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Nuclear Security Applications of Antineutrino Detectors: Current Capabilities and Future Prospects

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Antineutrinos are electrically neutral, nearly massless fundamental particles produced in large numbers in the cores of nuclear reactors and in nuclear explosions. In the half century since their discovery, major advances in the understanding of their properties, and in detector technology, have opened the door to a new discipline—Applied Antineutrino Physics. Because antineutrinos are inextricably linked to the process of nuclear fission, there are many applications of interest in nuclear nonproliferation. This paper presents a comprehensive survey of applied antineutrino physics relevant for nonproliferation, summarizes recent advances in the field, describes the overlap of this nascent discipline with other ongoing fundamental and applied antineutrino research, and charts a course for research and development for future applications. It is intended as a resource for policymakers, researchers, and the wider nuclear nonproliferation community.

POLICY SUMMARY

It is now possible to monitor the operational status, power levels, and fissile content of nuclear reactors in real time with simple detectors at distances of tens of meters from the reactor. This has already been demonstrated at civil power reactors in Russia and the United States, with detectors designed

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specifically for reactor monitoring and safeguards.[1] This existing near-field monitoring capability may be useful in the context of the International Atomic Energy Agency's (IAEA) Safeguards Regime, and other cooperative monitoring regimes, such as the proposed Fissile Material Cutoff Treaty.[2]

Though not part of any existing treaty, today's technology would allow cooperative monitoring, discovery, or exclusion of small (5–10) Megawatt thermal (MWt) reactors at standoff distances up to 10 kilometers. In principle, discovery and exclusion is also possible at longer ranges, as is standoff nuclear explosion detection at the kiloton level. However, the required detector masses are 10–100 times greater than the state of the art, and achieving these long range detection goals would require significant research and development (R&D) on several fronts. Many elements of the necessary R&D program are already being pursued in the fundamental physics community, in the form of very large antineutrino detection experiments.

Antineutrino detectors are likely not useful for the detection or monitoring of quiescent, non-critical fissile materials, regardless of the amount of material or the size of the detector, because emission rates from these materials are vastly lower than from critical systems.

The conclusions and recommendations of this paper are:

1. Practical near-field (less than 100 m) monitoring of pressurized water reactors (PWR) with antineutrino detectors has been demonstrated, and offers a promising complement to existing reactor monitoring methods for IAEA and other safeguards regimes. We recommend further investigation of near-field antineutrino monitoring capabilities for providing reactor operational status, thermal power and fissile content of reactors for safeguards. In particular, further R&D is appropriate in determining sensitivity levels at non-PWR reactors, in direct measurement and simulation of the evolution of antineutrino rates and spectra at various reactors, and in detectors with improved deployability characteristics. We also recommend close cooperation between the antineutrino physics community, the IAEA, and relevant government agencies worldwide to ensure that development is well matched to safeguards needs.

2. Mid-field (1–10 kilometer) monitoring of the operational status and presence or absence of 10 MWt reactors, and placing upper limits on plutonium production in such reactors, is possible with existing technology, assuming deeply buried (1 kilometer overburden) detectors and in parts of the world with few commercial reactor backgrounds. We recommend development of 1000–10,000 ton scale detectors with dual physics and nonproliferation aims. We further recommend R&D focus on reducing costs through, among other options, reduction in overburden while maintaining suitable signal to background levels, and improvements in collection of the light generated

by antineutrino interactions in water and scintillator detectors. Since they will normally occur within the borders of a country, mid-field monitoring regimes are likely to be cooperative in nature. We therefore recommend policy studies and cost-benefit analyses of cooperative deployments in the context of current or future treaties and agreements.

3. Far-field (10–500 kilometer) monitoring of the presence or absence and operational status of 10 MWt reactors, and placing upper limits on plutonium production in such reactors, would require detectors at the 10,000–10,000,000 ton (10 megaton) scale. For cost reasons, these would likely be composed of pure water doped with neutron capture agents. US and international groups have proposed detectors of this kind at the 100,000 ton scale. These proposals are now in the conceptual design phase with funding agencies, with the aim of achieving a variety of fundamental physics goals. We recommend that the technical nonproliferation community actively engage in these experimental and planning efforts. Such participation will help ensure that the best technologies from fundamental science are brought to bear on the nonproliferation problem. Similarly, the policy community as well as scientific and nonproliferation funding agencies, should analyze the consequences of the existence of such detectors, and in particular should consider planning scenarios and co-investment in projects involving joint physics and nonproliferation goals.
4. Detection of nuclear detonation offers the unique possibility of unambiguous remote confirmation of the nuclear nature of the event. Unfortunately, this capability is possibly the most challenging topic discussed in this paper. As discussed in earlier unclassified reports, 10–100 kilometer range of foreseeable detectors for 1 kiloton yield fission explosions appears most suitable for cooperative monitoring of test sites in relatively proscribed circumstances.[3] While there are differences in backgrounds due to the burst-like character of the fission bomb antineutrino pulse, much of the necessary detector development research will be accomplished in the course of R&D recommendations 2 and 3 above. In a policy context, we recommend analysis of the potential impact of various cooperative deployments on the Comprehensive Test Ban Treaty (CTBT) and other future test-ban verification regimes.

INTRODUCTION

This paper presents a comprehensive survey of applied antineutrino physics relevant for nonproliferation, summarizes recent advances in the field, describes the overlap of this nascent discipline with other ongoing fundamental and applied antineutrino research, and charts a course for R&D for future applications. It is intended as a resource for policymakers, researchers, and the wider nonproliferation community. A more complete treatment of the underlying physics and antineutrino detection technology may be found in an expanded paper by the authors.[4]

The paper is organized as follows.

In the following section we give a general overview of the information that antineutrino detectors can provide for reactor monitoring, reactor finding, and nuclear explosion detection, and provide illustrative examples of deployments. Next we describe the physics of antineutrino production and detection relevant for nuclear reactors in further detail, followed by a description of antineutrino production and detection from nuclear explosions.

"Near-field" (10 meters–1 kilometer) applications of antineutrino detectors, with an emphasis on existing demonstrations of cooperative monitoring and safeguards of nuclear reactors are considered. Current IAEA safeguards practices at different reactors are reviewed and the possible benefits of antineutrino detectors in the context of safeguards are considered. The paper describes the state of the art for antineutrino detection as applied to near-field monitoring. A set of general requirements for near-field deployments are presented, and R&D priorities for improved near-field monitoring antineutrino detectors are presented.

Current and future capabilities for finding operating reactors or excluding their presence in the "mid-field" (1–10 kilometers standoff) and "far-field" (10–500 kilometer standoff), and discuss R&D priorities for these detectors are surveyed.

Finally, the paper summarizes ongoing fundamental physics research that is relevant for applied antineutrino physics.

OVERVIEW AND EXAMPLES OF ANTINEUTRINO-BASED MEASUREMENTS OF NONPROLIFERATION INTEREST

The possible utility of the antineutrino signal for nonproliferation is easily understood apart from detailed production and detection mechanisms, which are described in the next section. In descending order of accessibility with current technology, the measurements of interest for the applications discussed in this paper are:

The antineutrino *rate* from a given source, whether a reactor or a fission bomb;

The antineutrino *energy spectrum*; and

The antineutrino *direction*.

Information Derived from Antineutrino Rate Measurements

The emitted antineutrino rate from reactors depends on the thermal power and fissile isotopic content of the reactor. The antineutrino rate can therefore be used to measure the reactor operational status (off/on) and power continuously and in real time. If the reactor power and initial fuel loading are known by other means, and the antineutrino event rates are sufficiently high (roughly hundreds or thousands of events per day or week) the antineutrino rate can be used to estimate the evolving amounts of fissile uranium and plutonium in the reactor core. For a given fuel type, the degree of neutron irradiation primarily determines these changing amounts of fissile material, and is referred to as the "burn-up." The fuel burn-up at discharge directly correlates with the amount of plutonium in spent fuel, and is an important parameter in the context of reactor safeguards.

Many experiments worldwide have performed antineutrino rate measurements at reactors.[5–10] Two experiments, described in the next section, have been built specifically to demonstrate reactor monitoring capability in the context of nuclear safeguards.[11]

The antineutrino rate from nuclear explosions depends on the fission yield and fissile isotopic content of the explosion. The short burst of antineutrinos emitted by a nuclear weapon can therefore be used to measure the total fission yield of a nuclear explosion, as well is to confirm that the explosion is indeed due to fission. An earlier study has provided a detailed examination of the utility, detector characteristics, and costs for fission explosion detectors.[12]

Information Derived from the Antineutrino Energy Spectrum

Like the antineutrino rate, the antineutrino energy spectrum depends on the reactor power and fissile isotopic content. Estimates of both the reactor fissile isotopic content *and* its thermal power can be derived from spectral measurements, without the need for independent measurement of the reactor thermal power, provided sufficient statistics are available. As with rate measurements, antineutrino spectral measurements have been made in numerous fundamental physics experiments.[13] Theoretical estimates have also been made of reactor antineutrino spectra for the major fissile isotopes.[14] These are accurate to a few percent, and are derived primarily from experimentally measured fission product electron spectra of these isotopes.[15] In combination with models of the reactor fuel evolution, such as ORIGEN, the antineutrino spectrum of a given reactor can be predicted.[16]

Information Derived from the Direction of the Antineutrino

The antineutrino direction can in principle be used to infer the location of a bomb or reactor. Directionality is difficult to measure for reasons described in later sections. However, the Chooz collaboration has successfully reconstructed the direction of antineutrinos from a known reactor source with a pointing accuracy of approximately 20 degrees.[17]

These three types of measurements underlie all of the potential uses of antineutrino detectors that are described in the following sections. To further

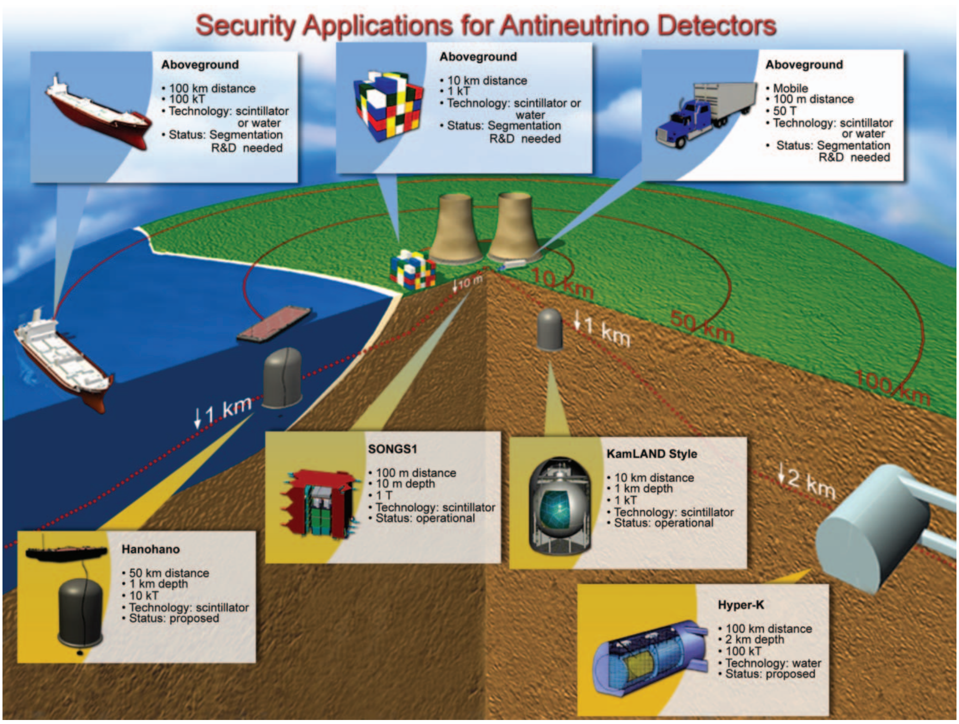

Figure 1: Representative deployment scenarios for antineutrino detectors. The 1 ton SONGS1 and 1000 ton Kamioka Liquid Scintillator Anti-Neutrino Detector (KamLAND) have been deployed and have operated for several years.

orient the reader to the possibilities, Figure 1 displays a number of possible deployment options, distinguished by range and by overburden. The sidebar presents examples of measurements that could be made currently or in the near term at three distance scales of interest. These ranges scales are:

1. *Near-field:* 10 meters–1 kilometer from a nuclear power or research reactor;
2. *Mid-field:* 1–10 kilometers from a nuclear reactor; and,
3. *Far-field:* 10 km and beyond from a nuclear explosion or a nuclear reactor.

We will return to these examples, with more detail in specific cases, in the application sections of the paper.

Figure 2 is a summary graph of the size of the detector as a function of distance from a 10 MWt reactor. Because of the highly penetrating power of antineutrinos, shielding and attenuation calculations, such as those required for gamma and neutron detection, are irrelevant for the purposes of calculating

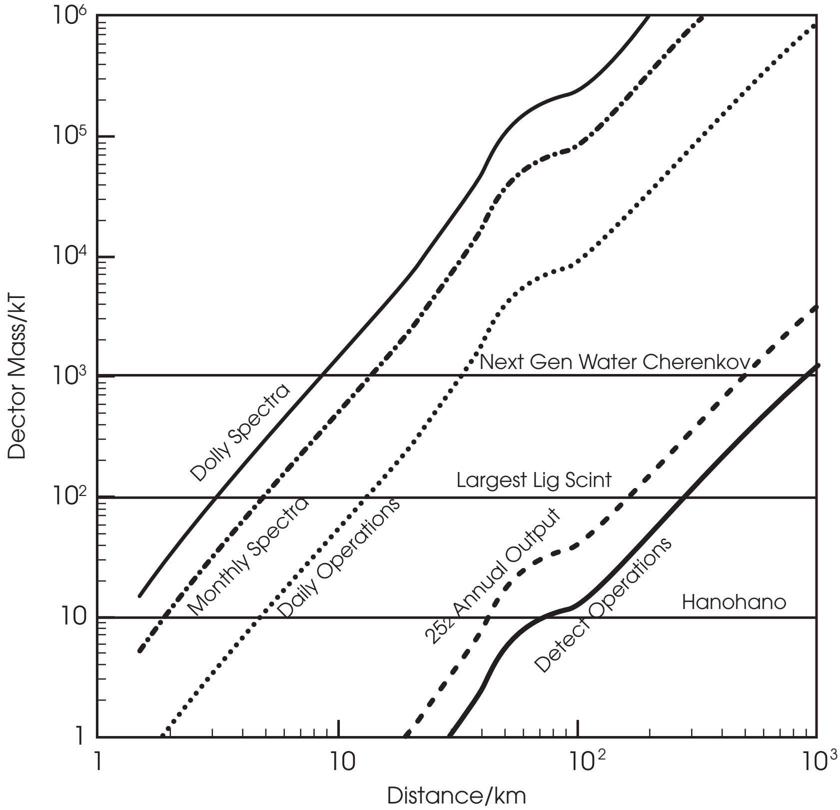

Figure 2: A plot of the required detector mass (in kilotons) for a given standoff distance (in km) and application, assuming zero background, and using the most commonly employed antineutrino detector interaction (inverse beta decay). Discovery refers to confirming the presence of a 10 MWt reactor within 1 year with greater than five events. Measuring annual output with 16 measured events in 1 year would provide an estimate of the reactor thermal power with 25% precision. Measuring daily operations would require 3600 events/year, measuring monthly spectra would require 36,000 events per year, and daily spectra would require about 3000 events per day. Most of the scaling behavior is determined by the inverse square dependence of the antineutrino flux. The kinks in each curve are caused by the known effect of reactor antineutrino oscillations, first measured by the KamLAND experiment. Further information about reactor antineutrino oscillations is found in the final section of this article (K. Eguchi et al. (KamLAND), *Phys. Rev. Lett.* 90 (2003)).

signal rates. For a given interaction and detector type, the main variables influencing detector size are the distance from the source, the source strength (fissile yield or reactor thermal power), and the amount of shielding against ambient backgrounds. There is also a comparatively small correction factor due to antineutrino oscillations, described later, that depends on the ratio of the antineutrino energy and the reactor standoff distance.

Representative Examples of Nonproliferation Applications of Antineutrino Monitoring and Detection

Near-Field reactor monitoring. A ~1 ton mass antineutrino detector operated at 24.5 meters from a 3.64 GWt reactor core at the San Onofre Nuclear Generating Station (SONGS) in Southern California has been used to non-intrusively monitor the operational status, relative thermal power, and fissile content of the reactor. The reactor operational status (on or off) is detected within 5 hours of shut down/startupwith 99% confidence. Reactor power is measured with 3% accuracy (relative to an initial value) in one week. With known constant reactor power and fuel loading, changes in fissile content corresponding to consumption of 500 kg of Uranium-235 and production of ~80 kg of plutonium are observable in approximately 4˜months. Further improvement can be achieved with modest design changes to this prototype. With approximately the same size detector at 5 meter standoff, similar precision for power and operational status could be obtained for a 100 MWt research reactor. The deployment is described further in section titled "Near-Field Applications: Safeguards and Cooperative Monitoring."

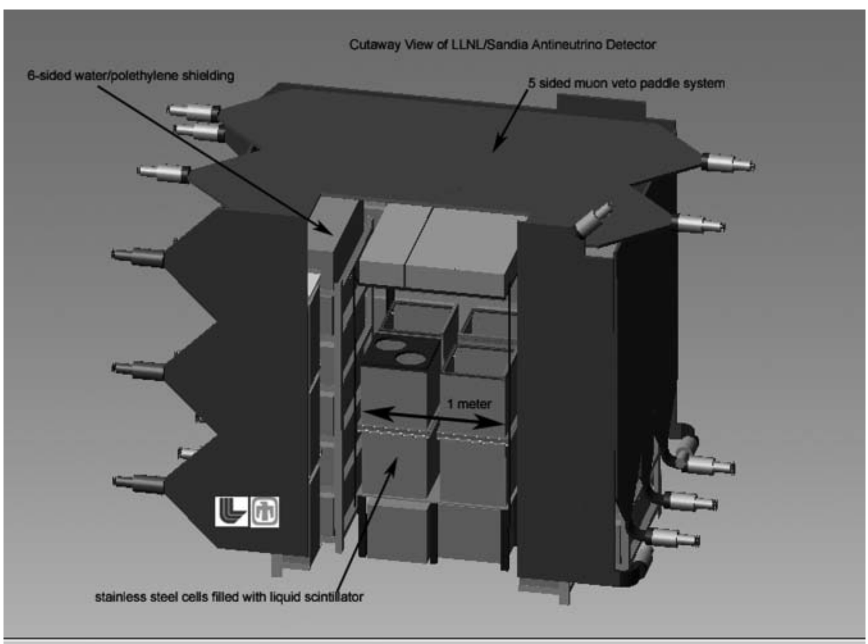

Figure 3: The SONGS1 detector, deployed by a Lawrence Livermore National Laboratory/Sandia National Laboratories team at the San Onofre Nuclear Generating Station in Southern California, demonstrated persistent cooperative monitoring of reactor power and fissile fuel content with an unattended sensor.

