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An Assessment of Antineutrino Detection as a Tool for Monitoring Nuclear Explosions

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The antineutrino is the only real-time inherently nuclear signature from a fission explosion that propagates great distances through air, water, and ground. The size and sensitivity of antineutrino detectors has increased dramatically in the last decade, and will continue to do so in the next, thanks in part to the renewed interest in neutrino physics brought on by the mounting evidence that neutrinos may have mass. The evolution of antineutrino detectors, and the evident interest of the signature as a means for monitoring nuclear tests motivates this review of the capabilities of existing and possible future detectors as test ban verification tools. Existing liquid scintillator ionization detectors, operating a few tens of meters below the Earth's surface and containing a few thousand tons of active material, could be used to monitor an area of a few square kilometers for nuclear explosions at the 1 kt level. Purified water Cerenkov detectors of sizes comparable to existing detectors (50,000 m^3) could be used to detect 1 kt explosions at distances of a few tens of kilometers. The addition of neutron-absorbing dopants such as sodium chloride or gadolinium to purified water would allow range extension out to approximately 1000 km for sensitivity to a pulse of 10 antineutrino events from a 1 kt explosion. Beyond 1000 km, backgrounds from the world's nuclear reactors would become prohibitively large (at this assumed signal strength). The engineering hurdles for such detectors would be formidable. The size of a doped detector operating at the 100 km range, suitable for cooperative monitoring of existing nuclear test sites, is about 60 times that of the largest existing water detector, and would require a factor of several dozen more photomultiplier tubes than what is now used in large scale physics experiments. Capital costs (primarily phototubes, excavation and the cost of maintaining high radiopurity) would amount to several billion dollars, even for a detector at this modest range.

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Detectors sensitive to a 1 kt explosion at only a few kilometer distance would still cost tens of millions of dollars. Due to these limitations, practical applications of this method for nuclear test detection are almost certainly out of reach for the foreseeable future.

INTRODUCTION

Seismic, radionuclide, hydroacoustic, and infrasound detectors will all be used to verify the Comprehensive Test Ban Treaty (CTBT). Individually and in concert, these sensors will detect, identify, and locate nuclear explosions in the atmosphere, underwater, or underground. They are part of a proposed international monitoring system that, while comprehensive, has limitations. Perhaps the most significant limitation is that the system may not be able to reliably identify, in real time, a very low yield (<~ 1 kt), underground explosion as a nuclear event, particularly if evasion methods such as seismic decoupling are employed.[1] This limitation exists because the shock waves and radiation from the underground explosion are damped or absorbed by the Earth itself. The Earth is, however, transparent to one form of nuclear radiation –- the antineutrino. Detection of the intense burst of antineutrinos generated by a nuclear blast might make it possible to identify low yield or decoupled explosions, thereby helping to resolve the ambiguities that exist in the current monitoring system.

The basic idea of detecting the antineutrinos emitted by nuclear explosions has been broached occasionally since the antineutrino was first discovered in the 1950s.[2] Since that time, advances in detection technology have led to the construction of very large, low noise detectors, with a 50,000 m^3 detector (SuperKamiokande, completed in 1995) already built in Japan, and a 1 km^3 detector proposed for construction at the South Pole.[3] Given these recent and planned increases in scale and sensitivity, the unique properties of the neutrino signature from nuclear explosions, and the apparent absence of a scientific review of neutrino detectors' capabilities in this regard, it is useful to investigate the potential of these systems and consider the improvements that would be required to make them useful for test ban verification purposes.

In this paper, we discuss the prospects for detecting the antineutrino pulse produced by low yield fission explosions. We consider two possible applications: cooperative monitoring at modest distances from a test (less than a few 100 km) and independent remote monitoring at great distances (1000 km to an Earth diameter).

We start with a brief review of some important existing verification technologies, including the four officially designated for use in the international

CTBT verification regime. Next, we consider the possible utility of antineutrino detectors as supplementary monitoring tools for test ban verification. We then investigate the sensitivity of two types of antineutrino detectors to fission antineutrino bursts, including estimates of range, detector size, backgrounds, and infrastructure requirements. We conclude by assessing the potential of antineutrino detectors for test ban verification and possible avenues for future research.

