Cooperative monitoring from outside the fence: the promise and practical limitations of remote antineutrino-based monitoring and discovery of nuclear reactors

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Abstract: We discuss the utility of and obstacles to remote antineutrino-based monitoring, 'outside the fence' of a reactor complex. From about 0.1-10 kilometer standoff distances, information about the thermal power and fissile inventory of civil reactors , down to a minimum power of about 500 Megawatts thermal (MWt) can be gained with detectors ranging in size from about ten tons at 100 meters, to about one kiloton at the 10 kilometer extreme of this radial band. From 10-100 kilometers, an excess antineutrino event rate above a robustly predicted background can be detected, and would be an indication of an anomaly, with known statistical significance, consistent with a small undeclared reactor, down to a minimum thermal power of 50 Megawatts (MWt). This latter application would require detectors in the few kiloton to 500 kiloton range, with the largest sizes needed at the extreme standoff limit of 100 km.

The above estimates assume current state-of-the-art detectors, or reasonable extrapolations therefrom. We examine costs and practical limitations for deployment, including the need for underground burial of the detector (to shield against backgrounds), the expense of construction and operation, and the possible social or policy impacts of such deployments.

We conclude that remote antineutrino-based monitoring has potential utility for cooperative monitoring regimes and confidence building activities, especially when non-intrusiveness, wide areal coverage, persistence, quantitative information about reactor operations or existence, and scientific engagement with the host country are desired by negotiators. The nonproliferation community will benefit from a demonstration of the capability, to gain insight into operational considerations and real-world utility of this new approach to cooperative monitoring of nuclear reactors.

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Antineutrinos and their relevance for non-intrusive reactor monitoring and exclusion

Antineutrino emission in nuclear reactors arises from the β-decay of neutron-rich fragments produced in heavy element fissions. The average fission is followed by the production of about six antineutrinos that emerge from the core isotropically and without attenuation. Due to the large number of fissions[a] continuously occurring in operating reactors, the number of emitted antineutrinos is large. Moreover, because of their highly penetrating nature, antineutrinos can't be shielded. Remote detection of 3 GWt-scale reactors at hundreds of kilometer standoff has already been achieved in kiloton-scale pure water[1] and in scintillator[2] detectors.

In nonproliferation contexts, we envision two applications in two standoff ranges, defined as the mid-field and the far-field.

1) Reactor monitoring:
For standoffs from one hundred meters out to roughly 10 kilometers, antineutrino detectors can monitor the operations of declared reactors with powers of about 500 MWt and above. We define this as the mid-field for antineutrino-based applications[b]. While the IAEA is largely satisfied with its current reactor monitoring protocols, safeguards protocols for new reactor types such as SMRs and Molten Salt reactors have yet to be fully defined. In these cases and others, antineutrino-based systems offer the potential for reduced inspection frequency, some degree of material accountancy (versus current, mostly item-accountancy-focused monitoring protocols), persistent monitoring, and outside-the-fence operation to maximize nonintrusiveness. Detector sizes range from about 5-10 tons at 100 m to 1000 tons at 10 km for detection of a 50% power drop in a 500 MWt reactor within 6 months, with 95% confidence.

2) Exclusion and discovery:
We define standoffs from 10 kilometers out to a maximum of 100 kilometers as the far-field. In this domain, antineutrino detectors can exclude or discover reactors down to a thermal power of about 50 MWt. The same capability can also be used in the 100 m to 10 kilometer regime that defines the mid-field. This capability may have relevance to the Additional Protocol agreements that are part of the Treaty for the Nonproliferation of Nuclear Weapons (NPT), which permit cooperative but minimally instrusive monitoring for undeclared reactor activities. It may also be useful as a component of future treaties in which monitoring of material production capabilities are a central element, such as the Fissile Material Cutoff Treaty, bilateral or multilateral Confidence-Building measures, or other treaties and agreements.

A further constraint on the far-field exclusion/discovery application relates to the world's antineutrino backgrounds, arising from other reactors. After approximately 10-20 km standoff from a reactor or region of interest, a contaminating background from the world's reactors begins to dominate. Since it comes from reactors, the signal is essentially

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[a] There are about 10^{20} fissions per second in a standard 3 GigaWatt thermal (GWt) core.