Midfield reactor operation/exclusion/discovery. The largest currently operational reactor antineutrino detector is the Kamioka Large Antineutrino Detector (KamLAND)[18]. KamLAND is 1000 ton liquid scintillator detector, operating at 1000 meters overburden. With this detector and overburden, the operation of a 10 MWt reactor could be excluded in a 10 kilometer radius in 3 months at the 95% confidence level, with no other reactors present. If a reactor is discovered, its power could be estimated to within 25% in 8 months. Additional known or unknown reactors would change the background levels and alter the detector size requirements. Midfield applications are considered in the section titled "Mid-Field Applications: Detecting and Monitoring Reactors From 110 km."

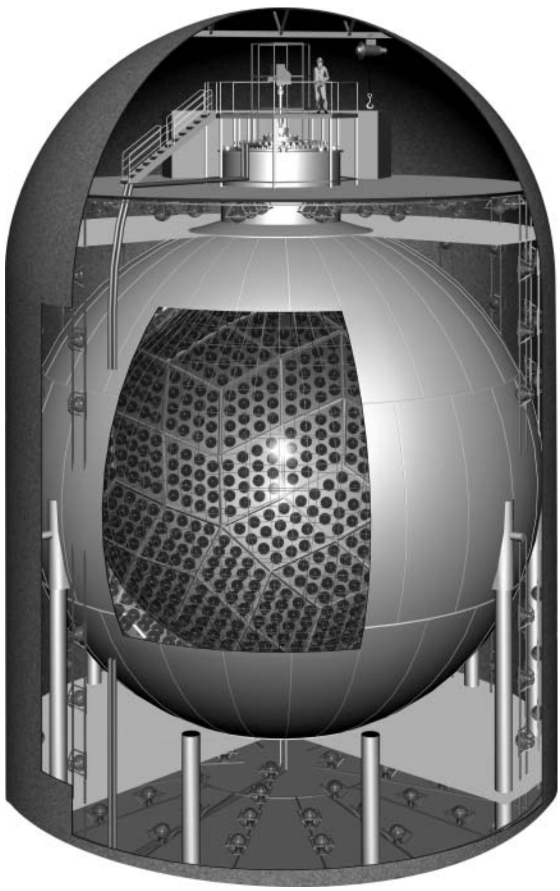

Figure 4: The 1000 ton KamLAND detector currently records antineutrinos from high power (1 GWt) reactors at 100s of kilometers standoff. In a region free of other reactors, it would be sensitive to low power (10 MWt) reactors at 10 kilometer standoff. The human figure in the image indicates the scale.

Far-field reactor exclusion/discovery. The operation of a 10 MWt reactor could be excluded within an 800 kilometer radius with a 1,000,000 ton water Cerenkov antineutrino detector. Detectors approachingthis scale, such as those being built for the U.S. Long Baseline Neutrino Experiment[19] (LBNE, shown here) are now being developedby various physics collaborations worldwide. The measured antineutrino rate would be approximately 5 events per year. The rate includes neutrino oscillation-swhich must be taken into account at this distance. Additional reactors would change background levels and increasethe detector size.

Far-field nuclear explosion detection. The fissile nature and approximate yield of a 10 kton explosion at 250 kilometer standoff could be confirmed with a 1,000,000 ton water Cerenkov detector. The detector would record 2–3 events in a few seconds from such an explosion. Far-field reactor and explosion detection are considered in the section titled Far-Field Applications: Detecting Reactors and Explosions at 10–500 km."

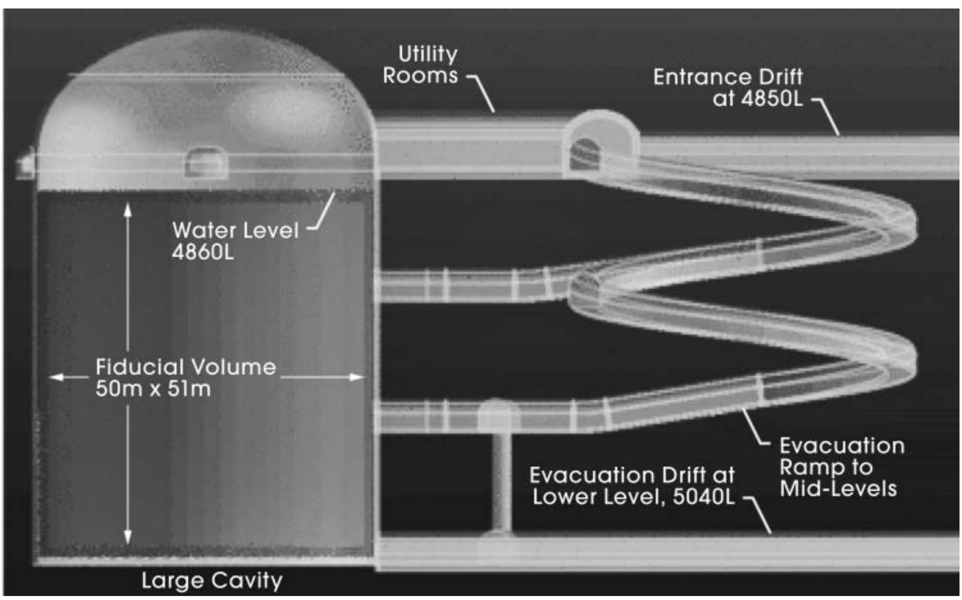

Figure 5: A schematic of a water Cerenkov antineutrino detector now being developed in the United States, with a scale approaching that requires for long range reactor discovery.

Tracking Fissile Mass in Nuclear Reactors with Antineutrinos

This section describes how the thermal power and fissile mass inventories of operating reactors can be tracked using antineutrino rate and spectrum measurements, and provides a basic introduction to antineutrino interaction mechanisms and detection technology, and to the many historical examples of deployed antineutrino detectors. These deployments—including two built explicitly for the purpose of testing and demonstrating cooperative reactor monitoring—have provided valuable information on cost, intrusiveness, and ease of operation in the context of safeguards. Because of the historically limited budget of the IAEA, these practical considerations are decisive when considering adoption of the technology within the IAEA safeguards regime.

As discussed earlier, both the total detected rate and energy spectrum of reactor antineutrinos change over time in concert with the core fuel inventory. The variation in either metric over the course of the reactor cycle is known as the "burn-up effect." The burn-up effect is an important feature of near-field reactor monitoring applications. Burn-up, in units of Gigawatt-days per ton of heavy metal (GWd/THM) measures the integrated thermal power output of reactor fuel per unit of fuel mass. It effectively tracks total neutron exposure of the fuel, and therefore uranium consumption and plutonium production in the core. Monitoring the antineutrino rate or energy spectrum measures the burn-up, and thus provides a near-real-time estimate of fissile inventories and power of operating reactors.

The detected time dependent antineutrino rate can be written in simplified form as:

$$N_{\bar{\nu}} = \gamma[1 + k(t)]W(t) \cdot P(R, E_{\bar{\nu}}). \quad (1)$$

Here $N_{\bar{\nu}}$ is the detected antineutrino rate, and γ is a constant depending on the reactor standoff distance and the detector efficiency. $W(t)$ is the reactor thermal power, and $k(t)$ is a time dependent variable that incorporates the changing fission rates from each isotope. The final term, $P(R, E_{\bar{\nu}})$ depends on the antineutrino energy and the standoff distance, and accounts for neutrino oscillations. Its value is unity for reactor antineutrinos for standoff distances of 500 m or less, but may be reduced by as much as several percent at 1 km. From the KamLAND experiment, the $P(R, E_{\bar{\nu}})$ is known to be approximately 0.6 (a 40% deficit relative to the expected flux) for reactors at roughly 200 km.[20] Past and ongoing neutrino oscillation experiments, which have measured or will measure this correction at this distance and greater distances, are discussed in a later section.

The size of the burn-up effect depends primarily on the core type, fuel composition and the reactor thermal power. For example, in a standard 1.5 year cycle of operation of a 3.6 GWt PWR, a 1500 kg net decrease in Uranium-235 and 250 kg net increase in Plutonium-239 content together induce a smooth gradual decrease in the parameter k(t) by about 10–12%. Operating conditions and results from two experiments showing this behavior in PWRs are described in the following section. This result is specific to a low enriched uranium-fueled (LEU) Light Water Reactor (LWR). LEU is less than 20% uranium, enriched in Uranium-235, or natural uranium. Other reactor types, such as Canadian Deuterium Uranium (CANDU) reactors, fast breeder reactors, or Mixed Oxide-fueled (MOX) reactors, will exhibit different variations in the antineutrino rate over the course of the fuel cycle.

What follows is a summary explanation of the origin of the burn-up effect. A more detailed analysis of this equation is found in Klimov (1994) and Bernstein (2009). The burn-up effect arises from a combination of two factors: the evolving fission rates of each isotope, and the differences in the detected (as opposed to the emitted) antineutrino energy spectra per fission from each isotope.

As an LWR proceeds through its irradiation cycle, the mass inventories of each fissioning isotope change. As a consequence, the relative fission rates of the isotopes vary significantly throughout the reactor cycle, even when constant power is maintained. This variation is shown in Figure 6, a plot of fractional fission rates in an LWR, operating at constant power over 600 days. Uranium-235 and Plutonium-239 contribute the most fissions. Though it accounts for most of the mass of the reactor core, Uranium-238 contributes only about 10% of the total fissions in these reactors.

The second factor contributing to the burn-up effect is a sizable variation with energy of the detected antineutrino spectra among the different isotopes. Although the variation occurs only at relatively high antineutrino energies, (above approximately 2 MeV) it has a strong effect on the detected rate and spectrum of reactor antineutrinos.

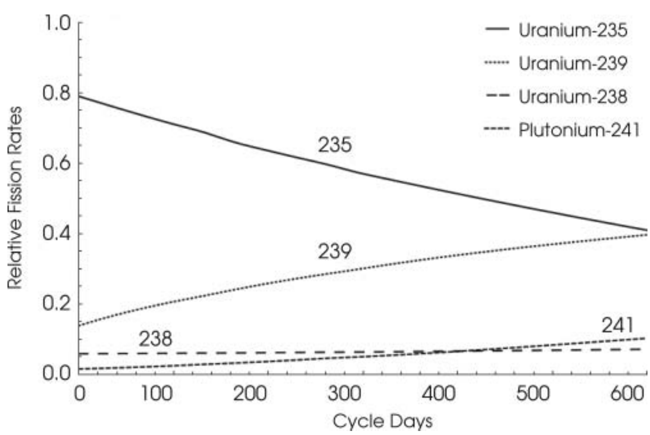

Figure 6: The fractional fission rates of the main fissile isotopes in a Light Water Reactor plotted versus cycle day.

Antineutrino emission in nuclear reactors arises from the β-decay of neutron-rich daughters of the fission process. Regardless of the isotope, each fission is followed by the production of about six antineutrinos, which corresponds to the average number of β-decays required for the fission daughters to reach stability. For a typical power reactor, the thermal power output is about 3 GWT, and the energy release per fission is about 200 MeV. For such reactors, therefore, the number of antineutrinos emitted from the core is approximately 10^{21} per second. These emerge from the core isotropically and without attenuation.

The antineutrino energy distribution contains spectral contributions from the dozens of beta-decaying fission daughters. Precise estimates of the distribution have been derived from beta spectrometry measurements and validated by many of reactor experiments.[21] Curve a) in Figure 7 shows the emitted energy spectra per fission above 1 MeV of antineutrinos for the two most important fissile elements. The width of the curves shows the combined experimental

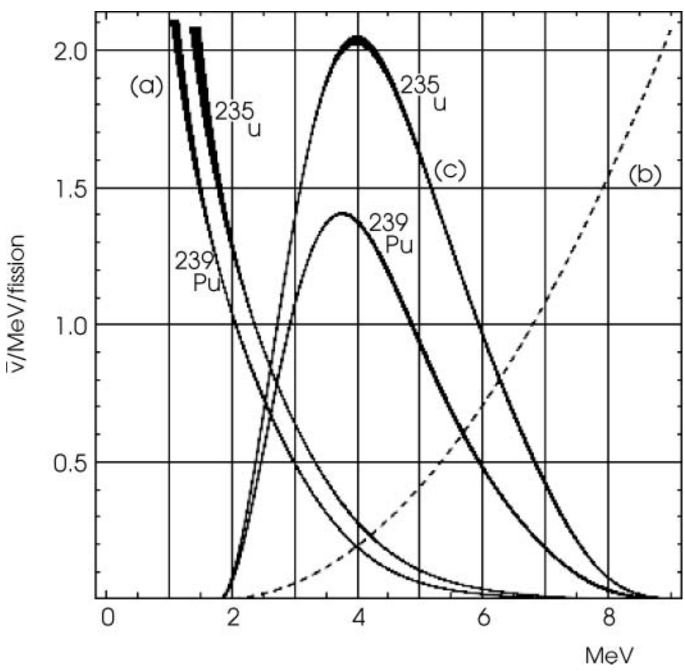

Figure 7: a) The antineutrino spectra from Uranium-235 and Plutonium-239, in units of antineutrino per MeV per fission. b) The inverse beta decay cross section, exhibiting quadratic dependence on energy. c) The antineutrino spectra as measured in a detector after convolution with the inverse beta decay cross section, also measured in antineutrinos per MeV per fission. Above approximately 3 MeV, the two spectra differ by 50% or more. Only the sum spectrum, weighted by the individual fission rate, is measured in an actual detector. The thickness of the emitted and detected spectral traces show the +/− 1 sigma uncertainties. The overall normalization has been scaled to fit the curves on the same plot.

and theoretical uncertainty in the energy spectra. Event to event, it is impossible to identify which fissile isotope produced an antineutrino of a given energy. However, at higher energies, the number of emitted antineutrinos does differ markedly among the isotopes, and the difference increases with energy.

The emitted antineutrino must interact in order to be detected. The most commonly used antineutrino interaction mechanism is inverse beta decay:

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

This threshold interaction proceeds only when the antineutrino has enough energy (1.8 MeV or more) to convert the proton to a neutron and simultaneously create a positron. Because the process depends quadratically on the incident antineutrino energy, the inverse beta interaction effectively selects and enhances the higher energy part of the antineutrino spectrum, which is most sensitive to changes in the fissile isotopic content of the core. Curve c) in Figure 7 shows the antineutrino energy spectra, after folding with the energy dependent inverse beta cross section. The quadratic dependence of the cross section is shown in curve b) of the figure. The detected spectra differ by 50% or more between the two main fissioning isotopes.

The detected antineutrino spectrum from an actual reactor consists of a sum over the individual spectra from each isotope, weighted by the fission rates. The changing contributions to fission of the different isotopes, combined with the pronounced difference in the detected antineutrino energy spectra between the most important isotopes, causes a change in the measured spectrum throughout the reactor cycle.

As with the antineutrino rate, the spectral change due to isotopic evolution has been measured empirically. Experimentally measured antineutrino spectra have absolute accuracies of about 2%, with errors dominated by uncertainties in the predicted reactor emission spectrum.[22] For standard PWR fuel cycles extending to 500 or 600 days, the bin-to-bin differences between beginning and end of cycle spectra range from 6–20%, with the most pronounced differences at higher energies. Because these differences are larger than the known 2% uncertainties in the predicted spectra, they can be and have been experimentally observed with energy resolving antineutrino detectors.

In summary, estimates of the operational status, thermal power, and plutonium content of reactors can be derived by measuring the change in the total rate or the energy spectrum of antineutrinos. Later sections describe results from practical detectors demonstrating these relations, and consider how the information can be used for reactor safeguards applications.

Reactor Antineutrino Detection and Background Rejection

Historically, organic liquid scintillator has been the most common choice of detection medium for reactor antineutrinos. It can be obtained in large quantities at low cost, has a high density of free proton targets to enable reaction 2, and it can be doped with different neutron capture elements to enhance sensitivity to the neutron in the final state of the antineutrino interaction.

Detection with liquid scintillator has been standard in nuclear physics ever since the early experiments leading to the discovery of the antineutrino. Modern liquid scintillator detectors, such as Rovno,[23] SONGS1,[24] Chooz[25] and Palo Verde,[26] have masses of several tons and have run for a few years each, with total detector-related systematic errors on the absolute antineutrino count rate as low as 3%. These detectors have very good time stability and relatively modest health hazards.

In the inverse beta process 2, both the positron and the neutron are detected in close time coincidence compared to other backgrounds. The positron and its annihilation gamma-rays produce scintillation signals within a few nanoseconds of the antineutrino interaction: this is collectively referred to as the prompt scintillation signal. This is followed by a second, delayed scintillation flash arising from the cascade of gamma-rays which come from decay of the excited nuclear state of the neutron-absorbing element following neutron capture. The scintillation light is recorded in photomultiplier tubes, with the number of scintillation photons proportional to the deposited positron and neutron-related energies, and the time of each deposition recorded. This time correlated pair of MeV-scale energy depositions, with the prompt and delayed signals separated by only a few tens or hundreds of microseconds, stands out strongly against backgrounds.

The neutron capture can occur on hydrogen, for which a 2.2 MeV gamma-ray is released. Often, a dopant with a high neutron-absorption cross-section is used, to improve the robustness of the signal. This brings the dual benefits of reducing the capture time and increasing the energy released in the gamma cascade following capture, compared to 2.2 MeV for hydrogen. For example, a 0.1% concentration of Gadolinium, which has the highest neutron absorption cross-section of any element, reduces the capture time from about 200 microseconds to tens of microseconds relative to hydrogen, and increases to 8 MeV the neutron-related energy available for deposition in the detector (arising from neutron capture de-excitation gamma-rays).

For the relatively small detectors needed for near-field reactor safeguards it is also possible to use non-hazardous liquid scintillators, blocks of solid plastic scintillator coated with neutron capture agents, doped water Cerenkov detectors, and other approaches, all of which can improve deployability and ease of use of the system. For mid-field detection, strategies such as segmentation and improved particle identification may be of use for the more stringent background rejection requirements imposed by the reduced flux available beyond 1 km. For far-field detection of reactors (or nuclear explosions), only large homogeneous liquid scintillator or doped water Cerenkov detectors appear practical. Detection at the various ranges is discussed in the section describing near, mid, and far-field applications.