Existing CTBT Verification Technologies

A variety of on-site and remote sensor technologies can be used for verification of the Comprehensive Test Ban Treaty, with each offering unique sensing capabilities. The technologies can be used to search for nuclear explosions in the atmosphere, underwater, underground, or outer space. The use of sensors of different types increases the reliability of detection, and can help identify otherwise ambiguous events.

On-site Technologies[4]

Candidate on-site nuclear detonation detection technologies include seismic, radionuclide, hydrodynamic, gamma, X-ray and neutron detectors as well as ground-based EMP sensors. Some of these technologies have the ability to detect an intrinsically nuclear signature from a low yield test. However, such systems are highly intrusive, requiring in some cases that the sensors have an unobstructed view, typically within meters of any suspect activity. On-site seismic, radionuclide, and EMP sensors can operate at greater distances from any monitored activity, but the probability of detecting and identifying illicit tests is diminished. On-site seismic sensors have the additional drawback (from the host country's perspective) of being able to detect vibrations produced by nearby legal, but sensitive, activities unrelated to nuclear testing.

Remote Technologies

Remote sensing technologies, in combination, provide extensive detection capabilities, although each technology is essentially limited to one detonation medium. The technologies for remotely detecting and identifying nuclear explosions in the atmosphere or outer space are highly capable, capturing the nuclear signature seconds to days after the event. Five of these (Bhangmeters, and X-ray, gamma ray, neutron, and EMP detectors) are designed to see immediate particle and electromagnetic radiation, while radionuclide sensors detect long-lived radioactivity from the explosion.

In contrast, the five remote technologies for detecting and identifying underwater or underground nuclear tests (radionuclide, seismic, infrasound, hydroacoustic, and satellite imaging) are less robust. Only radionuclide sensors can see an intrinsically nuclear signature from a fission explosion, and then only if the contained explosion accidentally vents into the atmosphere. The other four technologies can see various blast effects, but not direct nuclear radiation effects. Consequently, by utilizing evasion tactics such as decoupling, deeper burial, camouflage, concealment, and deception, it may be possible to conduct low-yield nuclear explosions underground that would escape detection altogether, or be incorrectly identified as non-nuclear phenomena such as earthquakes.[5]

From a verification standpoint, the incorrect classification of a seismic event is a particularly vexing problem. In the last ten years alone, there have been three documented cases where natural earthquakes were incorrectly identified as nuclear explosions. Two occurred in January and August of 1996 near the Russian nuclear test site at Novaya Zemlya.[6] In addition to the occasional occurrence of false positives, there is the more persistent problem of false negatives - the classification of low yield underground nuclear explosions as innocuous events.[7] Although seismic sensors have the best chance of detecting a low yield underground test, the relatively weak signal (m_b ~ 2.0-3.0) is not inherently nuclear and would be just one of the thousand estimated ambiguous seismic signals produced by earthquakes worldwide each year.[8] As a result, the rare occurrence of a clandestine, underground nuclear test could be lost in the noise.

The problems of ambiguous signals in the seismic remote monitoring system, and the intrusiveness of existing on-site systems, raise the question of whether other sensors might give useful supplementary information. In the following section we consider how antineutrino detectors fit into the existing verification framework.

Applications of Antineutrino Detectors for Verification

In many ways, the burst of antineutrinos produced in every fission explosion is an ideal nuclear detonation signal. A large number are made in every fission explosion – 10^{24} per kt of fission yield, produced by nuclear β-decay of fission products over roughly a 10 second time period. These travel isotropically from the source at the speed of light. The resulting antineutrino burst is unique – no other source produces an antineutrino pulse of this intensity and duration in this energy range. Since the material around the nuclear device does not appreciably affect the antineutrinos, the signal is independent of the medium in which the explosion takes place. By contrast, medium dependent distortions must be corrected in other sensor systems in order to reconstruct the original signal. In sum, antineutrinos provide the only known, intrinsically nuclear signal that travels large distances from underground nuclear explosions.

It is only recently that detectors large enough to be of interest for nuclear detonation detection have been seriously contemplated.[9] For example, the largest current antineutrino detector, SuperKamiokande, is of the appropriate volume (50,000 m^3) to detect a burst of five antineutrinos from a 1 kt detonation 25 km away. In the following sections, we consider possible applications of antineutrino detectors for both local and remote monitoring of nuclear tests.

