Monitoring nuclear reactors for safeguards purposes using anti-neutrinos

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Abstract. Preventing nuclear proliferation is a high priority for the international community. Monitoring of nuclear facilities to detect unauthorised removal of fissile materials from operational cores is central to this. Neutrino detection devices can be used to remotely monitor the core of operating reactors in a safe, reliable manner. Technology developed for the T2K experiment can be adapted to make a small footprint, reliable, anti-neutrino detector. Through, characterisation of the anti-neutrino spectrum there is a possibility to provide core material accountancy.

A prototype of such a device has been developed and demonstrated at the University of Liverpool. Based on the design of the T2K Near Detector Calorimeter, the device will detect anti-neutrinos through the distinctive delayed coincidence signal of inverse beta decay interactions. This poster presented data from detector commissioning. The detector is currently deployed at Wylfa power station, UK for field testing.

1. Anti-neutrino Reactor Monitoring for Safeguards

Safeguarding of nuclear materials is a concern for the global community. The detection of unauthorized production and diversion of weapon’s grade materials such as Plutonium-239 is particularly important to this end. Plutonium accounting is difficult for several 4th generation reactor designs such as pebble bed and liquid core reactors that do not have itemised fuel content.

Reactor anti-neutrino detection has been used in several neutrino oscillation experiments providing measurements of the mixing angles $\theta_{13}$[1] and $\theta_{12}$[2]. At reactor neutrino energies cross-section of inverse beta decay interaction, $\bar{\nu}_e + p \rightarrow e^+ + n$, is dominant. The detection of prompt energy deposit from the positron and the delayed energy despit from the neutron capture gives a delayed coincidence signal for enhanced background rejection. It is theoretically possible to unfold a reactor’s anti-neutrino flux and spectra to measure the plutonium content of the core in near to real time. As such, anti-neutrino detectors could provide material accountancy in a manner that is non-intrusive to reactor systems. The anti-neutrino flux cannot be effectively shielded to obscure covert operations or material diversion. These qualities can potentially make anti-neutrino based safeguards an attractive prospect with particular advantages for use with non-itemised reactor designs.

The detectors used in oscillation experiments are large (~1 kiloton) and expensive making them unsuitable for safeguards usage. Safeguards detectors must be of order 1 ton in order to be placed in close proximity to a reactor whilst being cheap enough for wide scale deployment. Lawrence Livermore National Laboratory developed a prototype, liquid scintillator based, anti-neutrino detector of order 1 ton in size. The detector was deployed at the San Onofre Generating Station where reactor anti-neutrinos were used to observe both the reactor’s operational state (on/off) and the fuel burn up during operations [3] as shown in Figure 1.
The observations made by the SONGS1 detector successfully showed the concept of a small scale reactor anti-neutrino monitoring device to be sound. However, the use of flammable liquid scintillator is not ideal for safeguards usage where the detector must be located close to the reactor core. Any ideal safeguards detector should also be robust, transportable and easy to operate. Failing to adhere to these ideal criteria creates an obstacle to use and wide scale deployment.

2. A Reactor Monitoring Detector based on the T2K ECal

The electromagnetic calorimeter (ECal) [4] for the T2K [5] near detector is a sampling calorimeter using plastic scintillator active layers with lead conversion layers. This technology suits many of the criteria for an ideal safeguards detector. The ECal modules were constructed at Liverpool University and Daresbury laboratory before being shipped to the J-PARC facility in Japan. The plastic scintillator poses little fire or explosion risk, is extremely robust and cheap. Robust and cheap Hamamatsu Multi-Pixel Photon Counters (MPPCs) coupled to wavelength shifting fibers are used for optical readout of the scintillator.

The calorimeter design has been modified using a gadolinium compound to act as a neutron capture agent, converting it into an anti-neutrino detector design. Gadolinium has a large thermal neutron capture cross-section (250,000 barns) and emits an 8 MeV gamma ray cascade giving a distinct signal for effective background rejection.

The fully constructed anti-neutrino detector contains more than 1 ton of active plastic scintillator. A picture of the full detector is shown in Figure 2. An internal veto system has been designed for rejection of cosmic ray events and to allow effective operation with no overburden, i.e. above ground. T2K Readout Merger Module (RMM) [5] boards have been adapted to accept inverse beta decay triggers as well as the cosmic ray veto signal.
3. Detector Commissioning and Testing
A small scale prototype was built with removable gadolinium dopant to observe the difference between gadolinium and hydrogen neutron captures (hydrogen has a smaller capture cross section and gives a single 2.2 MeV gamma ray on neutron capture). Californium-252 was used as a neutron source. The source was enclosed in lead shielding to attenuate its gamma ray emissions. Figure 3 shows the clear difference in neutron capture rates with and without gadolinium.

A full scale detector was subsequently constructed and tested using the same californium source with shielding. The full scale detector was also exposed to a colbalt-60 gamma ray source. Figure 4 shows the clear neutron-gamma discrimination of the detector.

![Figure 3](image1.png)  
Figure 3 A histogram of integrated charge deposit for neutron capture events in a small prototype detector. The integrated area of the curves is proportional to the neutron capture rate.

![Figure 4](image2.png)  
Figure 4 The neutron-gamma discrimination abilities for the full scale detector using Cf-252 and Co-60 sources. The x axis shows integrated charge for individual MPPC hits. The y axis shows total integrated charge.

4. Summary
An anti-neutrino detector for safeguards purposes has been constructed and commissioned at Liverpool based on the technology used for the T2K near detector ECal. Commissioning data shows the detector to be highly effective at neutron-gamma ray discrimination due to the use of a gadolinium neutron absorber. Combined with the ECal’s ability to detect positrons, the anti-neutrino detector is well suited to the observation of inverse beta decay interactions. The detector has been deployed at the Wylfa reactor site, Anglesey, UK for detector demonstration in a safeguards environment and is currently awaiting reactor start-up.

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