Aside from the neutrino oscillation effect that appears at very long ranges, the signal event rate falls off simply as the squared distance to the reactor or reactors, with no other attenuation effects even at Earth diameter standoff. However, as discussed later, relatively small systematic corrections to this oscillation, at the few percent level, may be revealed at the few kilometer standoff by a next generation of neutrino oscillation experiments.

Backgrounds depend in a more complicated way on overburden and nearby materials. Backgrounds are usually separated into "correlated" and "uncorrelated" types. Correlated backgrounds are those for which a single physical process is responsible for both the apparent positron and neutron signals, such as muon induced Lithium-9, or multiple neutron scattering. Uncorrelated backgrounds arise from two independent physical processes, such as two random gamma-ray interactions occurring within the time window that defines the antineutrino signal.

The cosmic ray muon flux, which is responsible for much of the correlated background, falls off exponentially with overburden. Overburden is usually expressed in meters of water equivalent (mwe). At distances relevant for near-field cooperative monitoring, out to approximately 1 km, overburdens ranging from 10–300 mwe have been shown to give sufficiently good signal to background ratios for precision measurements of the antineutrino flux at levels relevant for reactor monitoring applications. The KamLAND detector, currently the sole example of a dedicated far-field reactor antineutrino detector, with sensitivity to reactors at 200 km standoff and beyond, has an overburden of about 2700 mwe (or 1 kilometer of Earth).

For both near and far-field detection, an active muon "veto" system is often used to time-stamp the passing of muons through or near the main detector, allowing further rejection of muon-related backgrounds. These systems may consist for example of plastic or liquid scintillator read by photomultiplier tubes, and several other options have also been used.

Various combinations of lead and/or steel for gamma-ray attenuation, and polyethylene, water, and other materials for neutron attenuation are used as passive shields to reduce the uncorrelated backgrounds, which arise from local ambient neutrons and gamma-rays. The thickness of these shields are of the order 0.5–2 meters, depending on the signal strength and target signal to background ratio for the particular experiment. Since only a few experiments have been built specifically for cooperative monitoring, further optimization of shielding and overburden in the context of cooperative monitoring experiments is likely possible.

Antineutrino Detector Deployments Relevant for Reactor Safeguards

As seen in Table 1, a large number of experiments have successfully measured antineutrino events near nuclear reactors. This rich experimental history was inaugurated with the discovery of the antineutrino interaction at the Savannah River Site in the 1950s using the same organic scintillator technology that has become the standard for modern reactor antineutrino experiments.[27]

Following the discovery of the antineutrino, most of these experiments were built to search for evidence of neutrino oscillations, which appears as a deviation of the antineutrino flux from inverse square behavior, as a function of distance. Since there was little theoretical guidance on the oscillation spatial frequency, experiments were done at a range of different distances. The large number of experiments has provided a solid foundation of theory and experiment which can be applied to safeguards applications. Perhaps most important for near-field applications, the experiments have shown that oscillations do not affect the spectrum or inverse square behavior of the antineutrino flux out to approximately 1 km. This non-deviation is measured with absolute precision on the reactor antineutrino flux and spectra of the various experiments to the level of 2%. Experiments now being built, such as Double Chooz and Daya Bay, will improve the precision of flux and spectral measurements at these distance ranges. Additionally, the effect of isotopics on the antineutrino rate and spectrum has been clearly demonstrated by many of the earlier experiments. In some experiments, such as the first Chooz deployment, the direction of the antineutrino has been successfully reconstructed.[28]

Beyond the oscillation experiments, the Russian deployment at the Rovno complex in Ukraine and the U.S. deployment at the San Onofre Nuclear Generating Station in Southern California were deployed explicitly to demonstrate the feasibility of practical monitoring of reactors in a safeguards context with relatively small (cubic meter scale) antineutrino detectors. Results from these deployments are summarized below.[29]

The Rovno and SONGS1 Deployments

Russian physicists appear to have been first worldwide to recognize and exploit antineutrino detection as a tool for reactor monitoring.[30] Multiple basic and applied experiments were conducted over the course of many years, beginning in 1982, at the Rovno Atomic Energy Station in Kuznetsovsk, Ukraine. Independently, researchers at Lawrence Livermore National Laboratory and Sandia National Laboratories conducted a successful 2 year deployment of a safeguards demonstration detector at the San Onofre Nuclear Generating Station, a commercial PWR in Southern California. Together the experiments

Table 1: The characteristics of several previous reactor antineutrino detection experiments. The detector column includes the technique used, along with whether or not there was Pulse Shape Discrimination (PSD) in the electronics.

Experiment	Power (GW)	Mass (ton)	Distance (m)	Depth (mwe)	Detector	muon rate (s^{-1})	Deadtime (%)
ILL[1]	0.057	0.32	8.76	7	Helium-3 scintillator PSD	250	8
Gosgen[2]	2.8	0.32	38/46/65	9	Helium-3 scintillator PSD	260-340	8
Krasnoyarsk[3]	1.6	0.46	57/231	600	Helium-3 only	—	—
Bugey 3[4,5]	2.8	1.67	15/40/95	23/15/23	Lithium-6 scintillator PSD	—	2
SavannahRiver[6]	2.2	0.25	18.2/23.8	$\sim$10	Gadolinium scintillator PSD	—	—
CHOOZ[7]	4.4	5	1000	300	Gadolinium scintillator	1	2
Palo Verde[8]	11.6	11.3	800	32	Gadolinium scintillator	2000	2
KamLAND[9]	$\sim$80	408	$\sim$180,000	2700	Gadolinium scintillator	0.3	11
Rovno[10]	1.4	0.43	18		Gadolinium scintillator	350	7
SONGS1[11,12]	3.4	0.64	24.5	10	Gadolinium scintillator	600	10

[1] H. Kwon et al., *Phys. Rev. D. 24* 1097 (1981).
[2] G. Zacek, 2621 (1986).
[3] G.S. Vidyakin et al., *JETP Lett.* 59, 25 (1994).
[4] M. Abbes (1996).
[5] B. Achkar et al., *Nucl. Phys.* B 434, 503 (1995).
[6] Z.D. Greenwood (1996).
[7] M. Apollonio (1999).
[8] F. Boehm (2000).
[9] Eguchi (2003).
[10] A.I.Afonin et al., *Sov. J. Nucl. Phys.* 46, 944 (1987).
[11] N.Bowden (2007).
[12] N. Bowden et al., "Observation of the Isotopic Evolution of PWR Fuel Using an Antineutrino Detector" (2008) (http://arxiv.org/abs/0808.0698v1).

demonstrate the level of sensitivity now achievable with relatively simple detectors, as well as various practical aspects of deployment relevant for IAEA safeguards.

The SONGS1 and Rovno detectors both used Gadolinium-doped scintillator as the antineutrino target, a hydrogenous shield for screening out gamma-rays and neutrons, and PMT readout of the scintillation light induced by the positron neutron time-correlated event pair. The reactors were also similar: both are LEU-fueled PWRs, with 12–18 month fuel cycles. The physical locations of both detectors at their reactor sites are shown in Figure 8. The Rovno detector was deployed directly beneath the reactor core, providing excellent shielding from muogenic backgrounds and a convenient location about 18 meters from the core center. The SONGS detector was deployed in the reactor's "tendon gallery," an annular room that lies directly under the containment dome, and which allows access to steel reinforcement cables that extend through the containment structure. The gallery is 25 meters from reactor core center. Many commercial reactors have tendon galleries. They are well suited for deployment of an antineutrino detector because the large, vacant space is

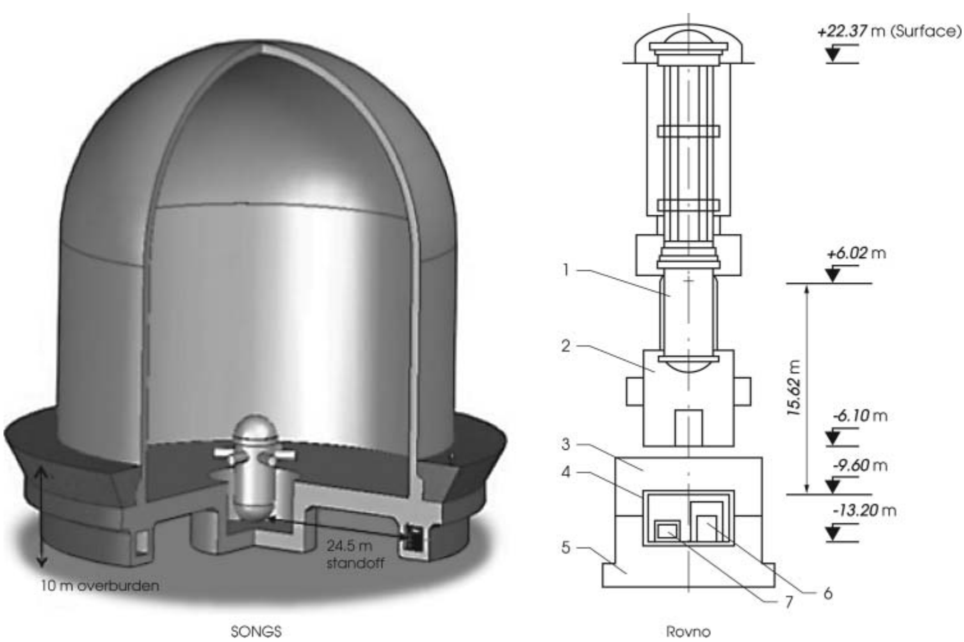

Figure 8: Left: The deployment configuration of the SONGS antineutrino detector at the San Onofre Nuclear Generating Station in California. The detector is located 24.5 meters from the center of the reactor core, directly beneath the containment dome. Right: The deployment configuration of the Rovno antineutrino detector, reproduced from Korovkin. The detector (item 6) is located directly below the reactor core (item 1), at a distance of 18 m from the core center and 35 m from the Earth's surface Left: (V.A. Korovkin et al., *Atomic Energy*, 56 (1984):233–239).

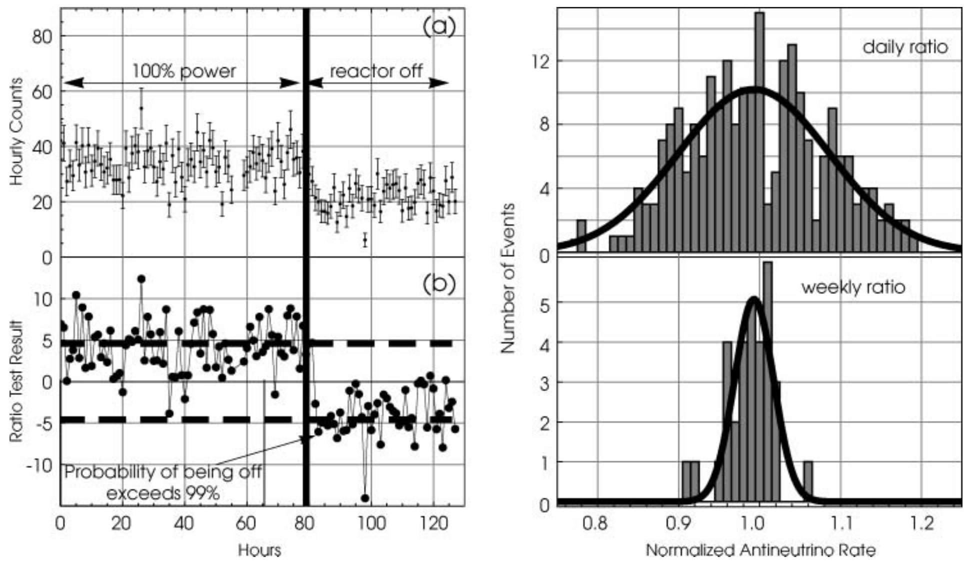

Figure 9: Left: (a): the hourly number of antineutrino-like events, plotted versus hour, through a reactor outage. (b): the value of the test statistic plotted versus hour over the same time range. In both plots, the vertical line indicates the hour in which the reactor shutdown occurred. The dashed lines in (b) are the 99% confidence level values of the test statistic, known as the Sequential Probabilistic Ratio Test. For this data set, these values are obtained only during the appropriate period (on or off), meaning that no false positives or negatives occurred. Right: Histograms of the daily and weekly detected antineutrino rate divided by the average of this quantity for the prior four weeks. Properly normalized, this relative metric gives a 3% accurate measurement of the reactor thermal power over the course of a month, limited only by counting statistics.

rarely accessed by plant personnel, and because of the muon-screening effect of approximately 10 mwe Earth and concrete overburden.

The key results from both experiments are the measurement of the reactor operational status, daily or weekly thermal power, and fuel burn-up through antineutrino rate or spectral measurements. The leftmost plot in Figure 9 shows a reactor turn-off as reflected in the hourly antineutrino count rate measured by the SONGS detector. A 99% confidence level confirmation of a change in the reactor operational status is determined within 4 hours.[31]

The rightmost plots in Figure 9 are histograms of the daily and weekly count antineutrino rate as measured in the SONGS detector, normalized to average weekly rate for the prior 4 weeks. This metric provides a relative estimate of the reactor power accurate to 3%. In an actual safeguards context, the burn-up effect would have to be removed using a reactor simulation. Aside from this effect, which is less than 1% over a month of operation for this detector and reactor, the main limitation on measurement precision is counting statistics.

Further precision can be obtained with a larger or more efficient detector, or by longer acquisition times provided that the reactor power was constant over the acquisition period. For comparison, thermal power measurements made at reactors by other means are accurate to the 0.5–2% level, depending on the measurement method.

Figure 10 shows antineutrino count rate measurements plotted versus cycle day from the SONGS and Rovno experiments. Both reveal the time dependent burn-up effect on the rate.

The change in the antineutrino spectrum over the course of the fuel cycle was also measured in the Rovno experiment. Figure 11 shows the ratio of the reconstructed antineutrino energy spectra in the Rovno detector at the beginning and end of the fuel cycle. The change in spectrum is most pronounced at the highest energies, consistent with predictions, and is caused by the net consumption of 521 kg of fissile material (both plutonium and uranium) over the course of the fuel cycle. While not directly quoting an uncertainty on this value derived from the antineutrino measurement, the Rovno group independently estimated fuel consumption from the reactor's thermal power records, and found a value of 525 +− 14 kg, close to the value estimated from the antineutrino spectral change.

In addition to demonstrating sensitivity to quantities of likely safeguards interest, these two experiments provide important examples of the simplicity and ease of operation of antineutrino detectors. Both demonstrated stable long-term unattended operation with a simple, low channel count detector design, non-intrusiveness to reactor site operations at a commercial power plant for several years, and remote and automatic collection of antineutrino data and detector state of health information. The detector location was completely removed from daily reactor operations, and no maintenance of the detector by site personnel was required. Only occasional detector maintenance was required, even for these non-optimized prototypes. All of these features indicate the potential utility of antineutrino detectors for IAEA safeguards, for which cost and simplicity of operation are essential considerations.

Worldwide Efforts to Develop Safeguards Antineutrino Detectors

Twenty-five years after the Russian demonstrations at Rovno, and several years after the first IAEA experts meeting on this topic, there are now many efforts underway around the world to explore the potential of antineutrino based reactor safeguards. These include programs in Brazil, France, Japan, Russia, Taiwan, and the United States. The evolution of these efforts is summarized in the agendas of annual Applied Antineutrino Physics (AAP) Workshops.[32]

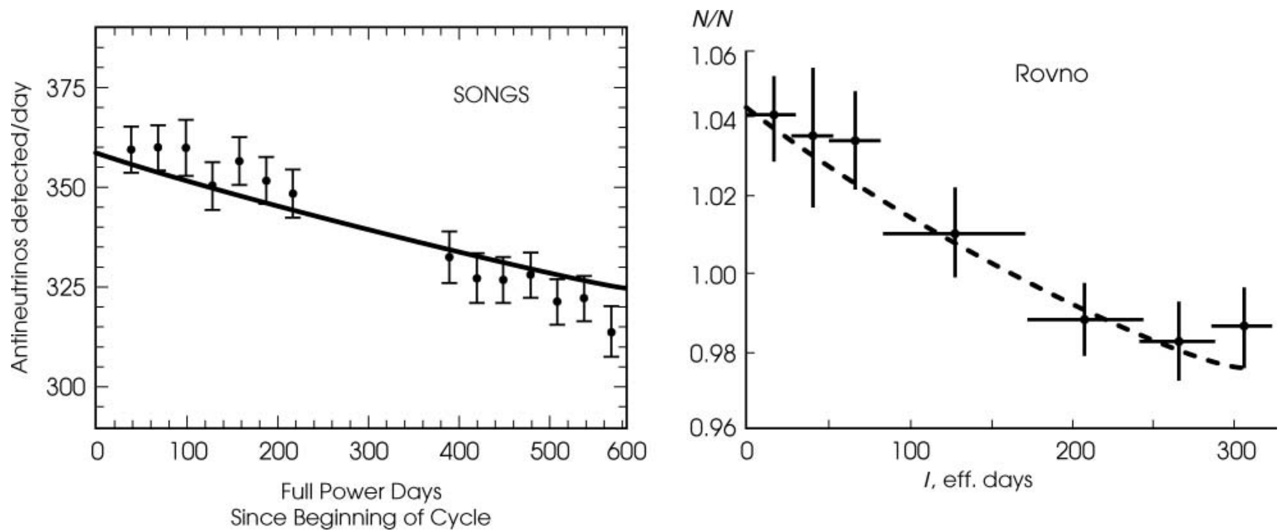

Figure 10: Two experiments demonstrating the existence of the burn-up effect on antineutrino rate. Left: the SONGS1 experiment. Data points, with statistical error bars, are the background subtracted antineutrino counts per day, averaged over 30 days, and plotted versus full power days in the cycle. In this experiment, the prediction and observation show an approximate 12% change in the count rate over the course of the 600 day cycle. Right: the Rovno experiment. The antineutrino rate N, normalized to the time average of the rate over the course of the cycle, plotted versus effective cycle day, for the Rovno experiment. The points with error bars are the data, the curve is a prediction based on a simulation of the reactor core evolution.

