedback was used to understand the perspectives of the nonproliferation community, to investigate needs that might be addressed by antineutrino detectors, and to examine the practicality of employing antineutrino detectors in the nonproliferation context. Based on this feedback, the team identified several nonproliferation applications for further study. The suitability of antineutrino detectors to each of these applications was determined by evaluating their performance against the core technical requirements associated with each application. These evaluations were performed in several different regimes, including cooperative and non-cooperative environments, as well as near, medium, and far standoffs. The analysis along with the evaluation of several use cases was submitted in a Use Case Study report.

The Use Case Study identified several nonproliferation applications for antineutrino detection. We believe that further study is warranted to allow pursuit of leads in the various possible user communities that have been identified in this work. Better understanding of user requirements will help inform the suitability of antineutrino detection techniques to nonproliferation needs.

8. RESULTS, DISCUSSION AND CONCLUSIONS

In FY12-14, our project activities, and related activities by University collaborators, have retired several of the most important risks facing a nonproliferation demonstration of the Gd-water Cherenkov technology for remote reactor monitoring. These are:

- Demonstration of the ability to recirculate a stable compound of Gd-doped water on a large scale (200 ton EGADS experiment, performed by collaborator Mark Vagins using non-DNN funds)
- Measurement of fast neutron and radionuclide backgrounds as a function of depth below the Earth. These are the most important backgrounds for the large detector
- Production of a Conceptual design for the WATCHMAN kiloton-scale Gd-doped Water Cherenkov Detector.
- Identification of two suitable underground site in the U.S. and approval from site management to accommodate our deployment. We have developed a Preferred and an Alternative site, based on cost and feasibility grounds for the demonstration. The Preferred site is the Morton Salt Mine in Ohio, the Alternative site is near the Advanced Test Reactor at Idaho National Laboratory in Idaho.
- A preliminary use case analysis, focused on a baseline capability with minimal extrapolation from the anticipated results of the WATCHMAN demonstration.

In FY15, we will focus on further exploration of use cases, and in concepts that can lead to enhanced sensitivity at long standoff from small reactors. These concepts are being explored in a University-Laboratory partnership, which builds on the successful relationships with the neutrino physics community that have been cultivated in the prior phases of the WATCHMAN venture.

9. PRESENTATIONS AND PUBLICATIONS

Presentations

Bernstein, A. “WATCHMAN: a demonstration of Remote Reactor Monitoring with Gadolinium Doped Water Detectors” ESARDA conference, Oxford, England, March 2014

Dazeley, S., "WATCHMAN Detector" APS April 2014

Dazeley, S., "WATCHMAN Detector Design" APS April 2014
Dazeley, S., "WATCHMAN: Reactor Monitoring and Neutrino Physics with aGadolinium Doped Water Detector" -- Neutrino 2014 conference, Boston, June 2014
Roecker, C., Marleau, P., Gerling, M., Brennan, B., "Measurements of neutron spectra underground relevant for remote detection of antineutrinos", APS March Meeting 2014
Bergevin, M., "The WATCHMAN Detector", presentation, Tokyo Institute of Technology, January, 2014.
Bergevin, M., "Simulation of the detector response of the 1-kton option of WATCHMAN", APS March Meeting 2014
Bergevin, M., "Detector response of the 1-kton option of WATCHMAN", Advances in Neutrino Technology (ANT2014), UCLA, September, 2014.
Bergevin, M., "WATCHMAN", Sandia National Laboratory, March 2014
Bergevin, M., "Low energy physics using Water Imaging Detectors", Tokyo Institute of Technology, February 2014
Bergevin, M., "The WATCHMAN Detector", presentation at the ANNIE Meeting, University of Chicago, March 3, 2014
Bergevin, M., "Simulation of the Detector Response of the 1 Kton Option of WATCHMAN," poster, Neutrino 2014, Boston, June 2-7
Bergevin, M., "Detector response of the 1-kton option of WATCHMAN", INPA, Lawrence Berkeley National Laboratory, July 2014
Publication
Marleau, P., Gerling, M., Reyna, D., Sweany, M., Bernstein, A., Bowden, N., Dazeley, S., Roecker, C., "Multiplicity and Recoil Spectrometer for Fast Neutron Background Measurements at Depth", SORMA 2014 conference proceedings.
Svoboda, R., "Medium Baseline Reactor Neutrinos and the Neutrino Mass Hierarchy", MIAPP Workshop, Technical University Munich, July 10, 2014.
Svoboda, R., "WATCHMAN", MIAPP Workshop, Technical University Munich, July 25, 2014.
Danielson, D. (student), "Investigation of the Sensitivity of WATCHMAN to Measure the Neutrino Mass Hierarchy," poster at the University and Industry Technical Interchange (UITI) Meeting, Walnut Creek June 3-5
Svoboda, R., "WATCHMAN" , Colloquium at University August 2014

[1] A. Bernstein, G. Baldwin, B. Boyer, M. Goodman, J. Learned, J. Lund, D. Reyna, R. Svoboda, "Nuclear Security Applications of Antineutrino Detectors: Current Capabilities and Future Prospects," Science & Global Security, 18, no. 3, (2010): 127-192.

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