Antineutrino Detectors Improve Reactor Safeguards

WHAT has the ability to pass through anything, yet remain virtually undetected? No, it's not a superhero, but rather, stable elementary particles known as antineutrinos. These invisible particles seldom interact with matter, carry no electric charge, and have almost no mass. Yet, they are proving to be effective tools for global security. In a project funded by the National Nuclear Security Administration's Office of Nonproliferation Research and Development, scientists from Lawrence Livermore and Sandia national laboratories are developing antineutrino detectors to help the International Atomic Energy Agency (IAEA) safeguard fissile materials within nuclear reactors.

IAEA is the international organization responsible for monitoring nuclear facilities for nonproliferation purposes. For some of its assessments, the agency must rely on operator declaration. Antineutrino detectors could provide a more precise method to confirm that reactors are operating according to IAEA standards and that fissile materials are not being diverted for use in an undeclared nuclear weapons program. The Livermore–Sandia team has developed autonomous detectors that continuously and accurately monitor antineutrinos in real time throughout the one- to two-year fuel cycle of a standard pressurized water reactor.

Flashes of Light Reveal the Antineutrino

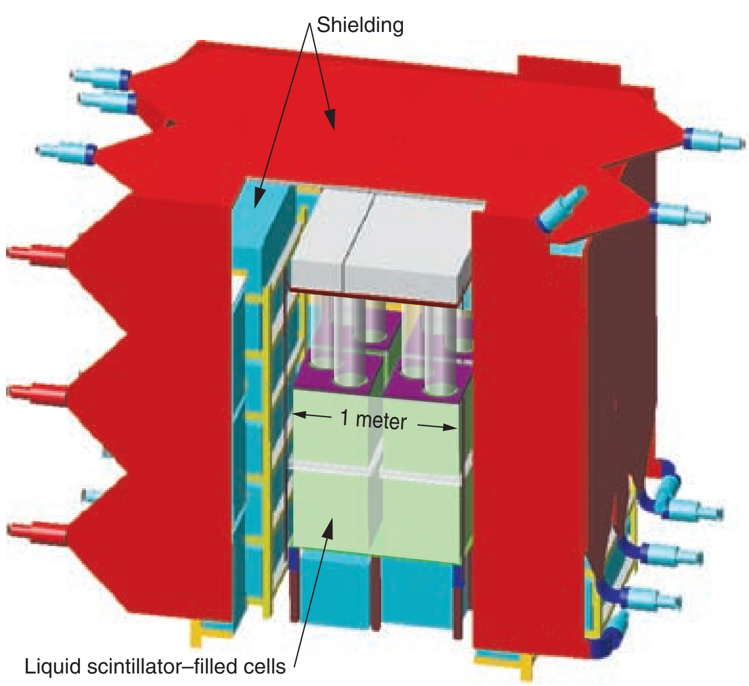
Reactor fuel rods contain the isotopes uranium-238 (^{238}U) and uranium-235 (^{235}U). Inside a reactor core, these isotopes absorb neutrons and undergo fission, producing antineutrinos with each decay. Some ^{238}U isotopes capture neutrons and decay into isotopes of plutonium-239 (^{239}Pu), which also fission and emit antineutrinos. However, the decay of ^{239}Pu produces substantially fewer antineutrinos than does the decay of ^{235}U within the energy range required for detection. Over the course of a reactor's fuel cycle, the antineutrino count rate drops as uranium content decreases and plutonium increases. In addition, the antineutrino count rate is proportional to the fission rate of the isotopes and thus is approximately proportional to the reactor's power. By monitoring this count rate, scientists can track both the thermal power and the fissile inventory of the reactor over time. Any deviation from what is considered "normal" would identify a potential problem.

The Livermore–Sandia detectors are designed to measure inverse beta-decay interactions. When an antineutrino collides with a proton, it produces a positron and a neutron. The interactions of these two particles create the antineutrino signature—two relatively intense flashes of light that occur so close in time to one another that they appear to be almost simultaneous. The bright two-step signature makes it easy to differentiate this interaction from those occurring in other processes, such as gamma-ray or ambient neutron interactions.

Testing, Testing . . . 1, 2, 3

The development team, led by physicists Adam Bernstein of Livermore and David Reyna of Sandia, is testing three prototype detectors at the San Onofre Nuclear Generating Station (SONGS) in San Clemente, California. The first detector, called SONGS1, has been operating there since 2004. (See *S&TR*, January/February 2006, pp. 21–23.)

SONGS1 uses a proton-rich liquid scintillator doped with gadolinium to induce the inverse beta-decay interactions. In this



SONGS1 is a liquid scintillator detector, one of three Livermore–Sandia prototypes being tested at the San Onofre Nuclear Generating Station (SONGS). Special shielding surrounds the liquid-filled cells inside the detector to protect them from background radiation and cosmic particles that could mimic the antineutrino signature.

design, an antineutrino from the reactor collides with a proton in the liquid, producing a positron and a neutron. Within a few nanoseconds, the positron, which carries away most of the antineutrino's energy, creates a flash of bluish scintillation light as it travels through the liquid and rapidly annihilates an electron. Gamma rays produced in this process induce further scintillation flashes. About 30 microseconds after the positron flash, the neutron that has traveled through the scintillator is captured by a nucleus of gadolinium. The neutron–gadolinium interaction also produces gamma rays, which immediately induce a second flash of light as they move through the liquid. Photomultiplier tubes detect these two bright light pulses, each only a few nanoseconds wide and separated by a few tens of microseconds.