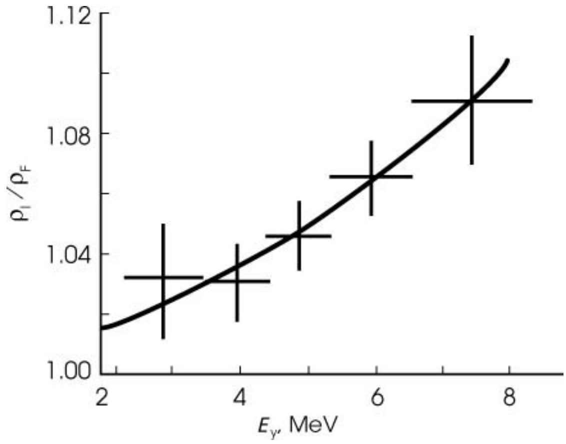

Figure 11: The ratio of beginning-of-cycle to end-of-cycle antineutrino spectra, as measured at the Rovno reactor. The points with error bars are the data, the curve is a prediction based on a simulation of the reactor core evolution. The result is reproduced from Klimov (1994). Figure provided by M.D. Skorokhvatov, RRC Kurchatov Institute, Moscow. Printed with permission.

Antineutrino Directionality

Directional information about antineutrinos is difficult to obtain. Using the inverse beta decay interaction, the Chooz collaboration has successfully reconstructed the direction of antineutrinos from a known reactor source with a pointing accuracy of approximately 20 degrees.[33] However, because of the stochastic relation between the antineutrino direction and the measured quantities in this detector, thousands of events were required to achieve this pointing accuracy. This number of events is incompatible with the low event rates required for discovery of small reactors in mid-field and far-field applications (1–500 km standoff distances). New methods of event-by-event reconstruction of the antineutrino direction are a key area of interest for long range applications.

Directional information can also be extracted from detectors that rely on Cerenkov light detection, such as the Super-Kamiokande detector.[34] The incident antineutrino direction is recovered by determining the apex and central angle of the reconstructed Cerenkov light cone. However, such detectors rely on antineutrino-electron scattering, which, as already discussed, is less suitable for security applications because of the smaller cross-section. This method also requires high statistics in order to reconstruct the source direction in an average sense.

Production of Antineutrinos in Fission Explosions

The burst of antineutrinos arising from a fission explosion arises from the same source as reactor antineutrinos: the chain of approximately six beta-decays that follow each fission. An unclassified picture of the antineutrino burst can be created using a few simple assumptions. First, unlike steady state reactors, all the fissions in the explosion are taken to occur within 1–10 microseconds. This must be true since criticality is maintained over time scales only of this order. For the same reason, the fissioning neutrons physically cannot have thermalized prior to the rapid disassembly (explosion) of the weapon. Therefore, the population of fission daughters, and the antineutrino energies are both characteristic of those produced by fast neutron fission. These two facts suffice to crudely define the important features of the burst: its number, energy and time distributions.

The total number of antineutrinos in the burst is directly proportional to the explosive yield.

$$N_{\bar{\nu}} \cong 6 \cdot N_{\mathrm{fiss}} \cdot Y \tag{3}$$

with

$$Y(\mathrm{kt}) \rightarrow \text{yield}$$
$$N_{\mathrm{fiss}} = 1.45 \times 10^{23} \rightarrow \text{number of fission/kt}$$

The antineutrino energy distribution is created by a fast neutron fission spectrum. Such a spectrum has been calculated theoretically by Vogel, (though not yet measured at a reactor or in an explosion).[35] Figure 12 shows the energy distribution of the antineutrinos emitted by a fission explosion, which in this simple approximation is that expected from a fast reactor.

The time distribution of the antineutrino burst is set by the half-lives of the fission products. These peak at relatively short times, ranging from a few milliseconds to a few seconds, with a long tail extending out to very long half-lives. Figure 13 shows an approximate time distribution of the events, based on the lifetimes of the known most probable fission daughters. The mean lifetime is about 2.5 seconds.

Detection of Antineutrinos from Fission Explosions

Summarizing the signal of interest, a detector must be capable of registering antineutrino events with energies up to about 8 MeV from a burst lasting a few seconds.

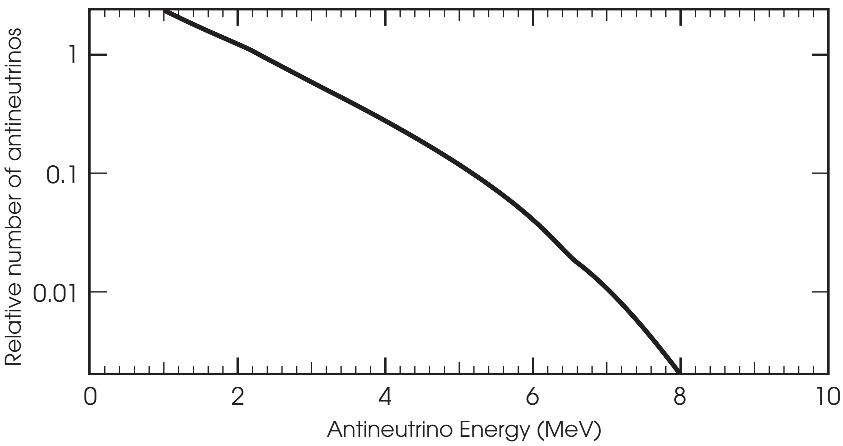

Figure 12: The approximate energy spectrum of antineutrinos produced in a Uranium-235 fission explosion.

Accounting for energy threshold, the number of events ($N_{\bar{\nu}}$) in an inverse beta detector as a function of yield Y, distance D and detector mass M is given by:

$$N_{\bar{\nu}} = 2.25\,\text{events} \times \left(\frac{\text{y}}{\text{kTons}} \times \frac{\text{M}}{10^6\text{Ton}} \times \left(\frac{100\,\text{kilometers}}{\text{D}} \right)^2 \right) \qquad (4)$$

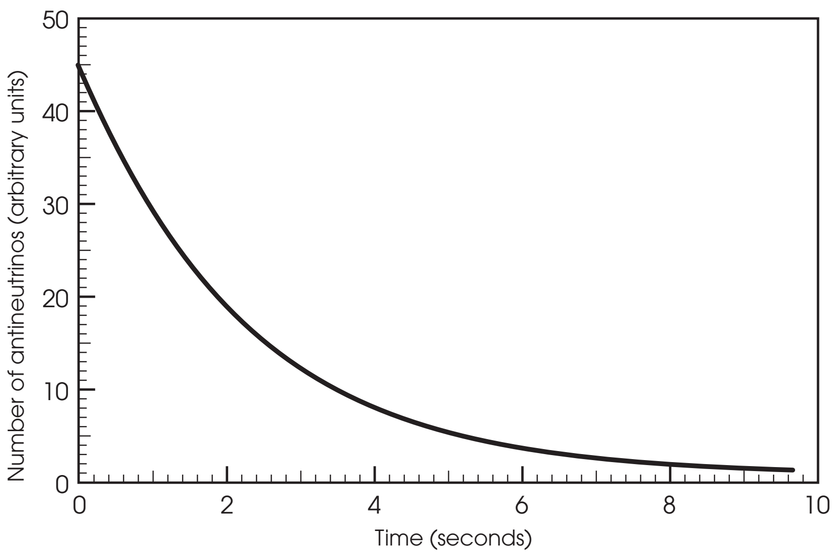

Figure 13: The approximate time distribution of the antineutrinos produced in a Uranium-235 fission explosion.

A water-based detector is assumed for the event rate estimate. Unfortunately this is a dauntingly small number. Equation 4 reveals that only about 2 events would be detected in a million ton detector at 100 kilometer standoff.

While the number of events is quite small, their burst-like nature is very effective for reducing backgrounds. However, as a result of this "antineutrino-starved" circumstance, only detection is possible, and that, clearly only with enormous effort. No spectral (or temporal) distributions are likely to be measurable in any realistic scenario.

In the penultimate section of this article we discuss the prospects and possible benefits of remote nuclear explosion monitoring with antineutrinos: a fuller examination may be found in Bernstein.[36]

NEAR-FIELD APPLICATIONS: SAFEGUARDS AND COOPERATIVE MONITORING

This section describes the goals and current protocols and technologies of the IAEA reactor safeguards regime, and then defines possible roles that antineutrino detection may play in this regime. Other operational concepts for cooperative monitoring beyond safeguards are also examined. The section concludes with a discussion of the R&D needs for future antineutrino-based near-field monitoring applications.

Current Reactor Safeguards Methods

The objective of the IAEA safeguards regime is "... timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons..."[37] The regime applies to all civil nuclear infrastructure, including commercial and research reactors. Since antineutrinos are produced in practically measurable numbers only by critical or supercritical systems, reactors are the only part of the IAEA safeguards regime for which antineutrino detection is potentially relevant.

"Timely detection" and "significant quantity" are essential elements of the IAEA safeguards regime. Table 2 shows the IAEA timely detection goals. These goals are based on the "conversion time," an estimate of the time needed to convert nuclear material of a given form into a weapon. A significant quantity (SQ) is defined as the amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. Table 3 shows the IAEA definition of a significant quantity.

IAEA safeguards methods divide into two categories:

1. **Nuclear material accountancy:** counting, examination, and direct measurements which verify the quantities and continued integrity of declared nuclear materials.

Table 2: IAEA timeliness goals for detection of diversion of nuclear material from reactors.

IAEA Timeliness goal	Material form
One month	Unirradiated direct use material (e.g., Highly Enriched Uranium (HEU),[1] separated plutonium, or MOX fuel)
Three months	Irradiated direct use material, (e.g., plutonium in spent or core fuel)
One year	Indirect use material (e.g., LEU)

[1]Greater than 20 percent uranium, enriched in Uranium-235.

2. **Containment and surveillance (C/S) measures:** C/S measures, such as video, tags and seals, and similar methods, are used to complement material accountancy methods.

Reactor safeguards activities vary according to reactor type, while possessing certain common features. At all reactors, safeguards begin with a Design Information Questionnaire (DIQ), provided by the State to the IAEA. The IAEA conducts an initial review and site inspection based on the DIQ information. The review consists of a comparison of the plant design documentation with the actual plant infrastructure relevant for safeguards. Throughout the lifetime of the reactor, the IAEA annually verifies the DIQ, in particular when the State reports any changes to reactor operations.

Once the reactor is online, the safeguards regime applies material accountancy and C/S measures to fresh fuel, in-core fuel, and spent fuel. The essential accounting methods are audits of plant operating records, in which the records are checked for consistency and compared with earlier reports to IAEA.

The IAEA verifies that fresh fuel shipped from a fabrication facility is identical to that received at the reactor, by comparing serial numbers on received fresh fuel against records of fuel shipments from the fuel fabrication facility. A similar procedure is applied for all materials shipped from the site. Shipments of spent fuel are closely scrutinized. Extra inspection trips are used if

Table 3: IAEA definitions for Significant Quantities of nuclear material.

IAEA Significant Quantity	Isotopic content
25 kg of Uranium-235 in HEU	HEU is defined as uranium with greater than 20 percent Uranium-235.
75 kg of Uranium-235 in LEU	LEU is defined as uranium with less than 20 percent Uranium-235 content.
8 kg of elemental Plutonium	Any isotopic mix of Plutonium except Plutonium with greater than 20 percent Plutonium-238.

necessary to verify the fuel integrity and check serial numbers of casks of spent fuel being shipped offsite or to onsite dry storage.

Beyond these common features, accountancy and C/S measures vary with reactor type.

LWR Safeguards

LWRs are distinguished by their fuel enrichment (typically LEU, 3–5% enriched) and by the property of off-line refueling. These factors mainly determine the IAEA safeguards protocols particular to LWRs. Off-line refueling means that the fissile material in the reactor is accessible only in reactor-off periods. These reactor outages are therefore the focus of much of IAEA verification activities at LWRs.

For fresh in-core and spent fuel, IAEA must verify every 3 months that no diversions of a SQ of Plutonium in core fuel and spent fuel have occurred, and must verify every year that no diversions of a SQ of LEU in fresh fuel, core, or spent fuel have occurred. The IAEA conducts Interim Inventory Verification (IIV) inspections at 3 month intervals to meet its Plutonium timeliness goal, and conducts a physical inventory verification (PIV) at LWRs once per year to meet its LEU timeliness goal. During the PIV, the IAEA verifies the presence of all nuclear materials onsite, and all shipments of nuclear material into and out of the site. Other inspections may occur during the year to verify movements of spent fuel to on-site wet or dry storage.

Declarations of Thermal Power

As part of the inspection process, the IAEA receives from the State an official declaration of the total thermal power generated by the plant since the last inspection period. The IAEA uses the power history of the reactor to analyze Plutonium production in the core. Although reactor power monitoring systems are available, and used in other reactor safeguards regimes (such as at research reactors, see below) these systems have not been implemented at LWRs as they have been found to be intrusive and difficult to maintain, with large cost and little benefit compared to C/S techniques.[38] Because of this expense and difficulty, the IAEA has no direct independent confirmation of the Plutonium ingrowth in the core beyond the internal consistency of the operator declarations.

Fresh Fuel and In-core Fuel Verification

During the PIV, the IAEA verifies the continued presence of fuel in the core by using an underwater camera to check serial numbers on fuel assemblies. The IAEA also counts the number of fresh fuel items, verifies their serial numbers, and randomly verifies a number of fuel assemblies to confirm that they contain uranium, using an approved statistical sampling plan. A gamma spectrum is measured, within which the 185 keV peak of Uranium-235 is identified, in order to verify the uranium content of the fuel. Once the reactor core is verified the IAEA depends on C/S, using a prescribed combination of seals on strategic hatches and canals in the reactor pool and surveillance cameras, to reassure that no tampering with the core fuel occurs until the next PIV.

Spent Fuel Verification

The IAEA also verifies and maintains Continuity of Knowledge (CofK) of spent fuel at LWRs. Spent fuel is the most attractive material from a proliferation standpoint since it contains the most Plutonium, is outside of the reactor, and thus more susceptible to diversion. During each PIV visit, the IAEA verifies the continued presence of spent fuel in the cooling pond using a night vision device tuned to the Cerenkov light spectrum emitted by the spent fuel. For old and/or low burn-up fuel with reduced Cerenkov output, the presence of spent fuel items is verified by spectroscopic detectors which detect the 662 keV gamma ray line from Cesium-137. Once the spent fuel pool is verified, the IAEA maintains CofK with surveillance cameras and in some cases by sealing the cover plates over the spent fuel pond.

Every 3 months the IAEA verifies the spent fuel for timeliness by verifying the functionality and integrity of surveillance equipment and seals. If no C/S system exists at the spent fuel pond, the IAEA must reverify the entire spent fuel pond every 3 months using Cerenkov or gamma-ray detectors.

CANDU Safeguards

At CANDUs, the main focus of safeguards is on accountability for spent fuel. As in LWRs, accounting records are audited during each visit and compared with past reports to IAEA. In addition, CANDUs are subjected to the following safeguards measures:

Verification of fuel in the core by continuously monitoring spent fuel discharges using a Core Discharge Monitor;

Counting and monitoring of spent fuel bundles as they are transferred from the vault to the spent fuel bay using Spent Fuel Bundle Counters. Where required, other vault penetrations are monitored to verify that all spent fuel is transferred to the spent fuel bay via the route containing the bundle counter;

Surveillance in the spent fuel bay. In addition, at some stations tamper-indicating containers of fuel are closed with seals as a complement to the surveillance system. At other stations, non-destructive assay instruments are used as a back-up for the surveillance system.

Since re-fueling of a CANDU occurs almost daily, permanently installed instrumentation is used to continuously monitor and track spent fuel movements. In contrast, because LWR cores are not usually opened more than once per year it is usually possible to apply IAEA safeguards seals to verify that the reactor pressure head remains closed between IAEA inspections.

Research Reactor Safeguards

Safeguards practices at research reactors vary considerably because of the diversity of core types and operational characteristics. Audits and C/S measures are pursued in a manner broadly similar to CANDUs and LWRs. However, a significant difference in some research reactor safeguards protocols is the use of Reactor Power Monitor (REPM), which monitors neutron levels, and the Advanced Thermo-hydraulic Power Monitoring (ATPM) which measures the flow and temperature differential on the primary coolant loop to verify core thermal performance. Since fuel in research reactors can be shuffled easily and targets positioned without any IAEA knowledge, there is potential in large (greater than 25 MWt) research reactors for unreported Plutonium production. This led to the creation and use of the REPM and ATPM. ATPM systems must be introduced into the coolant loop in the reactor in order to function.

Antineutrino-Based Reactor Safeguards Methods

The protocols just described rely in large part on C/S measures, operator declarations, and on so-called "item accountancy," which in this context refers to the counting of fuel assemblies or fuel rods. By contrast, antineutrino detection is a type of "bulk accountancy" method for directly estimating the amounts and rates of consumption and production of fissile material in the reactor core, in a manner that is nonintrusive to reactor operations, outside of containment, and under control of the safeguards inspectorate. These features provide a complementary set of capabilities that can further enhance the reactor safeguards regime.

The following examples show how the operational status, thermal power, and fissile inventory of reactors can be derived from the antineutrino rate and spectrum. The examples are suggestive but not exhaustive of how this information might be used in a safeguards context. In practice, each reactor type, LWR, fast reactors, CANDUs, and others, will require a specific safeguards analysis to establish the utility of antineutrino detectors within a particular safeguards protocol. Moreover, the full benefit of antineutrino-based safeguards metrics will be realized only by their integration with existing IAEA safeguards protocols. The specifics of this integration, while important, require direct assessment by safeguards experts, and are beyond the scope of this paper.

Operational Status

One reason to track the reactor power is to ensure that the reactor was not stopped and started with unusual frequency, or otherwise operated in a suspicious manner. For example, frequent shutdowns early in the fuel cycle could be indicative of attempts to recover low-burn-up fuel, from which plutonium would be easier to recover. The isotopics of such low burn-up plutonium are also somewhat more favorable for bomb design. This points to one possible benefit from antineutrino measurements: they can continuously and independently confirm the correctness of operator declarations of the reactor operating history between inspection periods. This type of measurement is of particular interest for off-line refueling reactors, such as LWRs or many research reactors. For example, the SONGS1 prototype detector, deployed at an LWR, has shown that shutdowns can be discovered with 99% confidence within 5 hours, and that a 20% change in the thermal power can be seen within about 15 hours.[39] On purely statistical grounds, provided similar signal to background rates could be achieved, the same sensitivity could be used for tracking the operational history of lower power reactors. For example, the SONGS sensitivity could be achieved at a 140 MWt reactor provided all detector conditions were identical, but with a deployment location 5 meters from the reactor core.

