WATCHMAN: A Remote Reactor Monitor and Advanced Instrumentation Testbed

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Abstract. The remote detection of undeclared nuclear reactors, which could be used for production of material used to make nuclear weapons, is a key goal for global nuclear security. To address this challenge, WATCHMAN is beginning construction in Boulby Underground Laboratory, in the UK. WATCHMAN aims to demonstrate the ability to monitor nuclear reactors at distances of tens of kilometers or farther, called far-field monitoring. The first phase of the experiment will consist of a kiloton-scale gadolinium-doped water Cherenkov detector to detect anti-neutrinos coming from the Hartlepool Nuclear Power Station, located at a distance of 25 km from Boulby. The predicted dwell time required for determining that one reactor core is turning on-and-off in the presence of another reactor core is about 10 months. In addition to reactor monitoring, WATCHMAN will also act as an Advanced Instrumentation Testbed for next-generation neutrino detectors.

1. Introduction
Within the last 70 years nuclear reactors have become commonplace, with about 450 known reactors operating all over the world. To the best of our knowledge many of these reactors are operating with peaceful intentions, producing electrical power for cities and isotopes used in medicine and basic scientific research. However, there’s an undeniable link between nuclear reactors and nuclear weapons: fissile material.

Nuclear weapons require the production of fissile material such as $^{235}\text{U}$, which can be found in uranium ore. The choice of $^{235}\text{U}$ for nuclear weapons is not necessarily the most optimal. The natural abundance of $^{235}\text{U}$ is less than 1% with the more benign $^{238}\text{U}$ making up the other 99%. Separating $^{235}\text{U}$ from $^{238}\text{U}$ is extremely difficult and expensive. The United States sustained an enormous campaign to separate these two isotopes for the Manhattan Project during World War II [1]. An alternative method, one used by all countries trying to develop nuclear weapons, is to make $^{239}\text{Pu}$. $^{239}\text{Pu}$ has a half-life of about 24,000 years and is easily produced by bombarding $^{238}\text{U}$ with neutrons inside a nuclear reactor. The $^{238}\text{U}$ nucleus transmutes into $^{239}\text{U}$ via neutron capture and quickly ($T_{1/2} = 24$ min) decays into $^{239}\text{Pu}$. Thus, one can produce plutonium simply by exposing natural uranium in a small nuclear reactor for a duration lasting less than one month and promptly remove it to avoid build-up of less desirable plutonium isotopes. Afterwards, the separation of plutonium from uranium is achieved with standard, well-known, chemical methods.
How is the world preventing mass production of materials that could be used for nuclear weapons? The first line of defense lies in the hands of the International Atomic Energy Agency (IAEA). The IAEA deploys a variety of reactor safeguard measures to verify that fissile material is not used for nuclear weapons manufacturing [2, 3]. Today, safeguard concerns face significant challenges and the IAEA has prioritized the research and development of new safeguard measures [4]. In this vein, the detection of reactor anti-neutrinos could provide a new mechanism for monitoring nuclear reactors at distances $\gtrsim 10 – 100$ kilometers [5].

2. Reactor Anti-neutrinos

Reactors are copious sources of $\bar{\nu}_e$, which originate in reactor cores during the beta decay of fission byproducts. Given that $\sim 6$ electron antineutrinos are released per fission, the corresponding isotropic emission rate in a typical nuclear reactor is $\sim 3 \times 10^{21}$ per second per GW$_{th}$. In hydrocarbon-based photon detectors, reactor anti-neutrinos are typically observed through the inverse beta decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow n + e^+$, which has a threshold of 1.8 MeV. The positron creates a prompt light signal that provides a measure of the anti-neutrino energy, $E_{\bar{\nu}_e} \sim E_p + E_n + 0.8$ MeV, where $E_p$ is the prompt energy with both positron kinetic and annihilation energies, and $E_n$ is the average recoil energy of the neutron (of order 10 keV). The neutron thermalizes and captures on a nuclear target creating a delayed light signal from de-excitation gammas. Detection of the prompt-delayed coincidence provides a mechanism for background suppression.

