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Development of an Antineutrino Detector to Monitor the Operation of a CANDU6 On-Load Refueled Reactor

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Development of an Antineutrino Detector to Monitor the Operation of a CANDU6 On-Load Refueled Reactor

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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 via a continuous, unattended and non-intrusive measurement technique.

Between 2003 and 2008, a LLNL/SNL collaboration successfully deployed several prototype safeguards detectors at a commercial Pressurized Light Water Reactor (PLWR) in order to test both the method and the practicality of its implementation in the field. The success of these deployments led the IAEA Novel Technologies Unit to convene an Experts Meeting in 2008 to assess current antineutrino detection technology and examine how it might be incorporated into the safeguards regime. One promising area identified was the ability to monitor On-Load Refueled Reactor (OLR) and Bulk Process Reactor (BPR) operations.

To directly demonstrate and assess the applicability of antineutrino detection technology in this context, we are developing a device for deployment at a CANDU6 OLR. The detector being developed incorporates many optimizations compared to earlier prototype designs and will consequently have much improved antineutrino detection efficiency. Once deployed at the Pt. Lepreau Generating Station, not only will this detector perform the first monitoring of the equilibrium operation of an ORR, it will also have a unique opportunity to measure the isotopic evolution of a fresh core to the equilibrium state.

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]. In addition, we have investigated similar devices based upon non-flammable, non-toxic and inexpensive materials [7], as well as the possibility of operating such devices in the high background found aboveground [8]. In this work, we describe the development of detector at a CANDU6 OLR [9]. The detector being developed incorporates many optimizations compared to earlier prototype designs and will consequently have much improved antineutrino detection efficiency. Once deployed at the Pt. Lepreau Generating Station, not only will this detector perform the first monitoring of the equilibrium operation of an OLR, it will also have a unique opportunity to measure the isotopic evolution of a fresh core to the equilibrium state. This work is a direct response to the suggestions of an Experts panel convened by IAEA in 2008. The Experts Meeting Final Report suggested monitoring of OLRs or Bulk Process reactors as an application for this technology.

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 a reactor core. 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.

Uranium and plutonium are both consumed by fission, while the competing process of neutron capture on ^{238}U produces plutonium. In reactors with periodic refueling (e.g. PLWRs, Boiling Water Reactors) the mass and fission rates of each fissile isotope varies in time. In reactors with frequent or continuous refueling (e.g. OLRs, BPRs), the refulling strategy usually attempts to keep the mass and fission fractions at a constant equilibrium value which is typically reached after several hundred days of operation beginning from fresh fuel.

In both cases, an antineutrino measurement provides a direct and non-intrusive means of verifying operator power declarations. In addition, comparison of the long term evolution of the detection antineutrino count rate with a prediction based upon a detail core evolution code allows for verification of the declared fuel loading and reactor operation. In the case of a PLWR, one expects measures a decrease in the antineutrino count rate with time. We had studied this case in detail [10]. For an OLR, once equilibrium has been achieved, one would expect to measure a constant antineutrino count rate. Sensitivity studies for this case will follow. Furthermore, an antineutrino detector can measure the evolution of an OLR core to equilibrium after startup from fresh fuel – the predicted change in detected antineutrino count rate for this situation is shown in Fig. 1. This may be of particular interest, as some spent fuel from this period will have low burnup.

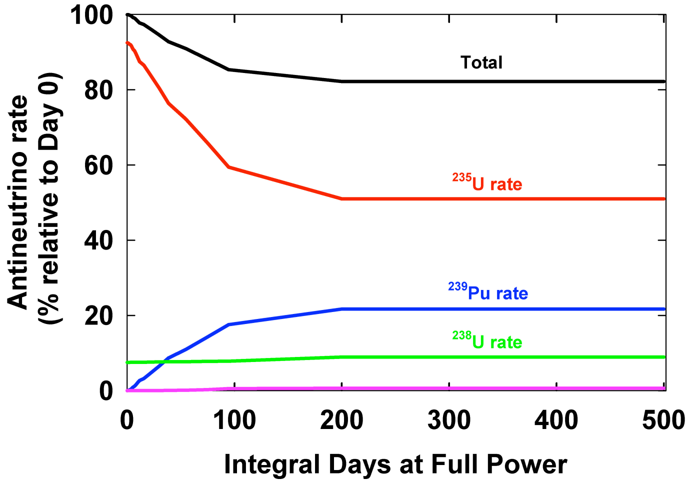

Figure 1: The predicted evolution of the antineutrino count rate for a CANDU OLR as it evolves to an equilibrium fuel configuration.

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 especially important for full determination of backgrounds in reactor-based antineutrino detectors. OLR's do have such outage periods, but they are typically of shorter duration than those at PLWRs.