Power

IAEA does not currently use power monitoring technologies at power reactors because of the intrusiveness and cost of these systems. Instead, the agency relies on the reactor operators' formal declarations of power throughout the fuel cycle to estimate core fissile inventories at the end of cycle. By contrast, antineutrino rate or spectrum measurements offer a means for the IAEA to independently check operator power declarations. Antineutrino rate measurements provide a non-intrusive, real-time estimate of instantaneous and integrated thermal power, folded with a correction term that explicitly depends on the burn-up. The power measurement is derived by dividing the measured antineutrino rate in Eq. (1) by the time dependent parameter k(t) which tracks the burn-up effect. If k(t) is completely unknown, the uncertainty in the power may be as high as about 10–12%, which is the size of the burn-up effect. If k(t) is provided by the operator, the precision on a *relative* measurement of thermal power—that is, relative to a power measurement initially verified by other means—has been demonstrated at the 3% level with a simple detector, limited only by counting statistics and after correcting for burn-up.[40] Additional improvement on the precision of the relative power measurement, approaching the 1–2% level, could be obtained with larger or more efficient detectors than the prototypes so far deployed.

With or without fuel burn-up information, an estimate of the reactor power derived from the antineutrino rate can be used to place an upper bound on the total amount of fissile material that could have been produced in a given period of time. This might be used at some research reactors under IAEA safeguards. Unlike a power estimate derived from the antineutrino spectrum, discussed below, this approach depends in part on operator declarations. However, it does provide an additional consistency check on the correctness of the operator declarations, and makes it more difficult for the operator to run the reactor in a fashion different than that declared to the IAEA.

Constraints on Isotopic Content Based on Antineutrino Rate Measurements

As introduced in the previous section, a reactor's fissile content throughout the cycle can also be estimated or constrained, using the measured $N_{\bar{\nu}}$ antineutrino rate. If only rate information is available, additional inputs are required to extract and estimate the fuel geometry: the initial fuel enrichment and isotopics, the reactor thermal power, the detection efficiency, and the predicted fissile isotopic evolution must all be known. Each of these inputs has associated uncertainties which limit the overall precision with which the fissile isotopic content can be estimated in an absolute sense. Historically, the total integrated absolute flux of antineutrinos emitted by a thermal reactor has been shown to be both predictable and measurable to an uncertainty of about 2%.[41] Recent work indicates that the uncertainty in the predicted flux can be further reduced to below 1%, based on improvements in the thermal power measurement methods available at some reactors, as well as a more comprehensive validation of the precision of the burn-up simulation codes.[42] For safeguards purposes, a measurement made relative to a known startup fuel content may suffice, in which case many of these uncertainties are reduced or eliminated.

A simple method for constraining the isotopic content is to compare a predicted antineutrino count rate trajectory over the course of a single cycle to the count rate evolution measured in a safeguards antineutrino detector, using a hypothesis test to assess the significance of the deviation. With this method, the safeguards inspector can confirm that the plutonium content is not changed outside of an envelope determined by the specific operating conditions of the reactor and the experimental limits of the detector. A recent analysis has shown that with an antineutrino event rate of 2000 counts per day, assuming negligible backgrounds, the replacement of ten assemblies bearing about 70 kg of Plutonium-239 with fresh fuel assemblies containing no plutonium could be detected with 90 days of accumulated antineutrino count rate data.[43] The required antineutrino detection efficiencies have been achieved in past experiments, including the Rovno experiment.

The method just described requires a baseline predicted antineutrino rate to be compared with the rate measured in the antineutrino detector. Coupled reactor and detector simulation codes, or template-based measurements can be used to provide the baseline prediction. Open source reactor and detector simulation codes are available with little restriction. Proprietary reactor simulation tools, which most accurately represent the isotopic evolution of the core, may in principle be available for safeguards inspectors, but their use represents an additional practical obstacle in a monitoring context. However, members of the KamLAND collaboration have demonstrated that the evolution in the antineutrino rate for Japanese PWRs and Boiling Water Reactors (BWRs) can be described with simple four-parameter equations, one per reactor type, which reproduce the results of full reactor core evolution simulations to within 1%.[44] This implies that detailed simulations of the fuel burn-up may not be necessary at each reactor in order to predict the antineutrino rate (or spectrum). Assuming this approach is extensible to other reactors, as is likely, it considerably simplifies the analysis of antineutrino data in a safeguards context.

The antineutrino count rate prediction also depends on a detector simulation. This is an important consideration, since systematic errors in the predicted detector response could lead to incorrect antineutrino count rate predictions, which would of course undermine the comparison with data. To avoid sensitivity to systematic errors in predicted response, a good alternative is to acquire real antineutrino data from an earlier cycle at a reactor of interest. This antineutrino count rate evolution over the course of the cycle is used as a template for comparison to subsequent cycles. This approach has the advantage that it accounts for systematic shifts in detector response, since these are automatically measured when the template data are acquired. The KamLAND analysis just described, which examines predicted antineutrino emission rates at a range of reactors, indicates that such a template is likely to be robust to small changes in fuel loading or other reactor parameters, such as boron concentration, that may occur from cycle to cycle. The approach does require that the initial template data be known by other means not to have arisen from anomalous operations, so that the baseline count rate evolution can in fact be considered standard. It also requires that the detector response be stable at the 1% level across multiple cycles. This has been demonstrated by both the SONGS1 and Rovno deployments.

The above approach tracks anomalous operations within a single cycle only. It does not directly address diversion in the sense meant by the IAEA, which includes a full inventory of fresh, in-core, and spent fuel throughout the reactor site. In an actual safeguards regime, information derived from the antineutrino detector will be used in conjunction with other safeguards methods to determine the absence of diversion of a significant quantity of fissile material. To determine the marginal utility of antineutrino monitoring in this context, it is useful to evaluate how the presence or absence of antineutrino rate information affects the ability to detect diversion in specific scenarios. One study has shown a 3-fold improvement in the probability of detecting diversion at a reprocessing plant, when inventory information derived from a SONGS1-style antineutrino detector is used in conjunction with other safeguards information, compared to a scenario in which this information is not available.[45] In this strawman diversion scenario, the antineutrino detector measured a 5% power increase, which resulted in the presence of an otherwise unaccounted for significant quantity of plutonium (8 kg), assumed diverted at a downstream reprocessing facility. This example, while useful, is illustrative only, and does not fully reflect the complexity of reactor safeguards, including such issues as the long residency times and large uncertainties in the fuel content of spent fuel cooling ponds at reactors. One of our key recommendations below is for the IAEA or a Member State safeguards expert to perform more detailed and realistic studies of how the information provided by antineutrino detectors can be used to improve sensitivity to diversion within the reactor safeguards regime.

Isotopic Content Based on Antineutrino Spectrum Measurements

As long as integral flux (i.e., antineutrino count rate data) alone is used to estimate plutonium inventory, both relative and absolute measurements would still require independent knowledge of the reactor thermal power, since it serves as a free parameter that could be used to tune the antineutrino rate and mask the burn-up effect. By using the full antineutrino energy spectrum, fissile inventories can be independently confirmed, with little or no input from the reactor operator. This is a considerable advantage in a safeguards context compared to flux based measurements. Measurement of a spectrum does require a somewhat more sophisticated detector and analysis than a simple counting detector. However, spectral measurements are regularly performed in reactor antineutrino experiments, including the Rovno safeguards demonstration.

Plutonium and uranium isotopic content and power can be derived from a fit to an integral antineutrino energy spectrum, taking the unknown fissions fractions and the thermal power as free parameters. Huber et al. estimate that the Plutonium content in a typical LWR cycle can be estimated to within 10%, or about 40 kg of Plutonium (Plutonium-239+Plutonium-241), by measuring the antineutrino spectrum with 10^6 events, assuming current 2% uncertainties in the predicted antineutrino energy spectra, and a 0.6% uncertainty in detector response.[46] The 0.6% systematic uncertainty in detector response has not yet been achieved, though the Double Chooz experiment, now being deployed in France, has set this level as a target. A three-fold reduction in the spectral uncertainties would lead to a 20 kg estimate of total fissile Plutonium content. This method requires no prior assumptions about reactor power or the fission fractions. A further refinement to this approach is to constrain the fit by a direct comparison throughout the cycle with the expected spectra based on a detailed simulation of the reactor core evolution.

After Rovno and SONGS: Demonstration Safeguards Projects

The Rovno and SONGS1 deployments both clearly demonstrate many of the expected requirements for antineutrino-based safeguards. They show that antineutrino detectors can extract measurements of direct safeguards interest for years at a time, without affecting plant infrastructure or interfering with plant personnel activities. The relatively simple design of the detectors, with their low channel counts, readily available raw materials, and low maintenance requirements, demonstrates that IAEA criteria for low cost, simple unattended remote monitoring capabilities can all be met. While absolute detection of significant quantities of fissile material have not yet been achieved with antineutrino detectors alone, initial studies indicate that the additional information provided by antineutrino detectors, in conjunction with other safeguards information, can constrain fissile content at the few dozen kg level, and improve ability to detect diversion in specific scenarios. Additional R&D may further improve the utility of antineutrino detectors for safeguards, as considered later in this section.

A logical next step from these efforts would be a deployment of a detector at an IAEA safeguarded facility in a non-nuclear weapons state, preferably with the direct involvement of IAEA. Such a deployment would represent an important advance beyond the earlier safeguards demonstrations, by serving as a pilot project and an example for IAEA safeguarded reactor facilities worldwide. Valuable information on integration of antineutrino detectors into the modern reactor safeguards regime would be gained from such a test deployment.

Beyond Safeguards

Aside from the existing IAEA safeguards regime, other existing or future cooperative near-field monitoring regimes might benefit from antineutrino detection. Examples include tracking the progress of plutonium disposition in reactors, verifying the cessation of fissile material production at a previously active reactor site for the Fissile Material Cutoff Treaty or similar regimes, or verifying core conversion in plutonium production reactors in weapons states. Monitoring the disposition of excess weapons materials in reactors is one example of a verification problem beyond safeguards that might be addressed with antineutrino detectors.

"Plutonium disposition" refers to the management of separated weapons-grade plutonium inventories declared excess to military needs by the United States and Russia. As defined in a 1994–1995 National Academy of Sciences study, an important goal for any plutonium disposition program is to comply with the "Spent Fuel Standard."[47] The Spent Fuel Standard requires that separated surplus military weapons-grade plutonium is converted into a physical form from which it is as difficult to recover plutonium as from ordinary commercial reactor spent fuel.[48] One proposed way to meet this Standard is to

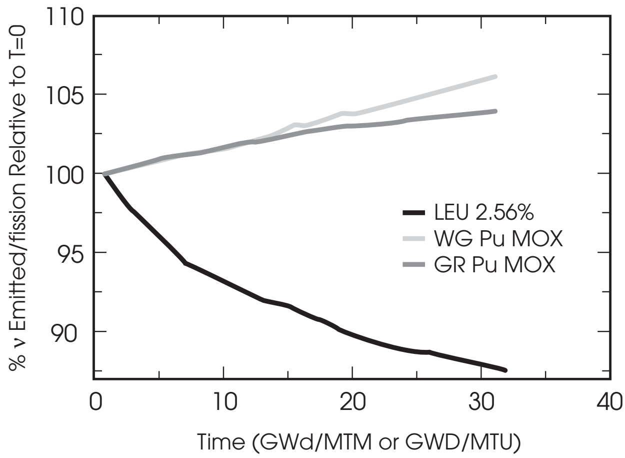

Figure 14: The variation in the emitted antineutrino flux from a PWR, according to fuel composition. The abscissa units are Gigawatt-Days per Metric Ton of Heavy Metal GWD/MTM or per Metric Ton Uranium (MTU)). The difference between LEU-fueled (black) and MOX-fueled (gray) cores is evident in the changing antineutrino rate. The distinction between weapons-grade (WG) and reactor-grade (RG) fuels may just be visible in high burnup conditions (greater than 20 GWD/MTM). The plot is from Hayes (2006).

convert the weapons-grade plutonium into MOX fuel, where the mixture typically contains 5% plutonium and 95% natural or depleted uranium, and to irradiate this fuel in a commercial reactor. In this context, antineutrino detectors could be used to verify that a reactor is actually burning weapons plutonium and not a substitute such as LEU fuel, or other separated MOX fuel not derived from weapons material. Figure 14 shows the predicted variation in antineutrino rate for a PWR operated with LEU, and with MOX fuel composed of either reactor-grade or weapons-grade plutonium. The weapons-grade plutonium used in this simulation contains 94% of the fissile isotope Plutonium-239, and the reactor grade plutonium contains 52% Plutonium-239. A detailed simulation of the evolution of the reactor fuel composition was used to predict the variation in antineutrino rate.[49] Since the absolute errors on rate are at the 2% level, changes between LEU and MOX should be clearly visible in an antineutrino detector, while changes in the isotopic mix of plutonium are at the current limit of sensitivity for antineutrino detectors.

R&D Needs for Near-Field Antineutrino Detectors

R&D needs for near-field applications divide into three broad categories:

1. Performing detailed systems analyses for IAEA safeguards and other cooperative monitoring applications in order to clarify how antineutrino detectors can be used in each area.

2. Improving sensitivity to anomalous changes in fuel loadings or reactor operations.
3. Improving the ease of deployment and operation of safeguards antineutrino detectors.

As with many applied physics efforts, the tension between the need for increased sensitivity and practical deployment concerns are the focus of much current R&D. For example, surface deployment is highly desirable from a practical standpoint, but greatly complicates detector design. However, because the technology is already demonstrated to work at a practical level, we view category 1 as the greatest unmet R&D need.

Below is a summary list of useful R&D directions for each of the above categories. A more detailed R&D roadmap, including a fuller discussion of prioritization, is found in Bernstein.[50]

1. **Safeguards Analysis R&D.** The study of diversion scenarios is a common methodological framework for evaluating the effectiveness of safeguards techniques. More study is needed to assess the benefits of antineutrino detectors for all cases of interest to IAEA. Performance against CANDUs, breeder reactors, and research reactors of various designs must be evaluated, as well as the effect of combining antineutrino-based metrics with other safeguards information. Understanding of the safeguards regime, along with a thorough command of the performance and limitations of antineutrino detectors is required for such analyses. Because of the newness of this technology to cooperative monitoring applications, antineutrino researchers and IAEA experts must work together to develop a more mature set of analytical tools and personnel capable of using these tools. A similar analytical framework is required to examine possible additional uses of antineutrino detectors outside of the current IAEA safeguards regime, for applications such as plutonium disposition, verification of a Fissile Material Cutoff Treaty, and others.
2. **R&D leading to Sensitivity Gains.** The following R&D paths, if successfully developed, would provide useful gains in sensitivity of antineutrino detectors.

   - Improvements in detector design, including increased efficiency from the current standard for a safeguards prototype detector (Rovno) of 30%, improved background rejection through methods such as particle identification, and reduction in detector systematic errors from the current $\sim$2% level to below 1%. The forthcoming Double Chooz experiment has a set a target single-detector absolute systematic uncertainty of 0.6%.[51]

- Development of a comprehensive code package that combines all the elements needed for complete simulation of antineutrino spectra. Currently, the isotopic evolution simulation packages are normally decoupled from codes that reproduce antineutrino spectra. A more comprehensive treatment, as outlined and initiated by the MCNP Utility for Reactor Evolution (MURE) project, is to build the spectrum on a per-fission basis, accounting for each individual fission products' contribution to the total spectrum.[52]
- Reduction in the absolute uncertainties in the predicted spectra of antineutrinos emitted per fission by each isotope beyond their current 2% level. This may be accomplished by a combination of more accurate experimental measurements of fission electron spectra, and improved analytic or Monte Carlo treatment of the process by which these electron spectra are converted to antineutrino spectra.[53] An analysis by Huber[54] has shown that a three-fold reduction in the absolute spectral uncertainties would result in a 20 kg (2.5 significant quantity) uncertainty on the absolute quantity of fissile plutonium in a PWR as derived from a spectral analysis. In the limit, with no uncertainty on the spectra of individual isotopes, the plutonium content could be determined to the significant quantity level, using only antineutrino information. While the absolute uncertainty in the spectra will never be zero, a relative cycle-to-cycle comparison of directly measured antineutrino spectra at a given reactor could effectively reduce the systematic effect of incorrectly measured spectra.

3. **R&D to facilitate deployment.** The SONGS and Rovno experiments have already demonstrated practical detectors suitable for near term use in a safeguards context. Nonetheless, there are a variety of methods for improving the ease of deployment and operation. The R&D avenues listed below would improve the ease of deployment and operation of antineutrino detectors.

- Development of detectors with improved safety and deployment characteristics compared to current liquid scintillator standard.
- Operating detectors at sea-level rather than underground.
- Shrinking the overall detector footprint including shielding.

While space does not permit discussion of all approaches, the Applied Antineutrino Physics conferences and literature contain much more information on these and other R&D activities worldwide.[55]

MID-FIELD APPLICATIONS: DETECTING AND MONITORING REACTORS FROM 1–10 KM

This section presents detector characteristics and performance at the two extremes of the defined mid-field deployment range—one kilometer and ten kilometer standoff. Signal and background performance targets are compared with results achieved in existing experiments. With sufficient overburden, existing technology allows deployment of detectors sensitive to 10 MWt reactors at one to ten kilometer standoff distances. Possible improvements in background rejection capability are discussed, which might be obtained with more sophisticated detection methods. A fuller discussion of mid-field detector design may be found in Bernstein.[56]

Detection and monitoring of reactors in the mid-field, between one kilometer and ten kilometers, is complicated primarily by the substantially reduced antineutrino flux compared to near-field monitoring. Depending on the outcome of current experiments the phenomenon of neutrino oscillations may also affect mid-field cooperative monitoring, through a few percent additional reduction in the observable electron antineutrino flux. Past oscillation experiments leave open the possibility of a systematic flux deficit due to oscillations as large as $\sim$15% relative to the predicted flux assuming no oscillations.[57]

In the mid-field, as for the near-field, we assume a cooperative monitoring regime which permits deployment of a detector at a suspect site. The aim may be to demonstrate that a country is not operating unknown illicit reactors, or that a known reactor or set of reactors is non-operational. Based on event rates and statistical considerations, these capabilities are the likely main focus of any future mid-field monitoring regimes. As shown below, precision power and fissile content monitoring require higher event rates than are likely to be accessible with practical detectors.