Cooperative Monitoring Applications of Antineutrino Detectors

Subcritical Test Monitoring

The CTBT bans nuclear explosions down to zero nuclear yield. The US and Russia have announced their intention to perform "subcritical" tests in which conditions for an exponentially growing fission chain reaction are not created. The activities associated with these tests are quite difficult to distinguish from those connected with low yield nuclear tests. The problem for the U.S. and Russia is to demonstrate that these declared subcritical tests are not actually low yield supercritical tests, and are not being used to mask such tests. At the same time, the two countries are reluctant to use monitoring systems that could reveal sensitive information. Since allowed activities at the test site typically do not produce antineutrinos,[10] and since the antineutrino pulse is the only intrinsically nuclear signal that can be reliably detected outside of the test cavity, antineutrino detectors, if feasible, would be excellent tools for monitoring a declared sub-critical test site.

Reduce Need for On-Site Inspections

An on-site antineutrino monitoring regime would also have value in resolving ambiguous events that may appear to be nuclear explosions with yields much larger than a few kilograms or even a few tons. The CTBT provides for on-site inspections to resolve suspicious events, but these inspections are not immediate, require a political process for approval, and can be highly intrusive over a very large area (up to 1000 km^2). A nonintrusive local monitoring regime could greatly reduce the likelihood of the host nation being required to submit to such an intrusive, and perhaps frivolous, CTBT verification inspection within the detector's area of regard. For example, a detector range of 100 km

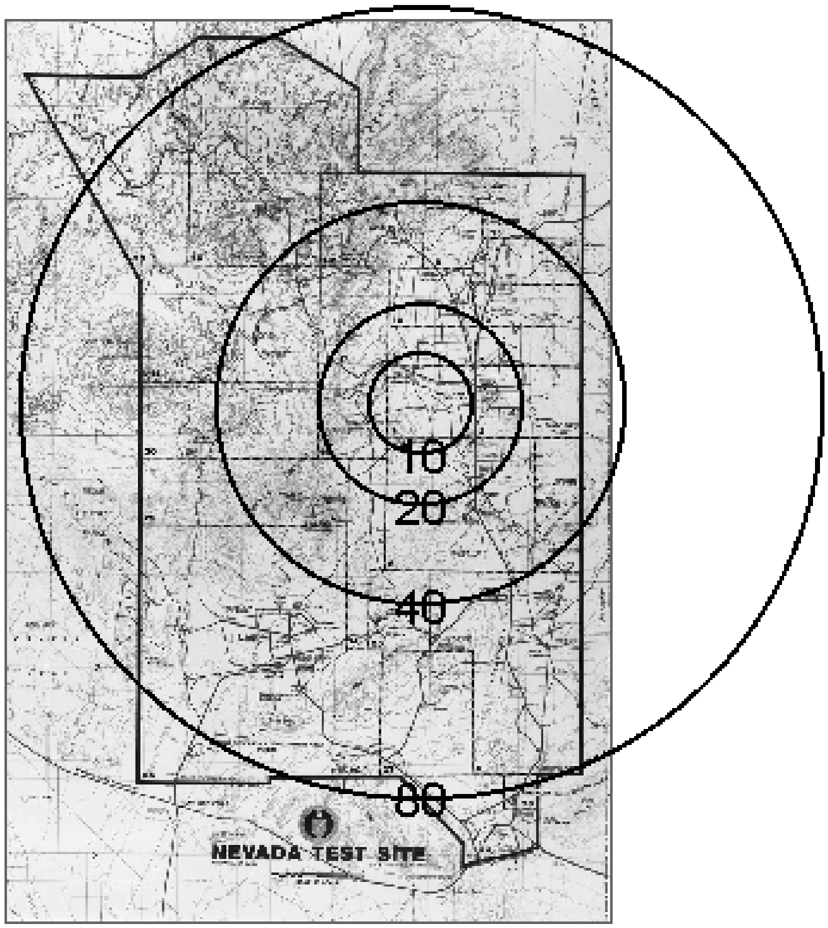

Figure 1: Nevada Test Site with range circles at 10 km, 20 km, 40 km, and 80 km.

for a 1 kt test is sufficient to cover most existing nuclear test sites (see Figure 1). Such a detector would greatly reduce the concern that decoupled kiloton-level nuclear detonations occurring at these test sites were missed by the world wide seismic network, and would reduce the need for intrusive inspections. As an additional benefit, a detector capable of sensing antineutrinos from a 1 kt explosion 100 km away would be able to detect an explosion with a few kilograms of yield 100 m away.