To zeroth order the IBD cross-section is $\sigma(E_{\nu}) \sim 10^{-42} \text{ cm}^2$ where the vast majority of reactor anti-neutrinos are produced with energies less than 10 MeV. The total interaction rate can be calculated with a combination of the flux and the IBD cross-section. However, for distances greater than 100 meters from a reactor, neutrino flavor oscillations are significant and must be accounted for when calculating interaction rates in any detector. As an example, a kiloton of water at a distance of 25 km from a 3 GW$_{th}$ reactor would experience several IBD interactions per day.

3. AIT-WATCHMAN

The Advanced Instrumentation Testbed (AIT) is a platform for the development of technology for reactor monitoring with anti-neutrinos, located at a depth of 1.1 km (2805 m.w.e.) in Boulby Underground Laboratory. The WATer CHerenkov Monitor for Anti-Neutrinos (WATCHMAN) will be the first detector built within this platform. The conceptual design consists of a cylindrical stainless steel tank having a diameter of 19 m and height of 20 m. The tank will be filled with about 6 kilotons of ultra-pure water loaded with gadolinium sulfate to a concentration of 0.1% by weight. A cylindrical support structure will be constructed inside the tank and will be instrumented with at least 3,600 10-inch photomultiplier tubes (PMTs) facing inward and 400 PMTs facing outward. The inward PMTs view a fiducial mass of about 1 kiloton Gd-doped water, neglecting the outermost region within 1.5 m of the PMTs. The outward-facing PMTs will be used to veto cosmic rays. A conceptual diagram of the WATCHMAN detector is shown on the left side of Figure 1. The water will continuously purified by an elaborate filtration system based on the technology developed by EGADS for Super-Kamiokande Gd [7]. This is necessary to maintain high optical transparency, which is essential feature for future detectors with fiducial masses on the order of hundreds of kilotons.

Boulby Underground Laboratory is located a distance of 25 km from the Hartlepool gas-cooled power reactor. Hartlepool has two cores, each with $\sim 1.5$ GW$_{th}$, for a total of 3 GW$_{th}$. For reference, the survival probability of reactor anti-neutrinos from Hartlepool to WATCHMAN is shown on the right side of Figure 1. The next closest reactor is Heysham (two cores with a total of 6 GW$_{th}$) at 150 km distance. Heysham will contribute 5% to the total anti-neutrino flux in WATCHMAN, while the rest of the world’s reactors contribute about 10% to the total...
Figure 1. A conceptual drawing of the WATCHMAN detector showing a stainless steel tank ∼20 meters tall and ∼20 meters in diameter is shown on the left. A support structure sits inside the tank and is instrumented with roughly 3600 inward-facing PMTs and roughly 400 outwards facing PMTs. A plot of the survival probability vs distance from reactors using current best-fit oscillation parameters [6] is shown on the right. WATCHMAN is indicated in red with error bars due to uncertainty in the oscillation parameters. Other reactor measurements with associate error bars are indicated by the black data points.

The depth of Boulby provides suppression of cosmic-induced backgrounds, such as $^9$Li and $^8$He, that could mimic the reactor anti-neutrino signal. Estimates of the cosmic-induced backgrounds in WATCHMAN have been made using existing theoretical models and measurements at similar depths [8, 9, 10]. Backgrounds from the accidental coincidences of radioactivity within the Gd-doped water, the surrounding detector components, and the rock cavern will also contribute to the total background budget. The fiducial volume, containing the innermost 1 kiloton of water inside the PMT support structure, was chosen as to minimize the impact of radioactivity from the surrounding detector materials. One of the most significant background for IBD detection in the Gd-doped water is $^{222}$Rn, which has been measured in the Super-Kamiokande detector under conditions similar to those planned for WATCHMAN [11, 12]. The total estimated background and signal budgets from all possible sources are summarized in Table 1. A summary of the monitoring sensitivity for several scenarios of interest to the non-proliferation community is summarize in the next section.