Of course, other methods exist for remotely verifying the operation or non-operation of known reactors, including thermal and visible wavelength satellite surveillance, monitoring of tritium releases and other radionuclides, and even actual destruction of infrastructure, such as was performed in 2007 (cooperatively) in North Korea.[58] Satellites and air or water borne radionuclides may also be used to search for unknown reactors. Within this context, the advantages of antineutrino based monitoring in the mid-field are similar to those claimed for near-field monitoring. The signal is an inevitable and unique indicator of the presence of an operating reactor, and can't be masked except by other reactors, nor imitated by any source other than reactors. Therefore, aside from destroying the reactor, the other approaches mentioned are more susceptible to masking or spoofing than antineutrino-based monitoring. For example, a determined proliferator could divert heat from a small reactor with underground cooling or other means, while radionuclide releases are susceptible to weather patterns, or might be captured to frustrate detection.

Reactor Signal and Background in the Mid-Field

Following a prescription set forth earlier, we assume a reactor power of 10 MWt. For simplicity, we also assume that no other reactors are contributing to the background, although the analysis is easily modified to incorporate this possibility. At 1 kilometer standoff from a 10 MWt reactor, a 100 ton fiducial mass detector would detect approximately 1 event per day. At 10 kilometer standoff from a 10 MWt reactor, a KamLAND-like antineutrino detector (1000 ton total mass, and 408 ton fiducial mass) would detect about one event per month. The KamLAND detector is shown in Figure 15.

For both standoff examples, the intrinsic detection efficiency for antineutrinos is assumed to be 85%, similar to the demonstrated efficiency of the KamLAND detector. Assuming no observed events, a background-free detector with an expected signal rate of 1 event per day or month, would allow exclusion at the 95% confidence level of a reactor at 1 and 10 kilometer standoff distances within 3 days or 3 months respectively. This conclusion remains valid as long as the expected background rate is comparatively low. For example, close to

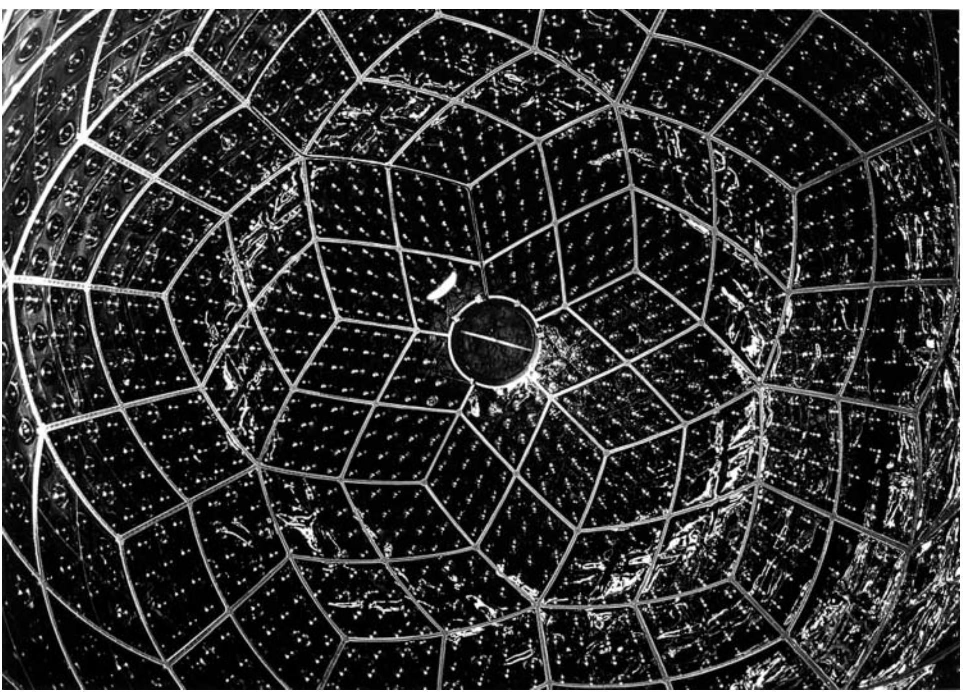

Figure 15: The KamLAND Detector: Buried 1 kilometer under the Earth, in an old mine northwest of Tokyo, KamLAND is the largest scintillation detector ever constructed. KamLAND is highly instructive for remote monitoring applications, since it unambiguously demonstrates long range reactor monitoring—albeit with reactor powers higher than those of likely interest in nonproliferation contexts. In particular, KamLAND clearly measures antineutrino flux from reactors in Japan and Korea at hundreds of kilometer standoff.

Table 4: Background rates achieved in the CHOOZ and KamLAND detectors.

Detector	Fiducial Mass (ton)	Overburden (mwe)	Total background rate	Correlated muogenic background rate	Accidental background rate
KamLAND 2003[1]	408	2700	0.4 per month	0.4 per month	0.002 per month
KamLAND 2006[2]	706	2700	5.5 per month	4 per month	1.6 per month
CHOOZ	5.5 ton	300	2 per day	1.8 per day	0.5 per day

[1]Eguchi (2003).
[2]S. Abe et al., *Phys. Rev. Lett.* 100 (2008): 221803.

95% confidence would still be achieved in the same time windows with 0.5 or fewer background events per day or month at 1 and 10 kilometer standoff respectively. The KamLAND reactor antineutrino experiment demonstrates that detectors of the necessary size and background rate for the entire range of mid-field detection can be built with current technology.

To further understand the performance and scaling properties of mid-field reactor monitoring detectors, it is useful to consider the KamLAND backgrounds in more detail. KamLAND background rates from two different analyses are summarized in Table 4. The CHOOZ detector background rates are also shown for comparison.

As shown in Table 4, backgrounds may be divided into correlated (muogenic) and uncorrelated or accidental backgrounds, with the accidental backgrounds arising primarily from radioactive elements within and surrounding the detector. At KamLAND depths, backgrounds are seen to be dominated by the correlated muogenic events, which include spallation neutrons and various long-lived activation products. The relative suppression of accidental backgrounds is especially pronounced if a severe fiducial mass cut is made, as was done in the first KamLAND analysis.[59] Below a few meters of overburden, after which the hadronic components of the cosmic ray background are screened out, backgrounds scale primarily with the underlying muon rate. Since higher backgrounds than were achieved in KamLAND can be tolerated at kilometer standoff distances, the most expedient simplification relative to the KamLAND design is to bury the detector at a shallower depth, in order to reduce excavation costs.

For example, in order to achieve a target background suitable for 1 km monitoring, of approximately 0.5 event per 100 ton mass per day, the required depth is about 600 meters (1600 mwe), which is about the depth of the neutrino experimental halls at the Waste Isolation Pilot Project plant (WIPP) site in Carlsbad, New Mexico.[60] Figure 16 shows the scaling of muon flux for various experiments as a function of depth.

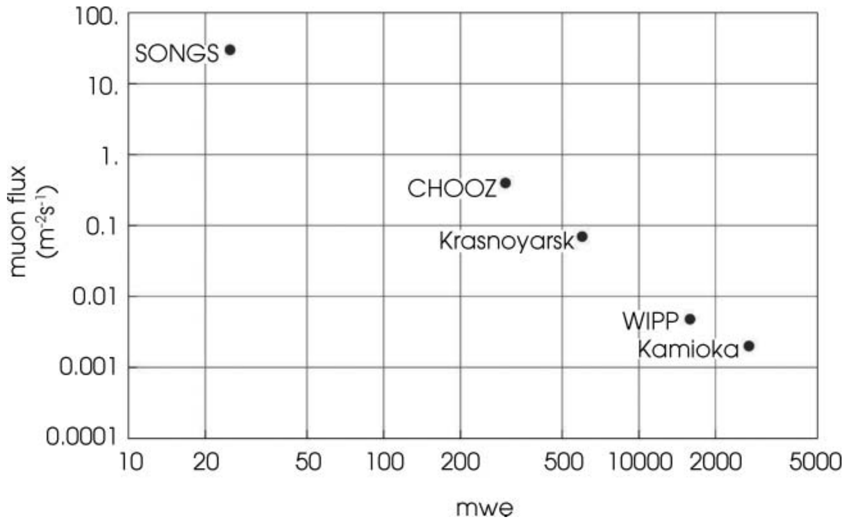

Figure 16: The muon intensity per square meter and second at various underground experimental sites worldwide, plotted versus the depth of the experiment in mwe. Kamioka is the site of the KamLAND antineutrino detector. WIPP is the Waste Isolation Pilot Project underground site in Carlsbad, New Mexico. Further information on the other experiments can be found in Table 1.

The Effect of Reduced Overburden on Backgrounds and Detector Performance

Throughout the 1–10 km mid-field range of interest, existing and proven designs such as KamLAND could be adapted for cooperative monitoring purposes with little or no modification, provided only that suitable underground deployment sites were available. However, excavation costs makes up a large or even dominant fraction of the total cost of buried detectors. For example, the Braidwood neutrino oscillation experiment estimated a $23 million construction cost of four detectors comprising 260 tons fiducial mass, compared with a $35 million cost for two shafts and experimental halls at a depth of 450 mwe.[61] Therefore, for reasons of expense and ease of deployment, it would be preferable to deploy on or near the Earth's surface. In shallow or surface deployments, the detector would have to be designed to allow rejection of the large backgrounds due to cosmic radiation. Compared to near-field deployments, this problem of above-ground or shallow-depth detection is made considerably more difficult by the larger detector size and reduced event rate. It is also important to note that while reducing overburden is a strong cost consideration, the channel count and complexity of the detector can also considerably raise construction and operating costs. The following discussion is meant to explore some of the detector-related considerations in this trade-off, rather than prescribing a specific path to deployment. In some cases, burial will remain the simplest and most cost-effective approach.

The background radiation at or near the surface of the Earth is composed of cosmic and terrestrial components. The terrestrial component, arising primarily from decays of uranium, thorium and potassium, and other radionuclides, depends strongly on the composition of local materials, but does not differ much from that in existing underground antineutrino detectors. For inverse-beta detectors, the relative rates from KamLAND and Chooz in Table 4 show that internal backgrounds can be kept at or below the level required for mid-field monitoring. While care must be taken to ensure pure materials and to control contaminants such as radon, the ambient radioactive component of the background does not present any unsolved technical challenge, and need not be considered further. The muonic component of the cosmic background at shallow depths is increased by about 3–4 orders of magnitude relative to the KamLAND depth. This steep dependence on overburden is seen in Figure 16. In addition to the increased muon rate, a significant change in the character of the cosmogenic backgrounds occurs in the last 5–10 mwe of overburden near the Earth's surface. Only about 63% of the cosmic ray flux at the Earth's surface comes from muons, the rest comes from neutrons, electrons/gamma-rays, and other hadrons. Below roughly 5 mwe, the muonic component of the backgrounds dominates the total flux, since most of the hadronic flux has been screened out. In this circumstance, the cosmogenic antineutrino-like background arises primarily from secondary fast neutrons induced by these muons as they pass through the detector and nearby materials. Above 5 mwe, temporally complex and spatially extended cosmic ray showers arising from hadronic interactions further complicate the background rejection problem.

In small detectors, the charged components of the cosmic ray background (muons, electrons, protons, and pions) are relatively easy to suppress using thick passive shields or veto techniques, while maintaining good signal efficiency. For 100 ton or 1000 ton scale detectors, however, the need to veto signals arising from typical cosmic ray fluxes of $1 - 2 \times 10^2\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$, with veto windows having typical durations of 100 microseconds or more, quickly increases dead-time to intolerable levels. For example, a cubic 100 ton scintillator detector at the Earth's surface would have a 65% dead-time arising from muons alone, assuming a 100 microsecond veto window. A cubic 1000 ton detector would have 100% dead-time with the same veto window.

Part of the background in a surface detector arises from the secondary neutrons produced by hadronic interactions in the atmosphere, and by muon interactions with surrounding materials. At sea level, the cosmogenic secondary neutron flux is some 100 times greater than it would be after only about 4 m of rock overburden. These high background rates confirm that the leading problem in designing a surface or near-surface midfield detector is to suppress cosmogenic backgrounds in the detector, and that simple veto strategies will not suffice due to the dead-time these strategies incur.

Summary for Mid-Field Applications

This section reviewed some of the technical issues associated with deploying a large inverse beta decay detector at or near the surface that would be useful in a mid-field detection scenario (1–10 km). Existing detectors such as KamLAND could be used for discovery or exclusion of small reactors throughout the mid-field, provided they are relatively deeply buried (100 of mwe). Costs associated with excavation are reduced with the use of detectors with improved background rejection for the dominant cosmogenic backgrounds, which increase quickly towards shallower depths. Since at these depths local detector shielding alone is insufficient for reasons of dead-time, we require improved specificity for the antineutrino signal, reducing dead-time and backgrounds, and thereby reducing overburden requirements in the mid-field. The directions considered most promising are:

- Reducing dead-time by vetoing only segments of the total detector rather than the entire detector.
- Improved identification of the particle types for the initial and final state positron and neutron.

A fuller discussion of background rejection, and an example of a possible segmented design, is found in Bernstein.[62]

FAR-FIELD APPLICATIONS: DETECTING REACTORS AND EXPLOSIONS AT 10–500 km

The distinguishing features of far-field applications are:

1. Detector sizes are tens of kilotons for tens of kilometer reactor standoff distances, hundreds of kilotons for hundred kilometer distances, and 100 megatons for 500 kilometer distances.
2. Event rates are of the order of a few per month for the small reactors of likely interest, even in very large detectors.
3. Neutrino oscillations must be taken into account.
4. Detector related backgrounds, and real antineutrino backgrounds from other reactors play a more important role.
5. Unlike near-field and mid-field applications in which there are examples of detection capability down to 10 MWt reactor power, no antineutrino

Table 5: Required fiducial detector masses for several possible remote reactor monitoring goals for 10 MWt reactors. 1000 ton scale liquid scintillator antineutrino detectors (KamLAND, Borexino) exist now; 10,000 ton (10 Kton) detectors are a straightforward extrapolation of this technology and are now being developed by several groups worldwide. 1,000,000 ton (1 megaton) Water Cerenkov detectors are also being considered by several groups for fundamental physics studies. 100 megaton detectors are not currently being considered. For the first two options, the background is assumed to be 1 event per year from all sources. Relative to the KamLAND detector, this would require background suppression by factors of 10, 100 and 1000, increasing with detector size. Since cosmogenic backgrounds dominate, suppression could be achieved by burying the detectors at 3 km water equivalent, compared to the 2 kilometers water equivalent depth of the KamLAND experiment.

Goal	Required Antineutrino Event Rate	No./Yr	Detector Mass 10 KT	1 MT	100 MT
Detect Operation ~1yr	~5/yr	~5	70 km	800 km	>>1000 km
25 percent accurate estimate of total annual energy	16/yr	16	35 km	400 km	>>1000 km
Detect reactor shutdown within ~1 week	> 10/day	3600	6 km	60 km	600 km

detectors have been built larger than the 1000 ton KamLAND detector, nor neutrino detectors larger than then 50 kiloton Super-Kamiokande detector.[63] However, instruments at the 100 kiloton to megaton scale are now being developed to study a wide range of fundamental physics topics.

The overlap of this work with fundamental neutrino and dark matter physics is discussed in detail in Bernstein.[64] This section describes the state of the art in antineutrino detection relevant for far-field monitoring, and introduces specific monitoring examples. The prospects for fission explosion monitoring are also briefly examined. This section concludes with a review of the necessary R&D paths for far-field nonproliferation applications. Table 5 illustrates the required fiducial detector masses for several possible remote reactor monitoring goals for 10 MWt reactors.

We begin our discussion with reactor monitoring. The example introduced previously sets the required detector scale. Exclusion of the presence of a 10 MWt reactor within an 800 kilometer radius, *with no other reactors present*, would require a 1 megaton water Cherenkov or liquid scintillator detector, with backgrounds suppressed by a factor of 100 compared to the KamLAND detector. As seen in Table 4 and discussed below, it is important to note that the dominant source of backgrounds derives from cosmogenic activation, which can be suppressed by additional overburden. While large, this detector mass

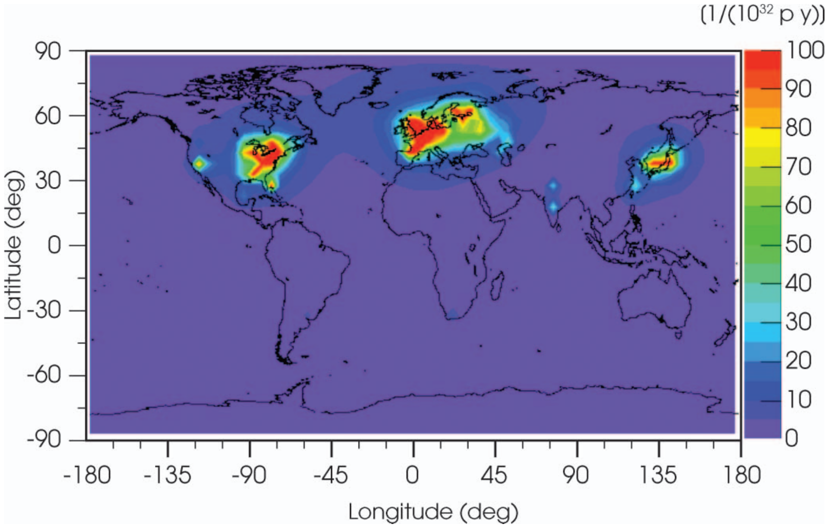

Figure 17: The predicted average antineutrino flux worldwide arising from known nuclear reactors. The color contours show the antineutrino interaction rate per 1032 proton per year, or about that of a 1000-ton detector per year. The red indicates areas where there are dense concentrations of reactors in France, the eastern United States, and Japan. Data are modeled based on known reactor powers, and are not from antineutrino flux measurements.

could be achieved by building about three modules of about 600 kilotons, a scale now being pursued for a wide range of fundamental physics research.[65] A Super-Kamiokande sized detector (50 kton), modified to be sensitive to antineutrinos, could measure the integrated power output of a 10 MWt reactor with 25% statistical precision, out to a distance of about 100 km.[66]

The large scale examples above (1 and 100 megatons) assume successful suppression of non-antineutrino backgrounds by 2–3 orders of magnitude relative to the current state of the art, *and* no reactor antineutrino backgrounds. In fact, reactor antineutrino backgrounds vary widely across the globe. Figure 17 shows the global antineutrino fluxes from all known reactors worldwide. These fluxes are an additional background beyond the detector-related backgrounds discussed in the previous section. Absent a directionally capable detector, they are irreducible without resorting to multiple detectors. An exception to this rule arises if the number of collected events in the detector is sufficiently high, in which case the specific signature due to neutrino oscillations can be used to provide some range information for a distributed set of reactors. This possibility is considered below.