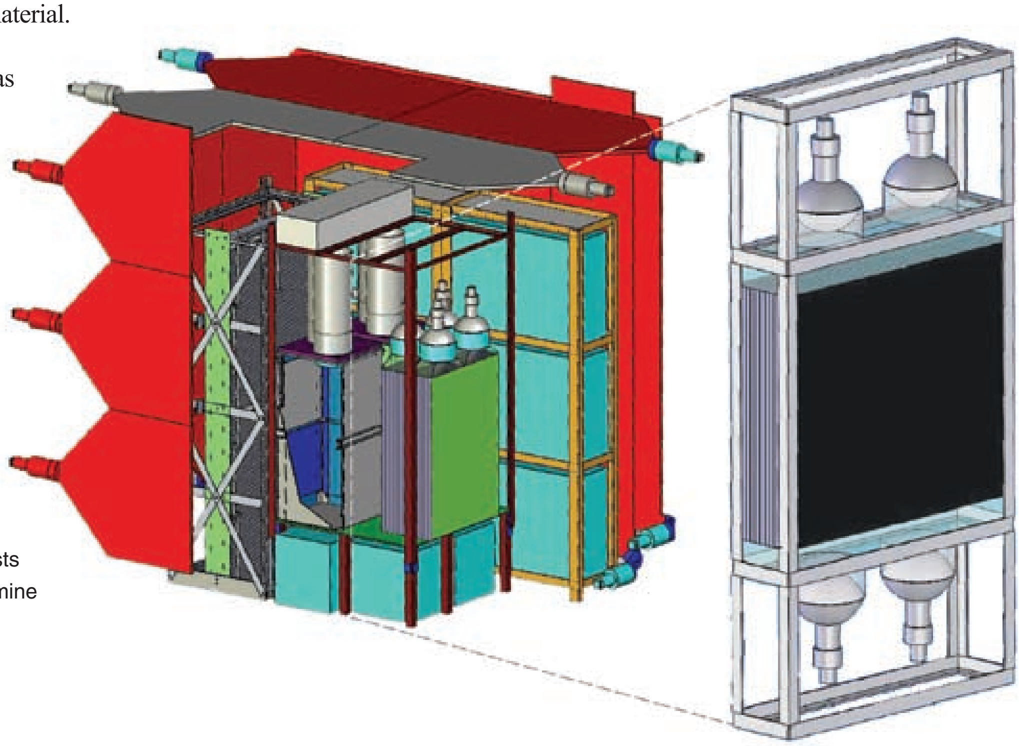
For the prototype test, the team installed SONGS1 about 10 meters underground at a 25-meter standoff from the reactor core in an area known as the tendon gallery. The detector can operate continuously in this area without disrupting facility personnel or day-to-day operations. The tendon gallery also protects the detector from cosmic rays that could produce antineutrino events. At this location, about one in every 100,000 antineutrinos produced by the reactor passes through the detector. According to Bernstein, antineutrino interactions are fairly easy to detect, even though the particles themselves rarely interact with matter. Of the 10^{17} antineutrinos that pass through the detector each day, about 4,000 collide with protons. Of these 4,000, about 400 result in a detectable signature in this simple detector.

Although SONGS1 has been successful in its field test, the device has a few drawbacks. First, it is large and heavy, measuring 3 meters per side and weighing 25 tons, including a 20-ton water shield. Second, the liquid scintillator is flammable, toxic, and carcinogenic, so the unit must be transported as hazardous material. Deploying this type of detector worldwide would thus be difficult. As a result, the team has designed two other prototypes, SONGS2 and SONGS3, that operate with less hazardous materials. The team is also evaluating detection methods that could lead to a smaller device "footprint."

SONGS2 uses a plastic scintillator instead of a liquid. Because gadolinium compounds degrade plastic's transparency, researchers mixed gadolinium into a paint and applied a 1-millimeter-thick layer of the mixture onto 2-centimeter-thick plastic sheets. They then alternated the gadolinium-painted sheets with pieces of plastic scintillator. In this design, an incoming antineutrino collides with a proton in the plastic scintillator. The resulting positron creates the first flash of light, while the neutron travels randomly through the plastic until it is captured by a gadolinium nucleus in the paint. As in the liquid detector, the neutron–gadolinium reaction produces gamma rays, which easily escape the thin layer of paint to create a second flash of light in the plastic scintillator.

