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Progress Towards Deployable Antineutrino Detectors for Reactor Safeguards

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Abstract

Fission reactors emit large numbers of antineutrinos and this flux may be useful for the measurement of two quantities of interest for reactor safeguards: the reactor's power and plutonium inventory throughout its cycle. The high antineutrino flux and relatively low background rates means that simple cubic meter scale detectors at tens of meters standoff can record hundreds or thousands of antineutrino events per day. Such antineutrino detectors would add online, quasi-real-time bulk material accountancy to the set of reactor monitoring tools available to the IAEA and other safeguards agencies with minimal impact on reactor operations.

Between 2003 and 2008, our LLNL/SNL collaboration successfully deployed several prototype safeguards detectors at a commercial reactor in order to test both the method and the practicality of its implementation in the field. Partially on the strength of the results obtained from these deployments, an Experts Meeting was convened by the IAEA Novel Technologies Group in 2008 to assess current antineutrino detection technology and examine how it might be incorporated into the safeguards regime. Here we present a summary of our previous deployments and discuss current work that seeks to provide expanded capabilities suggested by the Experts Panel, in particular aboveground detector operation.

1 Introduction

Reactor safeguards regimes, such as that implemented by the International Atomic Energy Agency (IAEA) in accordance with the Non-proliferation Treaty (NPT), are designed to detect and deter illicit or suspicious uses of these facilities. In large part, reactors are safeguarded by indirect means that do not involve the direct measurement of the fissile isotopic content of the reactor, but instead rely primarily on semi-annual or annual inspections of coded tags and seals placed on fuel assemblies, and measures such as video surveillance of spent fuel cooling ponds. When direct measurements do take place, they are implemented offline, before or after fuel is introduced into the reactor. These may include the counting of fuel bundles or the checking of the enrichment of random samples of fresh or spent fuel rods. Under the IAEA regime, reactor operators are additionally required to submit periodic declarations of their fissile holdings, including the amount of plutonium generated in each fuel cycle. This information is cross-checked for consistency against operational records and initial fuel inventories.

The antineutrino detection based technique being investigated here has been described elsewhere [1]. It differs from the declaration and item accountancy methods described above in fundamental ways: first, the detector is under full control of the safeguards agency, and is thus distinct from the operator declarations of power and burnup, which depend on the good faith of the operator. Second, as opposed to item accountancy, it can provide independent, direct, real-time bulk accountancy of the fissile inventory from well outside the core, while the reactor is online. Third, it provides a direct, real-time measurement of the power of the reactor, which constrains fissile content. These independent measurements can be directly compared to declarations and used in conjunction with other IAEA accountancy and surveillance metrics.

We have demonstrated many of the important features of this technique, including unattended and continuous operation for long periods of time, non-intrusiveness, and sensitivity to reactor outages and power changes, using a device called "SONGS1" [2-6], as well as similar devices based upon non-flammable, non-toxic and inexpensive materials [7]. In this work, we describe the development of two new detectors that could allow for aboveground antineutrino detection. These new designs improve the ease with which such monitoring devices can be deployed at reactors, since a much wider variety of deployment locations is likely to be available if there is no constraint upon required overburden. This work is a direct response to the suggestions of an Experts panel convened by IAEA in 2008. The Experts Meeting Final Report assigned the development of an aboveground antineutrino detection capability a high priority.

2 Antineutrino Measurements of Interest for Reactor Safeguards

The antineutrino count rate and energy spectrum are both directly related to the reactor power and the fissile isotopic content of the core. As a reactor proceeds through its irradiation cycle, the mass and fission rates of each fissile isotope varies in time. Uranium and plutonium are both consumed by fission throughout the cycle, while the competing process of neutron capture on ^{238}U produces plutonium. The change in relative fission rates occurs even when constant power is maintained. This variation in turn causes a systematic shift in the antineutrino flux, known as the "burnup effect". The effect has long been recognized and corrected for in reactor antineutrino physics experiments.

Antineutrino emission in nuclear reactors arises from the β-decay of neutron-rich fragments produced in heavy element fissions. In general, the average fission is followed by the production of about six antineutrinos that emerge from the core isotropically and for all practical purposes without attenuation. The average number of antineutrinos produced per fission is significantly different for the two major fissile elements ^{235}U and ^{239}Pu. Hence, as the core evolves and the relative fission fractions of ^{235}U and ^{239}Pu change, the antineutrino flux from the core will also change.

Using the ORIGEN/SCALE reactor simulation package [8], we have performed an assembly-level simulation of a PWR reactor core. The simulation package provides the mass and fission densities for each assembly in the core as a function of burn-up step. Using these simulated values in the formula

$$(1)\quad \frac{dN_{\bar{\nu}}}{dt} = k \cdot P \cdot \sum_i \frac{f_i}{E_i^f} \int dE_{\bar{\nu}} \cdot \sigma(E_{\bar{\nu}}) \frac{dN^i_{\bar{\nu}}}{dE \cdot fission}(E_{\bar{\nu}}) ,$$

we can predict the antineutrino rate from the reactor source as a function of time or burnup step. In the formula, k is a constant depending only on the detector mass and standoff distance, and P is the reactor thermal power. The defining relation for the isotope power fractions f_i is given by:

$$f_i = \frac{\frac{dN_i^{fission}}{dt} E_i^{fission}}{P},$$

where $\frac{dN_i^{fission}}{dt}$ is the fission rate and $E_i^{fission}$ the energy release per fission for the *i*th fissile isotope. The index *i* runs over the main fissioning isotopes: ^{235}U, ^{239}Pu, ^{241}Pu or ^{238}U.