In general, a local monitoring system would build confidence and reduce misunderstandings of the sort produced by the 1996 Novaya Zemlya seismic events. A local monitoring regime could be instituted under the CTBT or through separate agreements.

Applications of Remote Detectors

Because of the difficulty of extracting directional information from the antineutrino signal, long range detectors must operate in tandem with other technologies that can provide more specific information on location. Used in this way, an antineutrino detector would indicate that a nuclear detonation had occurred at a specific time (within a few tens of seconds) and within a certain distance of the detector, while other technologies, such as seismic detection, would provide more precise location of the suspicious event occurring in this time window. Long range antineutrino detectors, operating synergistically with detectors relying on other physical phenomena (principally seismic) would greatly reduce the problem of decoupling, decrease the number of false alarms, and increase the chances of successful and convincing attribution. Antineutrino detectors would also provide additional data on yield and possibly the fraction of yield from fission versus fusion.

The ideal detector would have a range of at least an Earth diameter (12,800 km) for a 1 kt detonation. However, shorter range detectors would also be valuable. For example, a detector with a range of 3000 km for a 1 kt yield, located in Greenland could detect a 1 kt detonation at Novaya Zemlya, or a detonation with a yield above approximately 10 kt anywhere on Earth.

Antineutrino Burst Detection Methods

The low interaction probability of antineutrinos imposes two general requirements: either the antineutrino flux must be high, or the detector volume large. To ensure a high flux, the detector should be as near as possible to the site of the explosion. If political and practical constraints do not allow this, the detector volume must increase. At the extreme limit of an Earth diameter (12,800 km), sensitivity to even five events from a 1 kt explosion would require a detector with a volume equivalent to that of a cube 2.3 km on a side.

In the following sections we define the event characteristics, and the size, composition, and proximity of detectors sensitive to nuclear explosions with yields at or below 1 kt.

Characteristics of Fission Antineutrinos[11]

On average, about 5-6 antineutrinos ($\bar{\nu}$) are produced per fission in a nuclear explosion. The total number is directly proportional to the explosive yield. The burst lasts roughly 10 seconds, with antineutrino energies up to about 8 MeV.[12]

$$N_{\bar{\nu}} \cong 6 \quad N_{fiss}\, Y \tag{1}$$

with

$Y(kt) \rightarrow yield$

$N_{fiss} = 1.45 \times 10^{25} \rightarrow \;\; number\ of\ fissions/kt$

Antineutrino Interactions with Protons

Proton targets are well suited for detecting MeV-scale antineutrinos because of the relatively high probability and low energy threshold of the elastic interaction. As shown in equation 2, the antineutrino ($\bar{\nu}$) converts the proton (p) into a neutron (n) and a positron (e^+).

$$\bar{\nu} + p \rightarrow n + e^{+} \tag{2}$$

The threshold energy for this interaction is:

$$1.8\,MeV \cong (m_n - m_p) + m_{e+} \tag{3}$$

where m_n, m_p, and m_{e+} are the neutron, proton, and positron masses respectively.

Two target materials are most frequently used for detection of MeV scale antineutrinos in real time: H_2O and liquid scintillator. The latter is far preferable in terms of sensitivity and energy resolution, but too expensive and impractical for detectors containing more than a few thousand tons of material.[13]

The energy spectrum of antineutrinos produced by fission of ^{239}Pu and ^{235}U, weighted by the $\bar{\nu}p$ cross section is shown in Figure 2. The emitted positron has the same spectrum shifted to lower energies by 1.8 MeV.

The Number of Interactions in Fission Antineutrino Burst Detectors

The size of the detector is fixed by requiring a minimum number of antineutrino interactions. Equation 4 (derived in reference 14) relates the number of interactions to the yield of the fission explosion Y in kilotons, the volume V in cubic meters, and the distance from test to detector r in meters. The coefficient α, with units $(kt)^{-1}m^{-1}$, depends on the density of the detection medium as shown in Table 1.

