

Monitoring Nuclear Reactors with Antineutrinos

As fissile materials are being created and destroyed in a nuclear reactor, tracking their inventory can be a tricky business. The International Atomic Energy Agency (IAEA), which is the United Nations agency responsible for monitoring civil nuclear facilities and nuclear inventories in nonnuclear weapons countries, uses a variety of accounting and surveillance techniques for this purpose. However, no easy method exists for peering into an operating reactor to accurately determine how much plutonium or uranium is present in the fuel rods in real time.

A team from Lawrence Livermore and Sandia national laboratories has designed a detector that uses an elusive elementary particle—the antineutrino—to make real-time measurements of plutonium as it is created in the heart of a nuclear reactor. This antineutrino detector can potentially help the IAEA and other agencies achieve the important goal of tracking global inventories of fissile materials, such as plutonium, to ensure these materials are not being diverted into weapons.

In the Heart of a Reactor

Antineutrinos are a by-product of the fission process that occurs in a nuclear reactor. Fresh reactor fuel rods contain uranium-238 and uranium-235, with the latter being the main fission isotope. When a fissile isotope absorbs a neutron, the isotope's nucleus can split into two energetic daughter nuclei and a shower of neutrons and gamma rays. The neutrons then cause more fissions, and the daughter nuclei decay, three times each on average, emitting an antineutrino with each decay. Uranium-238 can also capture neutrons, and some of these captures result in uranium-239, which decays to plutonium-239. Plutonium-239 can also fission, and its daughter nuclei produce antineutrinos as well.

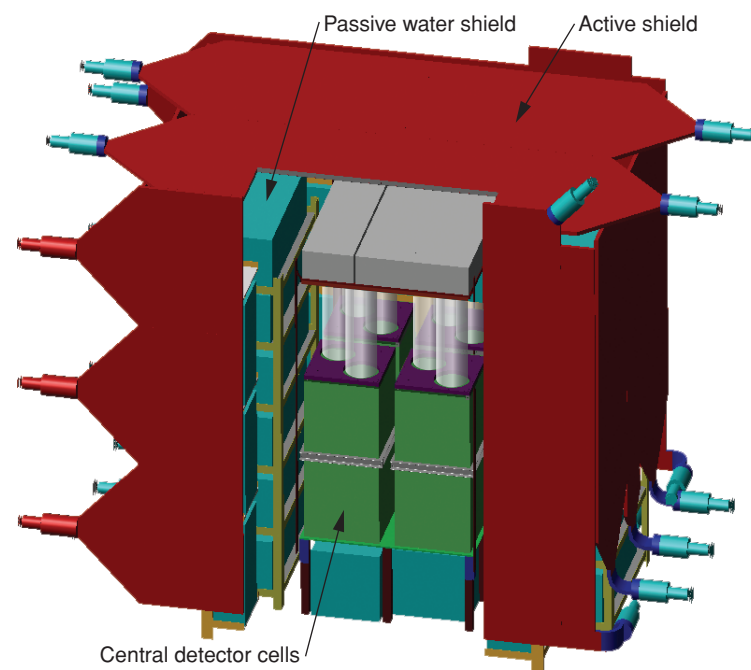
Over a broad range of antineutrino energies, the number of antineutrinos emitted by plutonium-239 differs substantially from the number emitted by uranium-235. As plutonium-239 builds up in the reactor over time, the antineutrino count rate measured in a detector will drop, by about 5 to 10 percent over the reactor fuel cycle.

Detecting the Elusive Antineutrino

Antineutrinos are elusive by nature. Similar to their counterpart, the neutrino, antineutrinos are electrically uncharged, nearly

massless, and rarely interact with matter. For example, about one interaction occurs when a beam of 10^{11} antineutrinos passes through Earth's diameter. (See *S&TR*, April 2003, pp. 13–19.) The high flux rate of antineutrinos from reactors—about 10^{21} per second—partially compensates for the low-interaction probability. The Livermore–Sandia detector makes use of the inverse beta-decay interaction, in which an antineutrino interacts with a free proton in the detector to create a neutron and positron (positive electron) that provide a measurable signature.

The detector consists of three subsystems: the central detector and two shields. The central detector, in which the antineutrinos are detected, consists of four stainless-steel cells filled with a cubic meter of liquid scintillator. The scintillator contains plenty of quasi-free protons and is laced with gadolinium atoms. When an



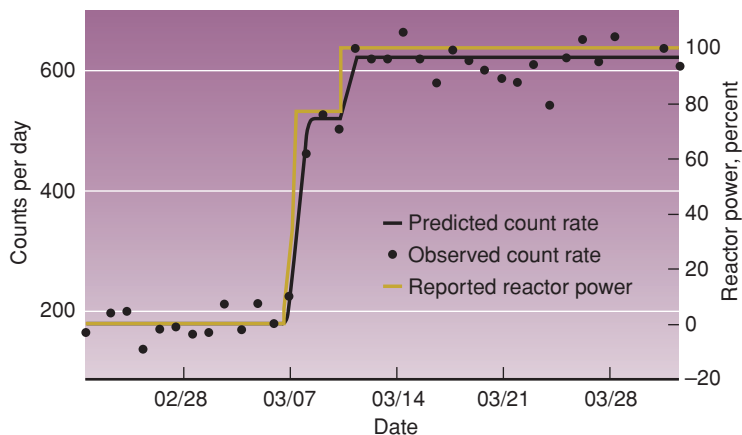
The prototype antineutrino detector consists of three subsystems: a central detector and two shields. Photomultiplier tubes above the central detector cells detect the antineutrino's signature.

antineutrino interacts with a proton, the created positron soaks up most of the antineutrino energy, converting it into a flash of visible photons as it induces scintillation. A fraction of a nanosecond later, essentially simultaneously, another flash is created when the positron annihilates with a nearby electron, producing gamma rays that also induce scintillation. About 30 microseconds later, a third flash of light is produced from the neutron when it is captured by and excites a gadolinium nucleus. The nucleus de-excites by emitting high-energy gamma rays, which again induce scintillation. The flashes of light are detected by photomultiplier tubes above the scintillation fluid and form a signature for the antineutrino interaction.