$\frac{dN^i_{\bar{\nu}}}{dE \cdot fission}$ is the antineutrino energy density in units of events per MeV and fission, and $\sigma(E_{\bar{\nu}})$ is the microscopic cross-section for the inverse beta decay process used to detect the antineutrino, depending on the antineutrino energy $E_{\bar{\nu}}$. $\varepsilon(E_{\bar{\nu}})$ is an energy dependent detection efficiency, defined as the ratio of detected to interacting events in the target. In equation (1) the sum is over all fissioning isotopes, and the integral is over the antineutrino energy. The equation clearly shows the antineutrino rate dependence on both the reactor power P, and on the sum over fission rates. While not the subject of this article, we note that the energy spectrum of the antineutrinos can be further exploited to extract or constrain the individual isotopic masses throughout the cycle.
Figure 1 shows that the antineutrino rate changes by about 12% between refuelings. The same simulations allow us to predict the beginning and end of cycle fissile masses.

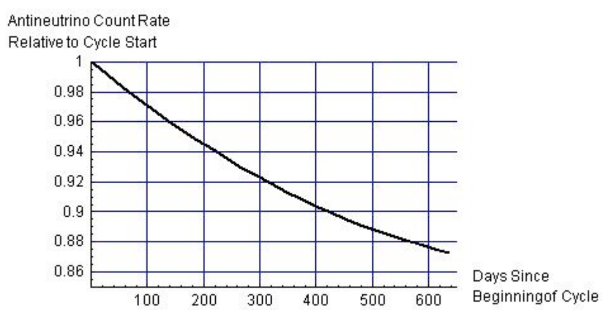

Figure 1: The predicted antineutrino count rate through a 637 day cycle, corresponding to the duration of SONGS Unit 2 reactor cycle 13. The rate is normalized to its value at beginning-of-cycle.

The current simulation marks an advance relative to our earlier simulations, since it includes specific densities on a per-assembly rather than core averaged basis. The input fuel isotopics for this simulation are taken from the San Onofre Nuclear Generating Station Final Safety Analysis Report [9]. This report provides a nominal fuel loading which differs by a few percent from the actual fuel load in recent cycles. The antineutrino rate curves shown in Fig. 1 will therefore differ – also by a few percent – from the actual results for the cycle covered by the current antineutrino data set. However, the approximate size of the burnup effect and the overall downward trend in the antineutrino rate are clearly revealed by the simulation.

3 Antineutrino detection through the inverse beta interaction

We use the (relatively) high probability inverse β-decay reaction

(2) $\bar{\nu} + p \rightarrow e^{+} + n$

Here the antineutrino ($\bar{\nu}$) interacts with quasi-free protons (p) present in the detection material. The neutron (n) and positron (e+) are detected in close time coincidence, providing a dual signature that is robust with respect to the backgrounds that occur at the few MeV energies characteristic of these antineutrinos. The addition of Gadolinium (Gd) or another neutron capture agent (e.g. ^{6}Li or ^{10}B) to the detection medium reduces the capture time of the neutron from about 200 μs to approximately 30μs, providing a much tighter time signature and commensurate reduction in uncorrelated background. Furthermore, neutron capture on Gd produces a shower of γ-rays with a total energy of close to 8 MeV, significantly higher than the 2.2 MeV γ-ray that results from the capture of neutrons on protons.

The signature of antineutrino interaction is thus a pair of relatively high energy events in a short time interval. Accidental coincidences from random neutron and gamma interactions, as well as correlated event pairs created by muogenic fast neutrons can also create antineutrino-like events. Modest overburden at the detector helps reduce the correlated backgrounds: a muon veto shield tags many of the surviving muons so that their associated backgrounds can be removed. Correlated backgrounds have the same time structure as the antineutrinos and are indistinguishable event-by event (in this detector) from antineutrinos. Therefore, these can only be measured during reactor outages, making the relatively rare outage periods (5% to 10% of the total cycle time) especially important for full determination of backgrounds in reactor-based antineutrino detectors.

4 Aboveground Backgrounds

There are several backgrounds that can mimic the inverse beta decay signal. The essential features of the inverse decay detection technique iare the near coincident detection of the two final state particles, and that one of the final state particles is a neutron that must be detected via a capture reaction. Therefore any process that produces a coincidence with a neutron capture can result in an antineutrino interaction mimicking signal. There are two major sources of such background:

1. The interaction of a cosmogenic fast neutron within a detector. Recoil protons set in motion as the neutron slows mimic the position in inverse beta decay, while capture of the neutron once slowed forms the delayed coincidence
2. The capture of two neutrons created in surrounding material by the same cosmogenic muon. These capture reactions will appear in the detector with the same coincidence time structure as an antineutrino interaction.

