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Size matters when monitoring reactors from a distance

At a mine in Virginia, researchers from Sandia and LLNL are hard at work helping the National Nuclear Security Administration (NNSA) meet a goal set in its 2011 Strategic Plan: to demonstrate remote monitoring capabilities for reactor operations by 2016.

"This is a really hard problem to solve," says Peter Marleau (8132), the project lead for Sandia's part of the project. "Our ultimate goal is to create a detector that can find or exclude hidden 10 MWt reactors at distances up to 100s of kilometers." This is a research reactor size, which could potentially be hidden from other detection methods while still breeding plutonium in quantities that could be of concern.

About five years ago, a collaboration between Sandia and LLNL proved the effectiveness of an antineutrino detector for reactor monitoring. Nuclear decay produces large quantities of antineutrinos – the antiparticles of neutrinos, fast-moving elementary particles with miniscule mass that pass through ordinary matter undisturbed. An antineutrino detector tracks the particles as they emanate from a reactor to measure operational status and thermal power. See the August 29, 2008 issue of *Sandia Lab News*.

But that technology is limited by range; the detector must be very close to the core of the reactor. To monitor from further away – tens to hundreds of miles – you need a really big detector, explains Peter. And by really big, he means Megaton scale.

One of the most viable options for scaling to these sizes is water lightly doped with gadolinium. "This is a path that science hasn't gone down yet," says Peter. "So this is pretty exciting research. We are pushing technology that could be very useful for physics detectors in the future."

Sandia and LLNL are teaming up with six universities – University of Hawaii, Hawaii Pacific University, Virginia Tech, and the University of California Berkeley, Davis, and Irvine – on a project funded by NNSA's Office of Nonproliferation and Verification Research and Development. The project is called WATCHMAN, or WATer CHerenkov Monitoring of Anti Neutrinos.

There is some precedence for a detector of this scale. Japan's Super-Kamioka Detector, or Super-K, has a massive 50-kiloton tank that stands 136 feet high. But as a neutrino observatory searching for proton decay, neutrinos, and cosmic rays, Super-K is not sensitive to reactor antineutrinos. Super-K uses ultra-clean water, not the doped water proposed for the WATCHMAN detector.

Because the WATCHMAN detector will break so much new ground, the team is first starting with basic research to optimize the design and location of the demonstration site of a smaller kiloton scale gadolinium -doped water detector. They are about halfway through a two-year scoping study.

Understanding background at shallow depths

One challenge for a detector of this size is background radiation. The bigger the detector, the more background radiation it is going to pick up. One solution to this, says Peter, is to place the detector underground.

"At a certain depth, cosmic radiation disappears," he explains. "But that kind of excavation would be very costly and time consuming for a detector of this scale. We're looking at what happens at shallow depths. Is there a more reasonable depth of a few hundred feet where background radiation drops off to a more manageable level? That's something we don't know because there just isn't much research on background radiation at shallow depths, especially with a water-based detector. We are after a low signal-to-noise regime to optimize the detector's effectiveness, so understanding background is huge."

In particular, the study is looking at background radiation created by muons that can mimic antineutrinos. Muons are fundamental particles created when cosmic rays collide with molecules in the upper atmosphere. Every second of the day, muons are hurtling down to earth—the rule of thumb, says Peter, is that a muon passes through your thumbnail every minute. They eventually attenuate when they are absorbed or deflected by other atoms.

"Muons are very high energy particles that are not easily stopped. When they interact with rock, they basically rip apart the nuclei in the rock and create a shower of particles that can look like an antineutrino signal in the detector," says Peter. A muon can also pass through a water-based detector and create radionuclides with decay particles that look like antineutrinos.

To understand how these phenomena affect background radiation at shallow depths, the WATCHMAN team is conducting a series of fast neutron measurements at the Kimballton Underground Research Facility (KURF), an underground science facility operated by the Virginia Tech Neutrino Science Center.

Splitting the problem

Early into the project, it became clear to the WATCHMAN team that a single detector could not encompass all of the muon interactions, so they split the problem. LLNL took on radionuclides while Sandia focused on the neutron spectrum, specifically muon induced fast neutrons with energies between 100 and 200 MeV.

LLNL's radionuclide detector, which is still in development, will be similar to the kiloton detector on a much smaller scale, about 3 meters across, with a tank that will hold gadolinium-doped water. "There has been no measurement of the production of radionuclides from muons interacting with water, so it's not a well bounded problem," says Peter.

Over the past year, the Sandia team members designed and constructed a one-of-a-kind detector that was delivered to the KURF site in early June. That detector, which the team dubbed MARS for Multiplicity and Recoil Spectrometer, combines two established modes of neutron detection to cover the entire energy spectrum of interest.

Think of it as a detector within a detector within many more smaller detectors. MARS consists of a 20-centimeter-thick pile of lead sandwiched between plastic scintillator wrapped in photo multiplier tubes to read out the scintillation light. The entire package is wrapped in paddle detectors to tag muons that enter MARS.

"We want to measure what is coming out of the walls of the cavern, not neutrons that are created within our detector by muon interaction," explains Peter.

The lead acts as a multiplier for high energy neutrons, so there are two modes of detecting neutrons. A high energy neutron can interact directly with the scintillator, which causes a large pulse of light that is captured by the photo multiplier tubes – this is the recoil. Neutrons at even higher energy levels interact with the lead, producing many more low energy neutrons – the multiplicity. The number of low energy neutrons produced is correlated to the energy of the neutron.

The antineutrino detector developed by Sandia and LLNL in 2008 found new life in MARS. “We were able to reuse the plastic scintillators with layers of neutron capture gadolinium from two detectors that were deployed at the San Onofre Nuclear Power Plant,” says Peter. “We added more photo multiplier tubes to increase light collection.”

MARS was then placed in a trailer so that it can be moved to three different locations within the mine to collect data at different depths. It is currently sitting at 600 feet; in a few months it will be moved to 350 feet and will finish the year of testing at 150 feet. This project is the first-ever continuous measurement as a function of depth.

Peter expects many in the scientific community to pay close attention to the WATCHMAN project as it develops. He describes the project as a good testbed for basic scientific research with the potential to make measurements that are of great interested to the scientific community.

“The idea of creating a detector based on gadolinium-doped water has been kicked around for some time, but no one has pursued it. We don’t have a choice – for long range detection we need a large detector and gadolinium-doped water is possibly the only feasible option for a detector of that size,” says Peter.

“In addition, there is no antineutrino detector in North America today. It is good to have several well separated independent detectors with different systematic uncertainties observing the same phenomena as a cross check. WATCHMAN could be America’s contribution to neutrino astrophysics.”

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Detecting Supernovas [side bar]

There is another benefit to WATCHMAN – when complete, it will be among the best supernova detectors in the world. A core collapse supernova produces an enormous burst of neutrinos. Knowledge gathered by measuring the type, time, and energy structure of those neutrinos can help answer many physics and astrophysics questions.

With gadolinium-doped water, WATCHMAN will be able to distinguish between neutrinos and antineutrinos. The number of neutrinos and antineutrinos as a function of time will be useful data for supernova physics models.

WATCHMAN will be smaller than Super-K, but that size could prove an advantage with a nearby Supernova. The signal of Supernova 1987A, which occurred 168,000 light-years from earth and was observable by the naked eye, overwhelmed Super-K.

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