The central detector is surrounded on all sides by a passive water shield. This shield attenuates gamma and neutron backgrounds. A second active shield placed outside the water shield detects and “vetoes” penetrating cosmic ray–related signals, which can mimic antineutrinos.

Scientists have two ways of tracking the amount of plutonium-239 and uranium-235 in a working reactor. One method involves examining changes in the total rate of detected antineutrinos over time; the second involves looking at changes in the antineutrinos’ energy spectrum.

By monitoring the rate at which antineutrinos are produced during the fission process, scientists can track the amount of fissile material in the reactor core. Because uranium-235 produces antineutrinos in greater abundance than plutonium-239 over a certain energy range, the rate of antineutrino production can be correlated to the amounts of specific fissile elements in the reactor



Data recorded over a one-month period in 2005 as the reactor “ramped up” to full power shows that the antineutrino count rate measured by the detector closely matched the predicted count rate.

core. “As the reactor core goes through its irradiation cycle, the amount of uranium decreases and the amount of plutonium increases,” says physicist Adam Bernstein, who heads the project at Lawrence Livermore. “Because the plutonium produces fewer measured antineutrinos than does the uranium, we can use the change in antineutrino rate over time to estimate how much plutonium has been created.” This drop in rate typifies the standard pressurized-water-reactor (PWR) fuel cycle.

For example, at the start of a PWR fuel cycle, the antineutrino count rate may be 1,000 per day. By the end of the cycle, that number would decrease to 900 per day, depending on the reactor type and fuel loading. “If anyone removes plutonium along the way or alters the operating parameters to increase plutonium production, those changes will show up in the antineutrino count rate,” says Bernstein. The correlation, known as the burn-up effect, can help provide a real-time inventory of the amount of plutonium and uranium isotopes in the reactor core. This method requires the reactor power to be measured independently; otherwise, the operator could mask the reduction in antineutrino rate caused by increased plutonium production simply by raising the power level.

The second method does not depend on knowing the reactor power. Because the detector is sensitive to the antineutrino energy and because the energy spectra of antineutrinos emitted by plutonium-239 and uranium-235 are different, scientists can determine the relative amounts of plutonium and uranium in the reactor by measuring ratios between the low- and high-energy parts of the energy spectrum. This ratio technique removes the need for an independent power measurement—albeit at the expense of a longer counting time—to achieve the necessary statistical precision.

Future Bright for Detector

“To be useful to the IAEA, the detector must be easy to operate, reliable, cost-efficient, and capable of uninterrupted operation for months or years at a time,” says Bernstein. “We’ve shown that our small detector of relatively simple design can be installed in a convenient location outside the reactor’s containment area, that we can count hundreds of antineutrinos per day, and that reactor power levels can be tracked on a time scale of hours. We have preliminary evidence for the burn-up effect in the data we’ve accumulated to date, which will be confirmed as more data are acquired. We’ve also demonstrated that the detector can run stably, continuously, and automatically for months. We can even calibrate the detector automatically, relying on energy peaks present in the natural radioactive background.”

Since 2003, the 1-ton prototype has been recording data at the San Onofre Nuclear Generating Station in San Clemente, California,

in a room about 25 meters away from the reactor core. The detector is 17 meters below ground, and the total footprint, including shielding, is about 2 by 3 meters. The antineutrino rate is calculated hourly on a local, dedicated data-processing computer, and summary data are uploaded continuously to a secure Web site.

The team is now refining the estimate of the detector's sensitivity to the reactor's plutonium inventory as well as working with the IAEA and other agencies to understand how this new technology will fit into existing regimes. Bernstein says, "We're encouraged by the interest from the IAEA and from safeguards and physics experts in Brazil, France, and Russia. The blending of practical application and fundamental particle physics has clearly struck a chord in these communities."

Other avenues of research have also opened. The detector built by the Livermore–Sandia team uses inverse beta decay to detect antineutrinos, but another method also exists: coherent scattering from nuclei, in which an antineutrino, zipping past the nucleus of an atom, causes the nucleus to "shake" and shed a few electrons in the process. The team has designed and proposes to build a small, liquid–gas argon detector to observe this

never-before-seen antineutrino interaction. An antineutrino detector based on coherent elastic scatter would take up much less space and weigh much less than the 1-ton detector currently being fielded.

"The IAEA considers 8 kilograms of plutonium to be a proliferation concern," says Bernstein. "About 400 civilian power reactors worldwide create thousands of kilograms of plutonium annually. An antineutrino detector, whether based on inverse beta decay or coherent scattering, could be used to help make the world safer by giving international organizations, such as the IAEA, another tool for determining whether a country is making extra plutonium in its civilian reactors—plutonium that could be diverted to a weapons program."

—Ann Parker

Key Words: antineutrino detector, coherent elastic scatter, International Atomic Energy Agency (IAEA), inverse beta decay, nuclear power reactor, plutonium, uranium.

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San Onofre Nuclear Generating Station in San Clemente, California.