Both of these background sources are cosmogenic, i.e. produced by cosmic rays. Therefore, all antineutrino detection experiments that have been conducted to date have used at least several 10s of meters (if not 1000s of meters) of overburden to attenuate these cosmic rays, especially muons, to some extent. Even a little overburden makes a considerable difference. For example, the SONGS1 detector operated under about 30 M.W.E. (Meters of Water Equivalent) overburden. We expect that attempting to operate SONGS1 aboveground would result in an increase in background by a factor of 100 to 1000, resulting in a reduction in Signal/Background of a similar fraction

(Signal/Background ~ 4/1 belowground). Useful reactor monitoring measurement could not be made with such reduced Signal/Background.

5 Techniques for Aboveground Operation

We have identified two techniques that might allow aboveground antineutrino detection:

1. Signal Identification and Background Rejection: if interactions could be identified as neutron captures via Pulse Shape Discrimination (PSD) techniques, or positron annihilations via event topology, neutron backgrounds could be rejected,
2. Background Insensitivity: if a detector were insensitive to background, e.g. insensitive to recoiling protons, a fraction of background would be unobserved.

For technique (1) we have investigated several novel scintillators that give unambiguous indications of neutron capture. These are inorganic scintillators that incorporate ^{6}Li, and that have high light yields and long scintillation decays times (100s of ns). These are combined with fast plastic scintillators in inhomogeneous arrays. PSD techniques are used to identify interactions in the slow scintillator (neutron captures) from those in the plastic (everything else). Liquid scintillators that can also distinguish between gamma ray or recoil proton interactions could be used in place of plastic, albeit at the cost of increased complexity. Nonetheless, this is also being investigated. This approach is inherently modular, resulting in a segmented detector. It is also possible that this segmentation could be used to select event topologies consistent with positron annihilation.

For technique (2) we have adapted a long-standing neutrino detection technique, Cerenkov detection, to the task of *antineutrino* detection, via the addition of Gd to highly purified water [10]. The Cerenkov light emission threshold for protons is much higher than that for electrons and positrons. Recoil protons set in motion by muogenic fast neutrons do not exceed this threshold. Therefore a water based Cerenkov antineutrino detector would be insensitive to that class of background.

The relative advantages and disadvantages of these two approaches are summarized in Table 1.

Method	**Background reduction**	**Advantages**	**Disadvantages**
Water Cerenkov (Gd doped)	Reduces background via insensitivity to proton recoils	Simple, non-combustible, non-flammable, inexpensive detection medium.	Cerenkov light yield is low, so limited energy resolution. Ineffective against multiple neutron background
Advanced Scintillator	Identify signal and/or background via segmentation and Pulse Shape Discrimination	In principle, can reject all backgrounds	Complex detector geometry may be inefficient. Materials may be expensive.

6 Aboveground Deployment of Antineutrino Detectors

To test the two techniques described above, we have built a flexible detector shielding enclosure with a 20' shipping container. The internal volume of this shield can support deployment either technological approach to aboveground antineutrino detection, and itself provides important background reduction. First, the shielding material, ~45cm of High Density Polyethylene, eliminates a substantial fraction of incident fast neutrons, while an inner 2.5cm layer of borated polyethylene reduces the thermal neutron flux. Second, a highly efficient plastic scintillator muon veto allows for muon correlated neutron production within the shielding material to be rejected, and for other muon correlation to be studied. Incorporating these shielding elements into a container allows for great flexibility in terms of deployment location, and eliminates almost all onsite integration activities. This is also an important step to making this novel reactor monitoring technology more widely applicable.

A 1 ton water Cerenkov detector has been integrated into this shield and was recently deployed about 50m from a reactor at the San Onofre Nuclear Generating Station. This is, of course, aboveground with no appreciable overburden. We will be able to measure the effectiveness of Cerenkov detectors as a background reduction technique over the coarse of the coming year, including, we expect, through a reactor refueling outage. While sensitivity to reactor parameters approaching that achieved using SONGS1 is not expected, we are hopeful that at least Reactor on/off transitions will be observed. A detector based upon advanced scintillators will replace the water Cerenkov detector, allowing that technology to be assessed as well.

7 Conclusions

Our experimental campaign using SONGS1 detector has demonstrated many of the essential features of antineutrino detection that make it of potential interest for IAEA safeguards, including practical deployment of a simple and robust detector, unattended operation for months to years at a time, sensitivity to fissile content of the core, and real-time power monitoring capability. In large part due to those results, IAEA convened an Experts Panel to examine the potential role of antineutrino detectors within the reactor safeguard regime. The final report produced by this panel suggested that development of an aboveground antineutrino detection capability, something that has never before been achieved, should be a high priority. We have identified two promising technological paths that might allow this advance. Having built an easily portable shielding system to support testing of these technologies, we have recently begun a field-testing campaign at a reactor. We will first assess the background insensitivity of a water Cerenkov detector, and will follow that with the testing of an advanced scintillator detector that has, at least, neutron capture identification capability.

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