[b] Less than 100 m standoff is defined as the near-field range.

indistinguishable from the signal of interest. By 100 kilometers, this background is so important that detection of the relatively weak signal from a distant 50 MWt reactor of interest is effectively impossible. Figure 1 shows regions of the world colored according to their reactor backgrounds, in units of detectable antineutrino events per kiloton and year. This ‘noise floor’ limits the exclusion capability to the medium and low background regions shown in the figure, and sets the extreme 100 km limit of the far-field domain with current and envisioned technology for at least the next decade.

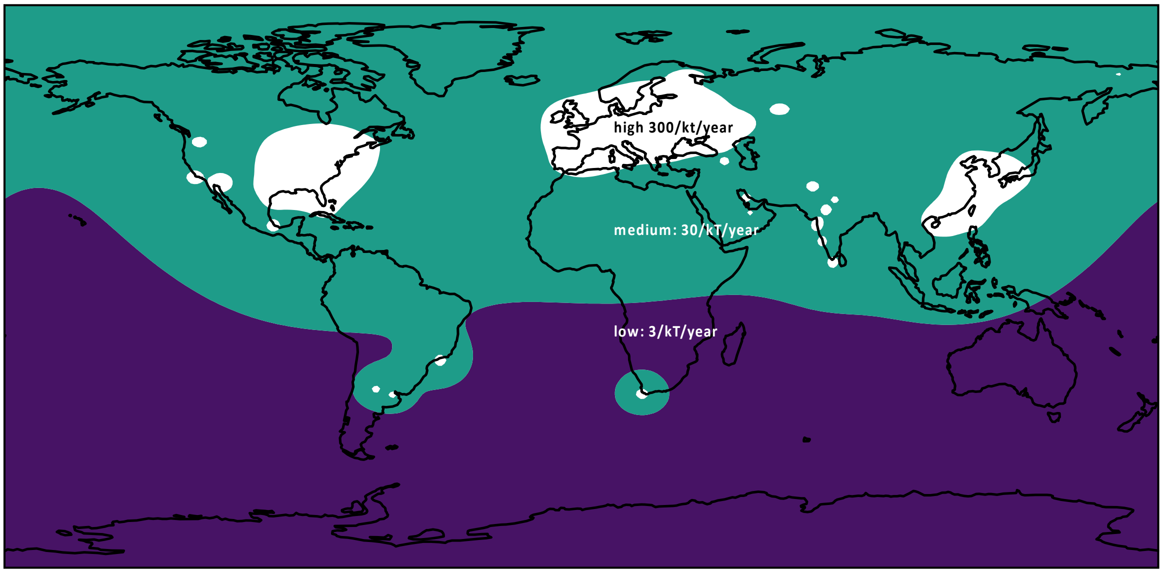

Figure 1: The distribution of antineutrino backgrounds from the world’s reactors. Purple, green and white regions correspond to 3, 30 and 300 reactor antineutrino background events on average per year. The source of the reactor type and location information is the IAEA’s Power Reactor Information System[3].

For this set of applications, antineutrino-based deployments offer wide areal coverage, nonintrusiveness, persistence, and clear quantitative metrics (i.e. accurate statistical confidence levels) for exclusion or discovery. In this context, the term discovery is used when the measured rate associated with finding a reactor has sufficiently high statistical significance, e.g. a five sigma deviation from background, compared to 2-3 sigma significance that may be used merely to conclude the absence of a reactor signal.

This combination of properties is not currently available through other means, whether cooperative, such as on-site inspection, or non-cooperative, such as radionuclide detection and satellite imaging. Discover and exclusion can also be applied in the mid-field, with actual deployments depended on the degree of nonintrusiveness and areal coverage sought by negotiators. Detector sizes range from about 500 tons at 10 km to 500 ktons at 100 km in low-background regions of the world, for exclusion of the presence of a 50 MWt reactor within 6 months, with 95% confidence.