North Korea, South Korea, Japan, and France would clearly be difficult locations for reactor monitoring due to backgrounds from large numbers of power reactors. However, monitoring in developing countries may have no significant local reactor antineutrino contributions (as for example in Africa and generally in the Southern hemisphere). The reactor-related backgrounds can thus be quite small out to standoff ranges of hundreds of kilometers. Even where these backgrounds are considerable, under many circumstances subtraction of known reactor signals is possible with a few percent accuracy. Power declarations for known reactors are currently required for IAEA safeguards. The same accounting could be performed more directly and with increased reliability if local antineutrino monitoring were available at each reactor.

For most of the long range monitoring examples considered here, the detector mass has been set to provide the minimum number of events possible to determine reactor presence or operational status. With the higher event rates made possible by very large detectors (tens of megatons) in the few hundred kilometer range, one can in principle take advantage of neutrino oscillation phenomena to separate the signature of closer target reactors from those background power reactors at greater distances. In the next section, this idea is illustrated with the hypothetical, topical, and difficult example of a hidden reactor in North Korea.

Discovery of an Undeclared Reactor in North Korea, Including Backgrounds from Reactors in South Korea, Using Antineutrino Rate Information

North Korea is chosen as an enduring and well known proliferation problem, and as an especially vivid indication of the confounding problem of reactor related backgrounds. It is important to emphasize that many places in the world would allow deployment of the few hundred kiloton to megaton scale detectors discussed above, due to the substantially reduced reactor-related antineutrino backgrounds and more favorable siting requirements. The example described here concerns only standoff, reactor power, and detector performance. No assumptions have been made about cooperation from North Korea or neighboring states or the many other practical obstacles that would have to be overcome for such a deployment to occur. Cosmogenic backgrounds are reduced by burial of the detector at 50% greater depth than the currently deployed KamLAND detector, and it is assumed that either liquid scintillator technology could be used, or that background suppression in water Cerenkov detectors is achievable at the same level as KamLAND. The latter assumption in particular is far from demonstrated.

To reduce backgrounds from the large installed capacity in South Korea as much as possible, it is postulated that a large and deeply buried detector could be built in southern China, near the North Korean border. The deployment scenario is shown in Figure 18. The detector size of 10 megatons allows 8 standard deviation confidence of detection of a sole 10 MWt reactor in Yongbyon above backgrounds, where both detector-related *and* other reactor

Figure 18: A hypothetical deployment sensitive to a 10 MWt in Yongbyon, North Korea. The size of the detector (or array of detectors) is 10 megaton. A 1 year dwell time would achieve an 8 sigma measurement of a 10 MWt reactor at the indicated location. Included in the calculation are backgrounds from all South Korean reactors, with sites in South Korea indicated by the triangles, as well as detector related internal and external backgrounds, using a rate per unit mass extrapolated from the KamLAND experiment.

backgrounds are accounted for. Reactor backgrounds are assumed to be fully reported by neighboring cooperative states, in this case primarily South Korea (with a small contribution from Japan). Exploitation of correlations among rates in a smaller (megaton scale) array of detectors would actually serve the purpose more appropriately. The detector related backgrounds are scaled from the KamLAND experiment (2003 analysis, see Table 4). The background estimate includes the suppression effects of recent purification efforts at

Table 6: The signal and background rates in a hypothetical 10 megaton detector deployed at 131 km standoff from an unacknowledged 10 MWt reactor in Yongbyon, North Korea. The depth is chosen to make cosmogenic backgrounds negligible compared to reactor backgrounds. The statistical significance is determined solely by counting statistics. Antineutrino oscillations provide greater resolution, as discussed in the text.

	Annual rate in a 10 megaton detector at 4 kmwe depth
Yongbyon 10 MWt reactor	1900 events
Background from ~38 GWt of S.K. reactors	185,000 events
Cosmogenic and internal backgrounds	12,000 events
Fluctuations in total background	450 events
Statistical significance after one year	~4 standard deviations

KamLAND, which reduce radon and associated backgrounds, and also assume 50% greater depth (3 km water equivalent, or about 1 km of rock, compared to the actual KamLAND depth of 2 km water equivalent). Total backgrounds are estimated at about 1% of the remote reactor signals. The estimated power reactor generated backgrounds are based on known South Korean reactor thermal power ratings. One may also assume cooperative reporting of daily power production by these reactors, which aids in background subtraction. Table 6 shows the expected signal and background rates.

Not included in this rate analysis is the time variation of known backgrounds, such as the South Korean power reactors. In the KamLAND experiment, the predicted neutrino flux varied by about a factor of two over several years timescale, as reactors went down for service and due to problems. This temporal signature further strengthens the analysis, but has not been employed in the present simulations.

Discovery of an Undeclared Reactor in North Korea, Including Backgrounds from Reactors in South Korea, Using Spectral Information

Neutrino oscillations, which change the type or "flavor" of the antineutrino as a function of distance and energy, have been observed with reactor antineutrinos and are discussed in the penultimate section. When one has an expected signal in the range of a thousand or so events, employment of neutrino oscillations provides a powerful tool to further distinguish signal from backgrounds, even when the total number of signal events is small (a few percent) compared to background. The detector, still 10 megatons in this example, would have to

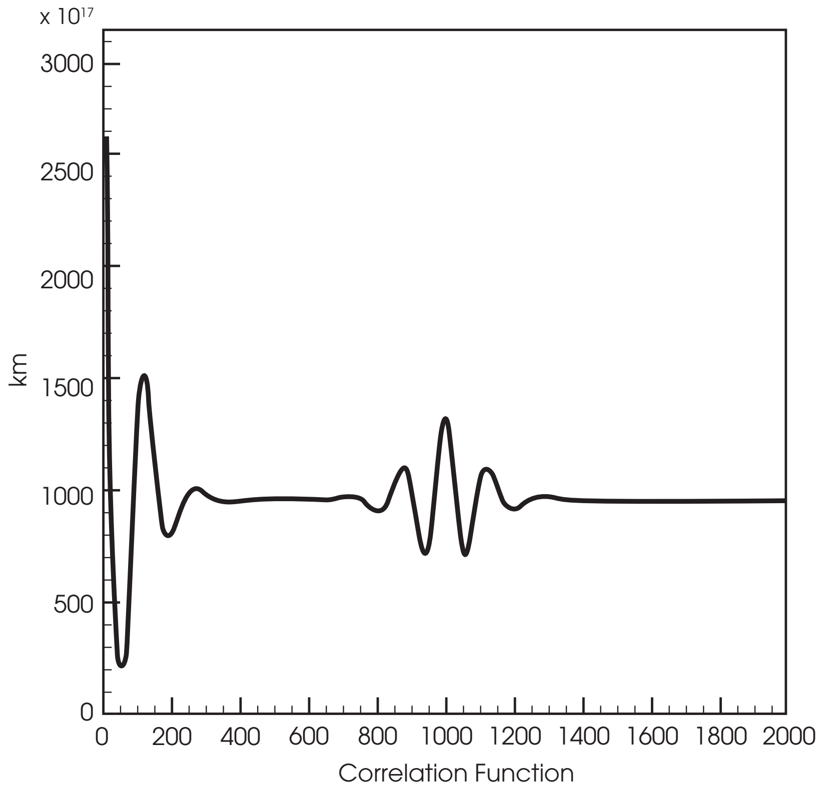

Figure 19: Correlation function versus distance for the hypothetical example of a 10 MWt reactor at 131 km distance and 10 GWt background reactors at 1000 km distance. The signatures are clear both for the background reactors and the "hidden" reactor at the unknown 131 km distance, with the range accurate to a few kilometers.

achieve energy resolution comparable to the KamLAND detector, so that a water based system would probably not be feasible. Nonetheless it is interesting to consider the spectral analysis technique in the far-field.

There are many ways to do this analysis. Here, optimal filtering in the energy distribution has been employed. With a known reactor antineutrino background, including the now well measured oscillations which distort the antineutrino energy spectrum, an optical filter or a correlation function can be convolved with the observed spectrum. This filter will yield a peak at the distance of the “unknown” reactor, with an amplitude proportional to the reactor power (see Figure 19).

These correlation functions can be further improved. The shape of the signature versus distance is exactly equivalent to a point spread function (PSF) in, for example, radio astronomy. Techniques have been refined to deconvolve the PSF, using for example the “maximum entropy method” or the “CLEAN” algorithm. The latter seems particularly attractive for this application as it allows sequential subtraction of the peaks, revealing underlying detail.[67]

The reactor distribution in this example is slightly simplified compared to reality, since South Korean reactors are distributed at four main distances, rather than a single distance, as discussed here. Nonetheless the example illustrates the additional power provided by spectral filtering. Not yet exploited are the opportunities for inclusion of directional information. While these various effects are considered here separately (counting statistics, backgrounds with time dependence, range dependent spectral distortions, and directionality), a real monitoring program would employ all simultaneously in a Maximum Likelihood approach, squeezing as much information as possible from the data set. It is difficult at this time to say how much this will add in analysis power, but 40–50% improvement seems reasonable.

In summary, with next generation scientifically motivated instruments in the one megaton class (see Figure 2), one could in principle monitor small reactors in the 10 MWt class out to ranges of order of 800 km, and at ranges of a few hundred kilometers make more detailed assessments of operations. These statements assume that the ambitious energy resolution, background rejection and underground mine engineering goals of these detectors are all realized. Worldwide, ongoing design efforts related to these detectors will aid more detailed assessments of reactor monitoring. The following sections describe planned detectors that approach scales of interest for far-field monitoring.

Next Generation Large Liquid Scintillator Detectors

The previous section discussed the 1000 ton KamLAND liquid scintillator detector, in which current background levels allow sensitivity to 10 MWt power reactors throughout the entire 1–10 km mid-field range, even extending partially into the far-field (out to 30 km). Next generation scintillator antineutrino detectors will likely be built on a scale roughly 10 times bigger. An example is the proposed 30,000 ton submersible Hanohano detector, a schematic of which is shown in Figure 20.[68] Assuming a fiducial volume of 10,000 tons, (extrapolated from the KamLAND self-shielding radius) and scaling rates from KamLAND estimates, Hanohano would have a 95% confidence exclusion range of about 70 km for a 10 MWt reactor in 1 year, assuming total *non-reactor* backgrounds comparable to KamLAND (including removal of radon in the latter experiment). However, in these deeply buried detectors, the non-reactor backgrounds depend primarily upon depth. Backgrounds from cosmic rays will be totally negligible below 4 km depth, and may be manageable at shallower depths. For example, the KamLAND detector operates at about 2.7 km water equivalent depth.

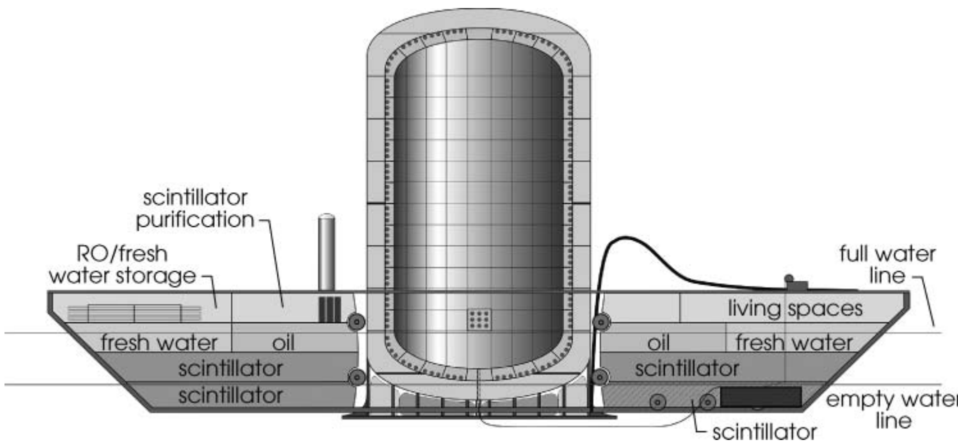

Figure 20: The proposed ocean-going 10 kiloton liquid scintillator detector Hanohano. Shown in cutaway profile, the cylindrical detector will be transported by a 100 meter long barge and lowered to depths up to 5 km for data collection. The detector is designed for study of neutrinos from reactors and measurements of geo-neutrinos from the Earth's mantle. It is mineral oil based, and is surrounded with large photo-detectors. While the ocean-going engineering presents challenges, the detection technology is a straightforward extrapolation from the operating KamLAND instrument in Japan, and other detectors.

The difficulty of background rejection increases at shallower depths, and this is an important element of future R&D, as discussed below.

The Hanohano detector is to be built primarily for antineutrino physics, geophysics, and astrophysics studies. It may be the first experiment after KamLAND to demonstrate remote detection and monitoring capability for a single reactor, including measurement of the reactor operational status and power at distances of 50–100 kilometers. The Hanohano design has particular interest for nonproliferation applications because of its flexible deployment platform, which allows submersion of the detector at various locations and depths in the world's oceans. It will also give experience in the sort of large detectors that will ultimately be needed for nonproliferation, and will help further develop the expertise and the scientific personnel to carry out remote monitoring tasks of the future.

An example deployment would be 55 km offshore of the San Onofre Nuclear Generating Station. This distance was chosen to allow maximum sensitivity to neutrino oscillation parameters in a fundamental physics experiment). At this distance, Hanohano would collect roughly 25 events per day for both reactors, which would easily allow determination of the operational status of either reactor within 1 day. While of little utility for nonproliferation, the example illustrates that relatively high statistics are achievable even at tens of kilometer standoff in next generation detectors.

Next Generation Large Doped Water Cerenkov Detectors

Beyond distances of a few tens of kilometers, and above detector masses of the order of 100 kilotons, the detection technology must almost certainly change from liquid scintillator to water. One central consideration is cost. Photomultiplier tube coverage costs scale with the linear dimension of the detector squared, while the proton target mass goes as the cube. Hence the cost of the organic liquid scintillator alone (at roughly $1/kg) will begin to dominate and eventually become prohibitive as one scales the size upwards. The cost of scintillator for a 100 kiloton detector is about $100 million. Assuming 40% PMT coverage and a cost of $10,000 per square meter of PMT, the PMT cost for the same detector would be about $40 million. Therefore, water (at about 1% of the cost of scintillator) is the preferable target material for very large detectors, in spite of its reduced energy resolution compared to scintillator.

While large water Cherenkov detectors have been built and detected MeV-scale neutrinos, no large water-based detector has yet demonstrated reactor antineutrino detection. The largest presently operational low energy *neutrino* detector based on water Cherenkov technology (leaving aside ice Cherenkov technology for the moment, see below) is Super-Kamiokande.[69] It has 50 kilotons gross and 22 kilotons fiducial volume and a present energy threshold of about 4.5 MeV. It has been operating since 1996 and its operation is well understood. Studies of water Cerenkov detectors on megaton mass scales have been put forward in Japan, the United States, and Europe.[70] These or others may be constructed for neutrino physics studies in the next decade, with projected costs in the range of $500 million and $1 billion.

To be relevant for far-field reactor monitoring, water Cherenkov detectors must be made explicitly sensitive to antineutrinos, using the inverse beta decay interaction of Eq. 2. This requires the ability to detect neutrons in the water, in order to exploit the two-fold time-coincident signal generated by the positron and neutron, which signature is needed to distinguish the anti-neutrinos from many other sources which cause a single flash of light (particularly solar neutrinos). Doping with Gadolinium (at the 0.1% scale) of large scale water detectors has been proposed as one way to make water Cherenkov detectors sensitive to neutrons. A detailed study of this option has been performed in consideration of a possible upgrade to the Super-Kamiokande detector, known as the GADZOOKS detector.[71] As a small scale proof of the detection principle, a Lawrence Livermore National Laboratory group has demonstrated water-based neutron detection, and sensitivity to inter-event time correlations identical to those produced by antineutrinos, using a 250 kg Gadolinium-doped water detector.[72] Other schemes have been proposed for neutron detection and for enhancing the light output in water Cherenkov detectors and these are matters of active study at present. As demonstrated by Super-Kamiokande, the achieved limit for light attenuation in purified water is roughly

80–100 meters, so that megaton scale detectors, with 100 meter linear dimensions, are not greatly affected by attenuation.[73] However, it remains to be demonstrated that attenuation lengths are not affected by wavelength shifters, or, crucially, Gadolinium doping. Moreover, larger detectors than 1 megaton would require modular construction or other expedients. Beyond the question of Gadolinium doping, many other obstacles remain for scaling the technique to the megaton scale and beyond. The relevant R&D paths are summarized at the end of this section.

Detection of Nuclear Explosions

Nuclear explosion monitoring is an important element of the proposed CTBT and similar regimes.[74] A variety of on-site and remote sensor technologies are used for verification within such regimes. The technologies can be used to detect nuclear explosions conducted in the atmosphere, underwater, underground, or in outer space. Depending on the geographical location and site access, explosive yields approaching 1 kiloton can be measured in some, though not all circumstances. Given this technology base, and the likely achievable capabilities of antineutrino detectors for explosion detection, antineutrino detection is likely to play at best a supplementary role in nuclear explosion detection in the near and medium term, most likely in cooperative contexts and as a confidence building measure. Its main possible advantages are unambiguous evidence of a fissile character of the explosion (rather than some other explosive or seismic event), and the ability to provide a competitive estimate of the device yield. A detailed comparative study may be found in Bernstein.[75]

A Role for Antineutrinos

The potential for ambiguity in seismic monitoring raises the question of whether antineutrino detectors might give useful supplementary information. The required detector size for a given standoff and number of events are shown in Figure 21. For example, detection of ten events from a 10 kiloton explosion at 200 kilometers would require a three megaton detector.