4 Detector Features

We have incorporated many improvements in the detector to be deployed at the CANDU 6 OLR, relative to that used in our first proof-of-principle demonstration. These improvements are necessary since the OLR deployment site is further from the reactor core (75m vs 25m) and the reactor power is lower ($800MW_{th}$ vs $1100MW_{th}$). The two primary differences in the detector design are the incorporation of a double ended optical readout for the liquid scintillator detection volume, and the use of a single homogenous detection volume. The design features that will allowed long-term robust operation with double ended readout required considerable R&D. Combined with a large homogenous detection volume, this feature provides at least a factor of two increase in neutron capture detection efficiency. Furthermore, it will not be necessary to perform a fiducial volume cut for achieve good optical collection uniformity, which again will increase detection efficiency. Finally, the arrangement of the shielding components has been substantially improved, so that we can expect to observe fewer background events.

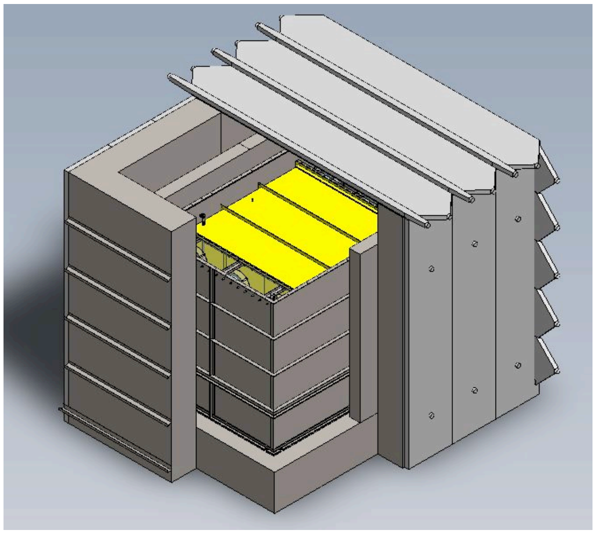

Figure 2: A cutaway drawing of the detector, showing the inner scintillator volume (yellow) surround by the shielding enclosure and muon veto paddles.

The device will have a footprint of approximately $10m^2$, and as is typical of these devices will comprise a central liquid scintillator target, a water shielding enclosure, and a plastic scintillator muon veto (Fig. 2). The expected performance of this system is directly compared to that of our previous SONGS1 system in Table 1. We note that none of the detector improvements made here are specific to this OLR deployment they could be readily incorporated into a device for a use at a PLWR, yielding greatly increase counting statistics and therefore precision.

	SONGS1 Detector	**OLR Antineutrino Detector**
Target Mass	0.64 tons	3.6 tons
Footprint	6 m^2	10 m^2
Absolute Antineutrino Detection Efficiency	10%	>20%
Antineutrinos Detected/day/m^2 *	65	500

Table 1: The new detector incorporates substantial improvements relative to the previous SONGS1 detector. Greater efficiency is achieved and deployed footprint is used considerably more efficiently.
(* in antineutrino flux present in SONGS tendon gallery.)

5 Initial Detector Performance

Initial assembly and testing of the central active volume of the detector has recently been completed (Fig. 3). The performance of the detector is inline with expectations. For example, the measured neutron capture response compares well with that determined via simulation (Fig. 4).

Figure 3: Assembly of the inner detector volume.

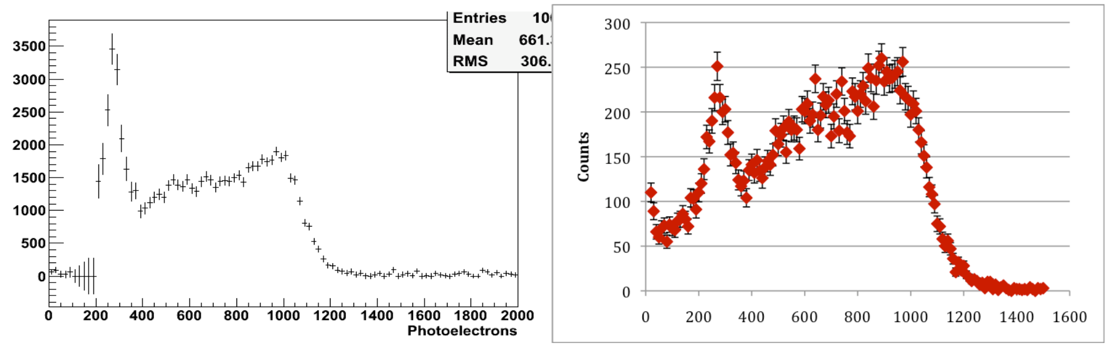

Figure 4: The measured neutron capture response of the detector (left) compares well with that predicted via a GEANT Monte Carlo simulation (right).

A feature of note is that the double ended optical readout allows for a degree of event position reconstruction. This is demonstrated in Fig. 5, where the location of an external source is indicated. This maybe a useful new background reduction technique, since the two inverse beta-decay reaction products are expected to interact in close proximity.