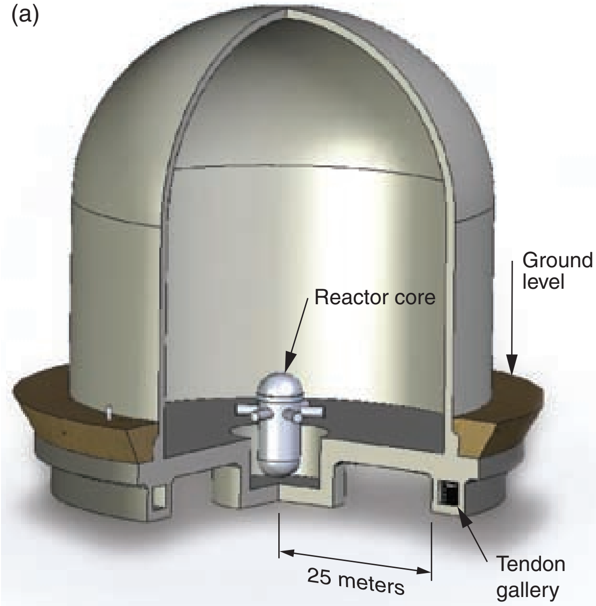
Instead of scintillation liquid or plastic, SONGS3 uses water mixed with gadolinium and measures Cerenkov light. Cerenkov light, predominantly ultraviolet but partially blue, is produced as charged particles move faster than the speed of light within the water. In this system, an antineutrino collides with a proton, which creates the positron and neutron. The first flash of Cerenkov light appears as the positron zips through the water. The neutron created during the antineutrino–proton collision is again captured by a gadolinium nucleus, producing the familiar gamma-ray cascade. These gamma rays in turn generate fast Compton-scattered electrons, which generate a second flash of Cerenkov light.

Although this water-based detector provides a measurable antineutrino signature, the interactions in water produce less light. According to Bernstein, "About 100 times fewer Cerenkov photons are generated compared with the amount of light produced in the liquid and plastic scintillators." Despite this fainter signal, the detector does have its benefits. First, water is more benign than scintillation liquid. Second, the detector is impervious to high-energy neutron radiation caused by cosmic muons, which can mimic the antineutrino signature in scintillator detectors. Because all three



For the SONGS2 design, researchers replaced half of the liquid scintillator with a plastic scintillator (see inset). Results from field tests for the three prototypes will be compared to determine the effectiveness of each design.

(a)



(b)

(a) For the field tests, detector prototypes are housed in the tendon gallery at SONGS. (b) The tendon gallery is a ring-shaped area about 10 meters underground and 25 meters from the reactor core.

detectors are underground, they are somewhat protected from these cosmic particles. However, the two scintillation detectors still require special shielding. The team is conducting tests to determine the amount of shielding needed for the water-based detector.

The two new prototypes were installed in the same reactor as SONGS1 and tested during a reactor shutdown in December 2007. The team is evaluating data from all three detectors to compare their performance. In August 2008, the reactor will undergo required maintenance, and all three detectors must be removed. One or both of the newer detectors will be tested at a surface location to determine the potential for aboveground operation.

The team is also working with scientists from the University of Chicago to develop argon- and germanium-based systems that will detect antineutrinos through a process called coherent neutrino–nucleus scattering. In this process, an antineutrino collides with a nucleus of argon or germanium, which results in nuclear recoil. As the recoiling nucleus collides with its neighbors, it shakes loose a few electrons. The germanium-based detector, which is being developed at the University of Chicago, uses a sensitive transistor to extract and amplify the electrons. The argon detector uses a dual-phase detection process. In the first phase, the electron signal is produced in liquid argon. In the second phase, the signal is amplified in an argon gas blanket above the liquid to generate copious scintillator light, which is detected by photomultiplier tubes.

"The coherent scatter process has a much higher antineutrino interaction rate per volume of detection medium compared with detectors that rely on inverse beta decay," says Bernstein. "This process has long been predicted but never observed. Detecting the coherent scatter signal with either approach would signify a major breakthrough." Because detectors that use coherent scatter have a high probability of interaction per unit mass, they can also have a much smaller footprint, possibly as small as 1 cubic meter with the necessary shielding. In April, the team installed the first germanium-based prototype detector at SONGS.

The Next Generation of Antineutrino Detection

The Laboratory's antineutrino detection technology could offer the IAEA a more accurate, less time-consuming, and more cost-effective method for reactor assessments. Although more precise detectors have been developed to study the fundamental properties of neutrinos, they are often much larger and more expensive than the Livermore–Sandia designs. "Our detectors are robust and simple to operate and maintain, which allows for widespread deployment," says Bernstein. The autonomous systems are also self-calibrating and require no maintenance for months at a time. Data about the detector, such as temperature, and the hourly antineutrino count rate are collected through a secure dial-up connection to Sandia and shared with teams at both sites.

Antineutrino detection research could also help in developing or improving devices to detect gamma rays and neutrons for other national security applications. According to Bernstein, "Antineutrino detector research is the perfect marriage between basic science and applications that are relevant to the Laboratory's national security missions." For a particle that has no electric charge and practically zero mass, the antineutrino may have a big future.

—Caryn Meissner

Key Words: antineutrino detector, Cerenkov light, coherent neutrino nucleus scattering, fissile material, International Atomic Energy Agency (IAEA), inverse beta decay, nuclear reactor safeguards, San Onofre Nuclear Generating Station (SONGS), scintillator.

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