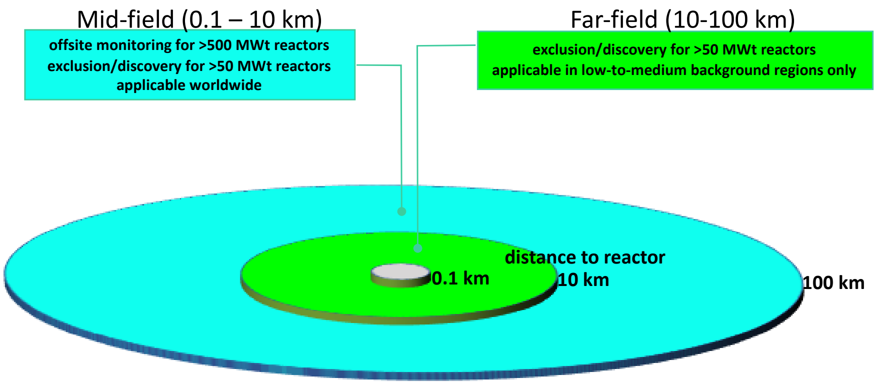

Figure 2: The mid-field and far-field standoff reactor monitoring/exclusion/discovery domains for antineutrino-based applications.

Figure 2 shows the mid-field and far-field standoff domains and ranges of utility for the two applications.

For both cases, but especially for the far-field applications, there are rich opportunities for scientific diplomacy. This is simply due to the intrinsic scientific interest of the detectors and their relevance for fundamental nuclear and particle physics. This scientific connection is reminiscent of, for example, the US-Russia 'Lab-to-Lab'[4] collaborative efforts following the Cold War - though likely with stronger overall scientific benefit. The collaborative work by scientists from both countries in the cooperative monitoring enterprise, and in some cases the redirection of expertise of former weapons scientists towards peaceful purposes, is an important potential benefit arising from this capability.

Detection principle

All reactor antineutrino detectors relevant for these applications make use of the 'inverse beta decay' (IBD) reaction of antineutrinos in proton-rich hydrogenous materials. In the IBD process, antineutrinos interact with a proton, generating a positron and neutron pair.

$$(1) \qquad \bar{\nu}_e + p \longrightarrow e^{+} + n$$

The positron (e^+) is detected first as it slows down and loses energy in the medium, while the neutron (n) is captured a few tens or hundreds of microseconds after the positron by hydrogen, or a doping agent such as gadolinium. The neutron capture process generates gamma-rays which deposit energy in the detector, creating with the positron a two-step time-correlated signature that is relatively hard to mimic by other physical processes.

Detector characteristics

While detector characteristics will vary somewhat across the mid-to-far-field standoff domains, there are a number of common features throughout.

1. First, all of the detectors rely on the detection of UV-to-visible light generated by the interactions of the antineutrino interaction products (positron and neutron) in a light-producing medium such as liquid or plastic scintillator, or water.
2. Due to the large target mass required to produce an appreciable interaction rate (with a minimum mass of around 10 tons or so at 100 m), detector designs are largely constrained to liquid media – specifically liquid scintillator, water (with or without dopants), or mixtures of scintillator and water.
3. All detectors are likely to have a homogenous design. Homogenous detectors consist of a single volume of a detection medium, which at the scales considered here usually implies a vessel filled with a liquid. The vessel walls are instrumented with photosensors to capture the UV-to-visible photons generated by the antineutrino interactions. Photon arrival times, the spatial distribution of photons among the light sensors, and total number of detected photons are all used to select the antineutrino-like signature from backgrounds.
4. With foreseeable technology options, some overburden is required at all mid-to-far-field standoff distances to help suppress backgrounds arising from unremitting flux of cosmic rays (muons, protons and other particles) that rain down upon the Earth . However, the amount of overburden ranges from perhaps 5-10 meters at 100 meter standoff, to as much as a thousand meters at the greatest standoff. With good detector design, some reduction of overburden is possible. Achieving such reduction is dependent on a robust R&D program and data provided by real-world demonstrations.

Further subdivisions of the design parameter space arise as we consider each standoff domain.