| Component          | Rate [events/week] |
|--------------------|--------------------|
| Hartlepool Core 1  | 4.2                |
| Hartlepool Core 2  | 4.2                |
| World Reactors     | 1.5                |
| Accidentals        | 0.9                |
| Fast Neutrons      | 0.6                |
| Radionuclides      | 0.1                |
| **Total**          | **11.3**           |

Table 1. Summary of the total background and signal budgets for a conceptual design of the WATCHMAN detector. The assumed signal depends on the monitoring scenario and is composed of either one, or both, of the Hartlepool reactor cores.
4. Reactor Monitoring Sensitivity

There are several different use-case scenarios that are of great interest to the non-proliferation community. Scenario (1) involves detecting the presence of an unknown reactor in an area of the world where few known reactors exist. Scenario (2) would involve detecting the presence of an unknown reactor operating in close proximity to a known reactor, which would be done in an attempt to reduce the detection sensitivity of the anti-neutrino flux of unknown reactor with another reactor flux of equal or greater magnitude. Finally, scenario (3) would be the observation of one reactor turning on and off in the presence of another reactor. A reactor turning off and back on with a frequency of about once every three weeks would indicate that the reactor is operating in a mode that is characteristic of those used to produce plutonium for nuclear weapons. Again, another mundane reactor is used to reduce detection sensitivity of the suspect reactor.

WATCHMAN will provide sensitivity benchmarks to the non-proliferation community for all three scenarios by measuring anti-neutrinos from the two cores of the Hartlepool reactor. Using the signal and background estimates in Table 1, the estimated dwell time (detector live time) to achieve sensitivity for each of the three scenarios described with 95% C.L. is about one week for scenario (1), one month for scenario (2), and 10 months for scenario (3). In future phases of AIT, upgrades are being planned such as new photosensors (Large Area Picosecond Photodetectors) or detection media (water-based liquid scintillator). Studies are underway to investigate the impact these enhancements would have reactor monitoring and the sensitivity for new physics.

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References

[1] F. G. Gosling, The Manhattan Project: Making the Atomic Bomb, DOE/MA-0002 Revised (2010).
[2] IAEA Department of Safeguards. Safeguards: Staying Ahead of the Game, IAEA Division of Public Information, Vienna, Austria (2007).
[3] Boyer, B. and Schanfein, M. In Nuclear Safeguards, Security, and Nonproliferation (ed J. Doyle), Elsevier, Oxford, UK (2008).
[4] IAEA Department of Safeguards. Long-Term R&D Plan, 2012–2023, STR-375. (IAEA, Vienna, Austria, 2013).
[5] A. Bernstein, et al., Nuclear Security Applications of Antineutrino Detectors: Current Capabilities and Future Prospects, Science Global Security 18, Issue 3, pp 127-192 (2010).
[6] M. Tanabashi, et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).
[7] C. Xu, Current status of SK-Gd project and EGADS, Journal of Physics: Conference Series 718, 062070 (2016).
[8] A. Roecker, Measurement of the High-Energy Neutron Flux Above and Below Ground, PhD thesis, University of California, Berkeley, 2016.
[9] S. Dazeley, et al., A search for cosmogenic production of β-neutron emitting radionuclides in water, Nucl. Instrum. Methods, A821, pp 151-159 (2016).
[10] D.M. Mei and A. Hime, Muon-induced background study for underground laboratories, Phys. Rev. D 73, 053004 (2006).
[11] Y. Takeuchi, et al., Measurement of radon concentrations at Super-Kamiokande, Phys. Lett. B 452, Issues 3-4, pp 418-424 (1999).
[12] Y. Nakano, et al., Measurement of radon concentration in Super-Kamiokande’s buffer gas, Nucl. Instrum. Methods, A867, pp 108-114 (2017).