Detection of even one antineutrino in coincidence with a blast, located and time-tagged by other means, would have important implications: one would know first that the blast was certainly nuclear; and one would know the yield within a factor of 2–5. With ten neutrino events, the yield would be determined within 30%, more accurately than is typically achieved seismically. Unfortunately the detector sizes needed for standoff detection are daunting: roughly 10–100 times larger than the largest detectors now being proposed, and 1000–100,000 times larger than state of the art antineutrino detector (KamLAND). A distributed array of such large anti-neutrino detectors offers the additional possibility of explosion location, as well as improved yield

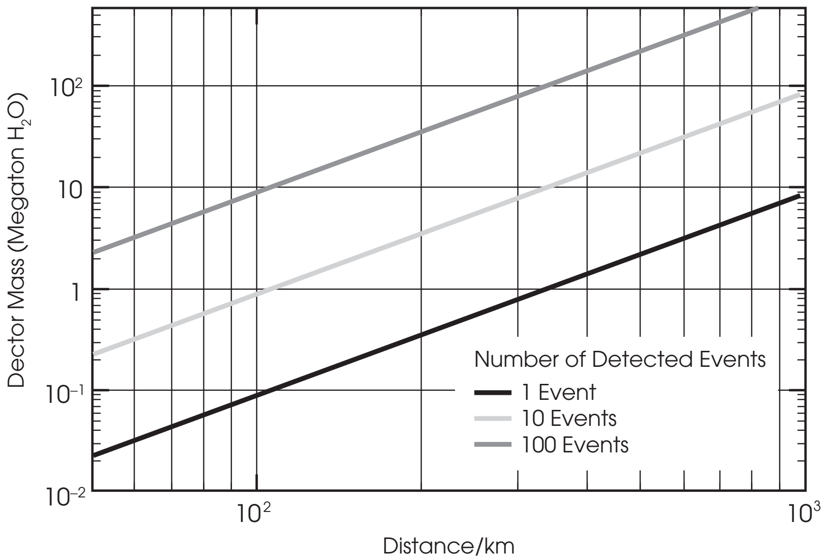

Figure 21: The number of events which would be detected on average for a given detector mass, versus the distance from the explosion of a nominal 10 kiloton-TNT equivalent nuclear weapon. Oscillation effects are not included in this crude estimate. The water based detector has an assumed energy cut of 3.8 to 6.0 MeV. The lower line would permit confirmation of the nuclear nature of the blast and a crude estimate of yield. The middle line, corresponding to 10 detected events, would allow autonomous detection and a 30 percent yield estimate. The upper line for 100 events would permit a 10 percent yield estimate, and extraction of other information (E. Guillian et al., Applied Antineutrino Physics Workshop 2007 (http://www.apc.univ-paris7.fr/AAP2007/Talks/Guillian.ppt).

estimates. For completeness Table 7 summarizes a set of possible nuclear explosion monitoring goals that could be enabled with such detectors.

Of course, while assumptions differ slightly, the numbers of events expected and required have not changed since the 2001 study (leaving aside the

Table 7: Possible goals for detection of nuclear explosions with a hypothetical 100 megaton detector. Detectors on this scale are for now beyond the level now being proposed for large antineutrino detectors in the fundamental science community.

Goal for a hypothetical 100 MT instrument	Number of Events	Range
Detect explosion seen by other means	$>$1 event in coincidence	1500 km
Estimate yield to 30 percent	10 events	500 km
Detect otherwise undetected explosion	5 events in 4 sec	700 km
Estimate range for known yield, via number of events	10 events	+/− 15 percent
Precision range, via oscillations	100–1000 events	+/− 1 percent
Location with 2 detectors	2 time$>$10 events	$<$250 km^2
Details of explosion (using time & spectrum)	1000 events	210 km

relatively small correction now known to come from electron antineutrino oscillations, which is not included in our tabulated examples). The main advance compared with the earlier study is that megaton scale detectors, required for the simplest standoff detection goals for kiloton scale explosions, are now being considered by various groups for fundamental physics studies, which was not the case a decade ago. If such detectors are developed, antineutrino detection might someday provide a transformative additional capability for CTBT verification.

Final considerations in the context of explosion detector are very large detectors such as Ice-Cube.[76] As currently operated, these detectors are relatively sparsely instrumented with PMTs, and are therefore sensitive only to GeV-scale or greater antineutrino energies. However, large detectors of this kind have been considered for MeV scale antineutrino detection, in the context of supernovae and gamma ray burst detection.[77] The essential idea is to search for very small but well-correlated fluctuations in response among many PMTs, induced by the pulse of antineutrinos engendered by some astrophysical event. This interesting idea merits further consideration in a nonproliferation context, since it might someday allow these very large scale detectors to be adapted to nuclear explosion detection.

Research and Development Needs for Far-Field Detectors

Currently, there is no global mandate for persistent long range monitoring of wide geographical areas for the existence of small reactors. While several areas of concern exist, such as the North Korean example, there is no strong call for capabilities beyond existing techniques such as satellite surveillance and airborne radionuclide measurements. This is in part due to the acknowledged cost and difficulties associated with such deployments, as well as the general unfamiliarity of antineutrino-based technology. The foremost need for far-field detection—and the simplest to address—is therefore further analysis by the nonproliferation community of the costs and benefits of antineutrino based monitoring.

Technical R&D avenues for far-field detection are much more difficult to address. They divide into issues related to sensitivity and those related to cost. Perhaps the most important advance, doping of water based detectors with Gadolinium compounds, has already been discussed in the section titled Next Generation Large Doped Water Cerenkov Detectors. Other important areas of research include:

1. **Background Suppression:**
   Far-field detection requires suppression of backgrounds in large scale water Cerenkov and liquid scintillator detectors to levels comparable to or

exceeding those achieved in the KamLAND experiment. Methods have been developed for purification of scintillator liquids from radioactive materials (the most notorious being radon and decay daughters). KamLAND, Borexino, and SNO+groups have all made great progress in bringing high radio purity to levels thought to be unachievable within the last two decades.[78] Backgrounds from detector boundaries and rock or water surroundings become less of a problem as detector size scales up, but material cleanliness remains an issue. Though well handled in present detectors, work is needed to make this a matter of industrialization in future huge instruments.

Cosmic ray muons and muogenic neutrons and isotopes decrease rapidly with depth. As stated earlier, below ~3 km water equivalent depth these are not a problem. At lesser depths they become problematic, and from experience they are known to be manageable at a depth of 2 kmwe. Shallower depths may be practical depending upon the size of the instrument and the target signal. Further study is needed to determine just how shallow is tolerable.

2. **Development of event-by-event direction reconstruction for the antineutrino signal:**

Antineutrino directionality is an extremely difficult problem to solve, but could transform concepts of operation by allowing real-time location of reactors and much improved background rejection. The challenge lies in the fact that the direction of the recoiling neutron and positron is only loosely correlated with the direction of the incoming antineutrino. When directionality has been achieved, most notably by the Chooz experiment with a reconstructed half-angle of about 20 degrees, this means that dozens or hundreds of events are required to extract the average direction of the antineutrino signal.[79] For long range detection in which only a few events are available, this is obviously of no use. However, since momentum and energy are conserved in each individual event, it is possible *in principle* to reconstruct the antineutrino direction on an event-by-event basis. This requires direct reconstruction of the positron and neutron momenta within the first few scatters following the antineutrino interaction, which in water and liquid scintillators occur within mere millimeters to a few centimeters of the event vertex. Thus what is required is a detector with a linear dimension of 10–100 meters, and position sensitivity on the scale of millimeters. Possible solutions included virtual segmentation via time projection chambers, or devices based on laser illumination and reconstruction of tracks, but the problem is enormously difficult and no solution appears imminent.

Concerning cost, the two dominant factors, at least for water detectors, are PMTs and excavation or, in the ocean, containment.

3. **Low cost photodetection:**
   At present all large instruments use PMTs. These large instruments (Super-Kamiokande uses 20 inch diameter tubes) are beautiful devices, low noise, and have high photon detection efficiency. But they involve significant mechanical complications, and the number required for a 10 megaton detector would be very difficult to manufacture and handle. The megaton class detectors mentioned above primarily anticipate using existing technology because of the long timelines for new devices. The cost of the present devices is also intimidating, at about $1/cm^2. For example, the cost of photomultipliers for a 10 megaton instrument would be approximately $1.1 billion. Progress is possible if increased funding and effort are directed towards advanced photodetection technology. Indeed there is a lot of commercial activity in this area, often directed towards small pixel sizes, for example the tremendous revolution in charge-coupled device (CCD) cameras. The precision for dimensions required has been demonstrated by flexible circuit manufacturers, with the prospect for being able to make the needed acres of photodetector in rolls like wall paper. There are however many concerns about manufacturing, noise levels, lifetime, and other factors. Ultimate manufactured costs have been estimated to be as low as a few cents per cm^2, down by a factor of 10–100 below those of present photomultipliers. Both within and beyond the neutrino detection community, there is great motivation to pursue this development.

4. **Ocean and Mine Tunnel Engineering:**
   While the problems are different, deployments of large detectors in mines and the ocean will require significant engineering R&D to proceed. In the case of mine based instruments, many of the problems are already under active study in Japan (HyperK), Europe (LENA), and the United States (DUSEL). There surely is a strong limitation on the size of such detectors with reasonable cost, the present limitation being thought to be in the scale of 1 megaton. Even at that size the excavation time becomes a problem (approaching a decade timescale). For the grand visions of detectors beyond the megaton scale it seems inevitable that such instruments be placed in the ocean. There have been very preliminary studies of engineering at these sizes, but beyond about 1 megaton (the mass of the world's largest oil tanker) is new territory. There are of course formidable engineering challenges including construction of giant bags, massive water purification, transportation, and others. One possible synergy comes from the large investments in underwater technology made by oil companies in recent years.

Summary of Far-Field Applications

This section reviewed some of the technical and cost issues associated with deploying a large inverse beta decay detector at ten to several hundred kilometer standoff distance from reactors. The several next generation detectors being proposed for physics experimentation might be useful for discovery or exclusion of small reactors in the far-field in some areas of the world. Of particular interest is the considerable and natural overlap in detector technology between the physics and nonproliferation applications, a theme taken up in the following section. Sensitivity goals for hundreds of kilometer distant monitoring of small reactors with no other reactors present are currently beyond the state of the art, with the required detector masses roughly a factor of ten beyond the current state of the art. Portable next generation liquid scintillation detectors such as the proposed 10 kiloton Hanohano can pursue fundamental physics topics while demonstrating and developing the technologies that move this area ahead. While affordability and allocations of national budgets ultimately relate to the desirability of the nonproliferation outcome, use of water Cerenkov technology, coupled with breakthroughs in the area of low-cost photodetection, appears to be the most cost effective approach.

Fundamental Physics and Reactor Antineutrino Detection

The fundamental science developed with nuclear reactor antineutrino sources has provided many of the ideas, and much of the R&D funding that have made nonproliferation-related reactor monitoring possible. Given the natural connection between the two fields at the level of technology, it can be expected that cross-pollination of this kind will increase over the next decade as new, more sensitive, detectors are built. Moreover, in a kind of reverse spin-off from international security applications to science, widespread deployment of antineutrino detectors for reactor monitoring could provide an important additional global resource for studying the fundamental properties of neutrinos.

Bernstein[80] provides a detailed summary of current physics projects that relate to nonproliferation applications at the level of technology. This section briefly describes the categories of research and highlights relevant planned or ongoing experiments which have a technology overlap with nonproliferation. The list of experiments here is not exhaustive but is illustrative of the overlap in R&D between nonproliferation and fundamental physics applications. More comprehensive surveys of various neutrino experiments worldwide are also available.[81]

Since their discovery, great strides have been made towards understanding the physical properties of neutrinos, with especially rapid progress at the turn of the millennium. It is now known that neutrinos have mass, and that the three types of neutrinos (ν_e, ν_μ, ν_τ) paired with the lepton (e,μ,τ) postulated by the Standard Model (SM) of particle physics do not correspond to the three types of neutrinos found in nature. Physical neutrinos propagate through space according to their mass. These physical neutrinos (ν_1, ν_2, ν_3) are now known to be quantum mixtures of the three types postulated by the SM. Thus they travel through space as (ν_1, ν_2, ν_3) but interact with matter as (ν_e, ν_μ,

ν_τ). Establishing this experimental fact was the culmination of over 20 years of measurements of neutrinos from the sun, and from cosmic ray interactions in the Earth's atmosphere. These pioneering (and somewhat astonishing) results have since been verified in detail with experiments using neutrinos from the sun, cosmic rays, nuclear reactors, and accelerators. Alongside and because of this impressive progress, a number of new research questions have arisen. First, considering only reactor-based experiments, there are three principle areas of research:

1. **Measuring the amount of mixing between the neutrino (and antineutrino) types.**

   Neutrino mixing, also known as neutrino oscillations, can be described as a mathematical transformation of vectors corresponding to the three different neutrino types or flavors. It occurs for neutrino *and* antineutrino flavors separately, so that the phenomenon can be observed with reactor sources. Neutrino mixing can be thought of as a rotation in space of the physical neutrino vector. Geometrically, three angles can be used to describe such rotations, which are conventionally labeled θ_{12}, θ_{23}, and θ_{13}. The first two of these angles have been measured while the third is as yet unknown. Thus there is currently a program to increase the measurement precision for the first two angles, and make an initial measurement of the third angle, $\theta_{13.}$ Some of this work has and will be done at nuclear reactors. The reactor oscillation experiments all use the inverse-beta reaction—as do proposed reactor monitoring detectors. In addition, much of this program requires a high precision knowledge of the antineutrino reactor flux and its variation with reactor type, fuel loading, and operational history, essentially the same types of measurements needed for non-proliferation monitoring. This R&D includes the ongoing Double Chooz and Daya Bay experiments. Hanohano, with a proposed deployment location of 55 km from the SONGS reactor in California, is an example of a medium distance experiment.[82] Its physics goals are to measure θ_{13} via spectral analyses. It would demonstrate robust remote deployability of large (10,000 ton) detectors of interest for nonproliferation.

2. **Studying collective interactions of neutrinos and antineutrinos with nucleons in nuclei, known as coherent scattering.**

   Coherent scatter detection programs are active at University of Taiwan, University of Chicago, and Lawrence Livermore National Laboratory.[83] The cross-section for coherent antineutrino-nucleus scattering is much higher than the inverse beta process. The resulting small detector size and/or high rates that are potentially achievable through coherent scatter mechanism make such detectors of possible interest for reactor monitoring. However, because the coherent scatter interaction is identical for all flavors of neutrino and antineutrino, it is important to point out that they suffer from a probably irreducible limiting background, arising from solar neutrinos. At standoff distances beyond a few kilometers from a GWt scale power reactor, the solar neutrino signal, which is indistinguishable from the reactor antineutrino signal in these detectors, will dominate the measured signal in any coherent scatter detector. This means that the utility in a nonproliferation context is likely limited to near-field applications, out to a few kilometers.

3. **The search for antineutrino magnetic moments.**
   In addition to neutrino mixing, there is also a program of using reactor antineutrinos to look for a non-zero neutrino magnetic moment. Neutrinos, like neutrons, are electrically neutral. Unlike neutrons, they behave as point particles and have no (as yet) measurable magnetic moment. In some theories, neutrinos *would* have a very small magnetic moment, which might be detected via a deviation of the "standard" weak interaction at low energies. This type of experiment typically requires detectors with extremely low backgrounds and very high neutrino rates. This is because they need to use very low energy reactor neutrinos to achieve the required sensitivity, below the threshold of the inverse beta decay reaction.[84] They therefore rely on antineutrino-electron scattering, which might be relevant for future non-proliferation detectors. The recoiling electron follows roughly the direction of the incident neutrino, allowing one to obtain the direction of the source. Two recent experiments that have conducted a search for a non-zero magnetic moment are the TEXONO experiment at the Kuo-Sheng reactor and the MUNU experiment at the Bugey reactor.[85]

In addition to these experiments, there are several R&D areas that require detectors that are very similar to those needed for reactor antineutrino detection.

1. **Supernovae neutrino detection.**
   Supernovae antineutrinos are of great interest for astrophysics and cosmology, and are close in energy (~10–30 MeV) to reactor antineutrinos. Detection of supernovae antineutrinos has already been accomplished with fairly large water Cerenkov detectors. In a remarkable breakthrough, the Kamiokande-II and the 10,000 ton Irvine-Michigan-Brookhaven (IMB) experiment both successfully recorded a few second burst of antineutrinos from supernovae 1987A.[86] Next generation large water Cerenkov detector proposals, such as Hyper-kamiokande, the proposed U.S. water detector at the Deep Underground Science and Engineering Laboratory (DUSEL) in South Dakota, and the European MEMPHYS detector all include supernovae detection as an important element of their overall physics goals.[87]

All of these detectors would also represent important strides forward for far-field reactor monitoring applications.

2. **Detection of antineutrinos generated within the Earth (geo-antineutrinos).**

   The 1000 ton KamLAND liquid scintillator detector, described earlier, was the first to measure antineutrinos produced by radioactive decays of naturally occurring uranium and thorium isotopes from the Earth. The 10,000 ton Hanohano detector is also expected to acquire geo-antineutrino signals at one or more locations in the ocean. Geo-antineutrino detectors are particularly relevant for nonproliferation since they are of necessity large—at minimum 1 kiloton—and since the endpoint of the geo-antineutrino energy spectrum, at roughly 3.3 MeV, is *lower* than that for nuclear reactors. The world's first geo-antineutrino spectrum was measured by the KamLAND detector.[88] The large size and low energy threshold requirements for geoantineutrino detectors make them directly relevant for mid-field and far-field reactor monitoring applications.

3. **Long-baseline neutrino experiments using accelerator generated beams.**

   These are experiments with high energy neutrino beams, but make use of multi-hundred-kiloton Water Cerenkov detectors. An example now funded as an experiment in the United States is the United States Deep Underground Science Laboratory Long-Baseline experiments (LBL-DUSEL).[89] While the neutrino energy scales differ greatly from the MeV scale of interest for reactor monitoring, the LBL-DUSEL experiments are designing large water Cerenkov detectors which are of potential interest for nonproliferation applications.

Each of these areas demands advances in large scale liquid scintillator and water Cerenkov detectors, the same technologies needed to improve mid-field and far-field reactor monitoring.

Beyond neutrino searches, large water Cerenkov and scintillator detectors may be used in pursuit of a range of other physics goals. Correlated signals with gamma-ray bursts, searches for proton decay, monopoles, quark nuggets, and other phenomena have all been proposed using detectors similar in scale and design to those discussed in the preceding sections.[90]

CONCLUSIONS

In this paper, we have sought to demonstrate the breadth of ongoing activity in the area of antineutrino detection for nonproliferation, and the natural connection between this work and current and next generation detectors for particle astrophysics. The last decade has made near-field monitoring capability a reality. Albeit with considerable additional effort, the next decade may usher in reactor monitoring capabilities well beyond these cooperative near-field demonstrations. We hope this paper motivates the science and non-proliferation policy communities, as well as the global scientific community with an interest in neutrino and dark matter physics, to explore and, where possible, exploit the implications of this connection for both fields.

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