Far-field exclusion and discovery detectors design

In the far-field, detector sizes for discovery range from about 500 tons at 10 kilometer, to as large as 500 ktons at the 100 kilometer extreme. This limits detectors to water-based or scintillator-based homogenous designs. For cost reasons and ease of deployability, water-based detectors are likely preferred as standoff increases, though there is some effect on detection efficiency and background rejection. Recently, in an exceptionally pure and deep detector, the SNO+ detector in Canada, detection of reactor antineutrinos at standoff was achieved using purified water only[1]. To make measurements at shallower depths, and to reduce stringent purity requirements, neutron capture agents can be added to the water. These additives help boost the signal strength arising from the final state neutron in the IBD process described earlier. Small admixtures of scintillator can also be added to the water, and this has been demonstrated in the laboratory[5,6] . The water-scintillator combination offers the potential for compromise between the ready availability, and relative ease of purification enjoyed by water detectors, with the increased light yield that characterizes scintillating media.

Mid-field monitoring detectors

For monitoring detectors in the ~100 meter to 10 km mid-field regime, the detector designs have some additional flexibility in design, and additional research and development can help optimization for nonproliferation applications. Pure scintillator detectors are more likely to be deployable at these scales, for which the maximum detector size is no more than a few kilotons, a scale that has been demonstrated by the KamLAND and BOREXINO underground neutrino experiments. Because the total photosensor count and number of readout channels is generally lower at these standoffs, there is also some increased flexibility in the choice of photosensor and readout architecture.

Practical Considerations

Deployment Costs

A significant practical consideration is the expense of deploying and operating antineutrino detectors. Costs differ dramatically with the size and required burial depth of the detector, ranging from of order 0.5-1 million dollars for ten ton detectors operating at shallow depth and at the minimum mid-field standoff of 100 meters, to a several hundred million dollars for 300 kiloton-scale water Cherenkov detectors, the largest currently under construction (HyperKamiokande)[7], to an estimated three billion dollars[8] for the largest U.S. neutrino detector now being contemplated, known as the Deep Underground Neutrino Experiment. The main cost drivers are the expense of excavation, and the cost of the detector components. These are considered below.

Excavation Costs

Excavation of a cavern, or if necessary, the digging of a vertical shaft or horizontal tunnel are significant cost drivers for mid-field deployments and likely dominate costs for far-field antineutrino detector deployments. For example, a 90-meter deep, 24-meter diameter vertical shaft is estimated to cost $60 M in 2011 dollars, while a 15-meter cross section drift extending 120 meters horizontally from the shaft bottom is estimated to cost ~$2 M[9]. Deeper and larger caverns such as would be appropriate for a far-field deployment are being built by the DUNE experiment in an existing 1.5-mile deep mine. Early estimates of costs for a cavern and infrastructure capable of accommodating a ~30 kT detector are in the range of $500 M in 2012 dollars[10] . This estimate is for underground excavation in an existing deep mine.

Due to these expenses, existing caverns or tunnels can and should be used according to their proximity to areas of interest for reactor monitoring. Some nuclear sites include excavated underground spaces for various uses, which could be used for detector deployments, reducing costs for tunnel or shaft excavation. The space would still have to be prepared to accommodate the antineutrino detector, itself a significant expense.

Research into reducing the required deployment depth through improved technology or data analysis methods could increase the number of candidate (shallower) existing deployment sites. For example, improved discrimination against backgrounds using water-based scintillator[6], opaque scintillator[11], or other media could help facilitate deployment at shallower depths.

Detector costs

For detector costs (versus excavation costs), the main cost driver is the cost of photosensors, followed by the cost of the target medium. Photosensors cost range widely, but an exemplary estimate for a large detector is ten dollars per square centimeter of coverage. Lower-cost light-collection techniques are therefore an important contributing factor for reducing detector costs. Wavelength shifting plates, low-cost and passive devices which channel light into an active photosensor from areas larger than the photosensor, are an example of a promising technology for reducing light collection costs.

The second-largest detector cost driver after photosensors is the choice of detection medium (and related purification systems.) Scintillator costs also range widely, but a representative figure is the cost of bulk mineral oil, roughly $1000 per ton.
Other costs, comprising a smaller fraction of the total, include purification systems, power supplies, electronics, and infrastructure such as liquid tanks and calibration tools.