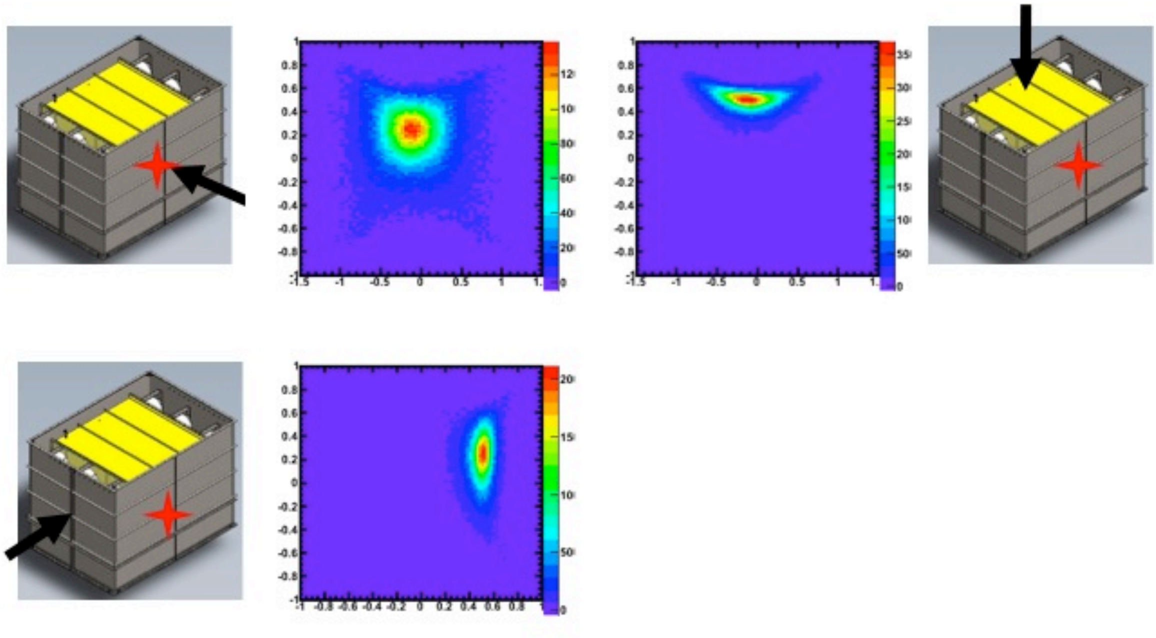

Figure 5: The position sensitivity that can be achieved using the double-ended optical readout is demonstrated. The red star denotes the position of a ^{252}Cf neutron source. Each plot is a projection of the position sensitive parameters deduced from neutron interactions onto the plane indicated by the black arrows.

6 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.

Incorporating many lessons learnt from the SONGS1 detector, we have developed and are testing a much-improved detector for deployment at a CANDU 6 OLR. Despite being considerably further from the reactor, this device will record a similar number of antineutrino interactions as did the SONGS1 device. In addition to providing a large increase in detection efficiency per unit area of deployed footprint, the new device is also likely to offer improved background reduction and rejection. When deployed at a CANDU 6 OLR sometime in 2012, this detector will perform the first online-monitoring of this unique reactor type.

References

[1] A. Bernstein, Y. Wang, G. Gratta, and T. West, *J. Appl. Phys.* **91** (2002) 4672.

[2] N.S. Bowden, et. al, First Results from a Nuclear Reactor Monitoring Antineutrino Detector, *Proceedings of the 45th INMM Annual Meeting*, July 2004

[3] A. Bernstein, et. al, First Recent Results from a Test of Reactor Monitoring with a Cubic Meter Scale Antineutrino Detector, *Proceedings of the 47th INMM Annual Meeting*, July 2006

[4] N.S. Bowden, et. al, Experimental results from an antineutrino detector for cooperative monitoring of nuclear reactors, *Nuclear Instruments and Methods in Physics Research A* 572 (2007) 985 .

[5] A. Bernstein, et. al, Monitoring the thermal power of nuclear reactors with a prototype cubic meter antineutrino detector, *Journal of Applied Physics* 103, 074905 (2008).

[6] N.S. Bowden, et. al, Observation of the isotopic evolution of pressurized water reactor fuel using an antineutrino detector, *Journal of Applied Physics* 105, 064902 (2009).

[7] N.S. Bowden, et. al, Advances Towards Readily Deployable Antineutrino Detectors for Reactor Monitoring and Safeguards, *Proceedings of the 49th INMM Annual Meeting*, July 2008.

[8] N.S. Bowden, et. al, Progress Towards Deployable Antineutrino Detectors for Reactor Safeguards, *Proceedings of the51th INMM Annual Meeting*, July 2010.

[9] G. Jonkmans, et. al, An Antineutrino Detector for Monitoring a CANDU Reactor, *Proceedings of the 51th INMM Annual Meeting*, July 2010.

[10] V. Bulaevskaya, et. Al., Detection of Anomalous Reactor Activity Using Antineutrino Count Rate Evolution Over the Course of a Reactor Cycle, arXiv:1009.2123v1

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