Table 1 provides definitions, maximum detector sizes (total volume), advantages and drawbacks, for three promising media. These are oil-based light-emitting media known as liquid scintillator; water detectors doped at the part per thousand level with a neutron capture agent, and a more recently developed hybrid scintillator-water mixture known as water-based scintillator.

Medium	**Advantages**	**Disadvantages**
Liquid scintillator	• Proven design • Fewer light sensors compared to alternatives • Best for monitoring applications requiring good energy resolution	• Combustible • Must be transported or manufactured onsite
Gadolinium-doped water	• Nontoxic • Readily available • Large detectors possible due to high light transmissivity • Attractive for discovery/exclusion applications	• Inferior background rejection • Poor energy resolution • More light sensors than alternatives
Gadolinium, water, and scintillator mixtures	• Reduced environmental impact compared to pure scintillator • Possibly improved background rejection compared to water • Mixture adjustment provides performance flexibility	• Least mature technology

Table 1: Available detection technologies for mid-field and far-field applications.

Time to Deploy

Aside from financial costs, another consideration is the time needed to deploy the detector. The timeline for deployment of kiloton-scale detectors in existing caverns has ranged from 3-5 years[12]. Longer times would be required for so-called 'greenfield' excavation of a new tunnel or mine, and for deployment of larger detectors. While this may be a consideration in some cases, nonproliferation concerns regarding reactor programs, and the search for solutions to these concerns, can persist over decades, so that the deployment time need not be a factor compared to the time devoted to finding political/technical solutions to the nonproliferation problem. Still, research into options for rapid deployment could offer important operational and cost gains.

Other Technical Considerations

Though it is difficult to provide a complete list of technical concerns for this nascent area of research, some general considerations are worth noting. First, detailed understanding of backgrounds to the antineutrino signal is essential to gauging the size and sensitivity of far-field detectors. Similarly, improvements in the underlying parameters describing antineutrino properties, including the so-called mixing angles and neutrino masses, as well as the branching fractions to the fission daughters that create antineutrinos, would all help to improve the accuracy of predictions. Improvements in the understanding of both the signal and backgrounds can be gained from at-scale tests and demonstrations of the technology.

Public, Political and Nonproliferation Community Acceptance

The installation of a mid-to-large-scale detector in a country would need to be managed carefully to ensure public acceptance. Along with assurances provided by the international partners, the host country would need to explain to its citizens the value of the installation, including the scientific benefit and the benefit of reducing international tensions with the other states involved in the activity. The SESAME accelerator in Jordan is an example of a successful mid-scale technological deployment whose purpose was to bring together nations with diverse populations and perspectives for a common scientific and confidence-building aim[13].

The findings of the international neutrino monitoring team must also be acceptable politically. Much as with protocols established for validating CTBT data, antineutrino-based data would need to ensure that results met a standard that satisfied all parties prior to the reporting of any conclusions to international bodies. Among other approaches, data integrity checks used in the particle physics community could be used to help demonstrate the integrity of the data and the associated analysis.

It is difficult to generally define an acceptable cost level for treaty negotiators and the nonproliferation community. Each specific circumstance will have its own cost-benefit trade-offs. Generally, closer-in deployments will be favorable on cost grounds. Conversely, the benefits arising from acceptance of monitoring by an otherwise intransigent partner, wide areal coverage for the exclusion capability, the possibility of cooperative scientific and nonproliferation engagement, and the knowledge gained from system may raise the value of larger and more distant detectors in the eyes of negotiators.

Experience within the WATCHMAN collaboration has shown that the prospect of meaningful synergy between important nonproliferation goals and fundamental science activities offered by antineutrino detection has already met with enduring interest from a range of stakeholders, including both scientific and nonproliferation funding agencies. Based on experiences like the SESAME project and Lab-to-Lab project mentioned above, we expect this interest would be present on both sides in an international nonproliferation demonstration with a counterparty. An at-scale field demonstration of the technology will offer the wider nonproliferation community and public the opportunity to evaluate the implications of the technology for real-world applications.

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