$$N_{int} = \frac{\alpha \ Y \ V}{r^2} \quad (4)$$

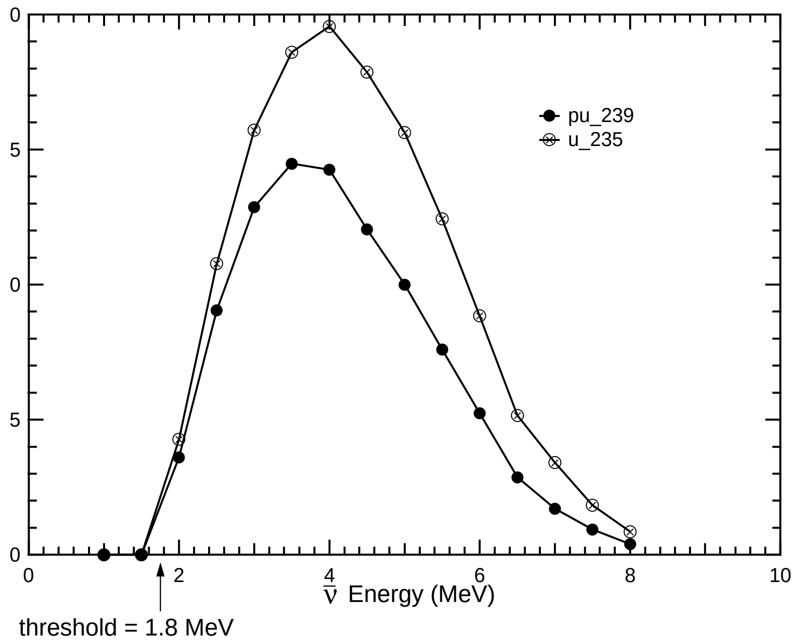

Figure 2: The energy spectrum of antineutrinos produced by the fission of Pu_{239} and U_{235} weighted by the $\bar{\nu}$ p cross section. The interaction threshold is 1.8 MeV.

Table 1: The constant α in equation 4.

Medium	**Water**	**Ice**	**Liquid Scintillator**
value of $\alpha \times 10^4$	5.4	5.0	4.24

By fixing the yield and number of $\bar{\nu} p$ interactions, equation 3 can be used to generate approximate detector sizes suitable for use at various ranges. To give a rough idea of the scales involved, the volume needed to ensure at least two detected antineutrinos with 96% confidence from a 1 kt nuclear explosion at 1000 km is about $(420\ \mathrm{m})^3$.[14]

Antineutrino Detection in Liquid Scintillator

Antineutrinos interact with protons in liquid scintillator as described in equation 2, producing a positron and a neutron. The positron deposits all of its energy within the scintillator volume, giving a prompt scintillation signal. The neutron will capture on proton targets after a mean time of about 150 μs (depending on the proton density of the scintillator) via the interaction:

$$n + p \rightarrow d + \gamma(2.2\,MeV) \tag{5}$$

The photon produces visible ionization energy as it Compton scatters in the liquid scintillator.

The neutron signal can be significantly enhanced and the capture time reduced by using a doping agent with a large thermal neutron capture cross-section. Equation 6 shows the interaction in the case of gadolinium.[15]

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s}(8\,MeV) \tag{6}$$

(*indicates excited nucleus). The neutron is absorbed about 30 μs after production, producing an excited Gd nucleus that releases several MeV of gamma rays. The exact time delay and energy release depends on the element and concentration, with concentrations in existing experiments ranging from 0.1 to 2.5 percent.

Photomultiplier tubes detect the visible light emitted as the positron and the neutron-capture gamma rays ionize the liquid scintillator. The light output is high: thousands of photons per MeV of deposited energy. The high light yield of the scintillator and the sharp time correlation of the positron and neutron signals allows for effective rejection of backgrounds, even for the relatively low energy antineutrinos produced by fission.

An Example of a Liquid Scintillator Based Fission Burst Detector

Here we use design parameters and background estimates for the 1000 ton KamLAND liquid scintillator detector, currently being built in a mine site in Japan.[15] This type of detector is designed for the detection of fission antineutrinos (from reactors) with energies in the same range as those produced by a nuclear explosion. The largest liquid scintillator detector now in operation is the 1600 ton Large Volume Detector (LVD) at the Gran Sasso Laboratory in Italy.[17]

In the KamLAND detector, the visible scintillation light generated by positron decay and neutron capture is recorded with 1300 photomultiplier tubes. Events are selected according to the magnitude of the energy depositions of the positron and neutron, and the spatial and time coincidence between the positron and neutron.

Backgrounds in KamLAND-type detectors are generated by cosmic rays, terrestrial radioactivity, supernovae, and reactors. These backgrounds are analyzed in detail in reference 14. At a depth of 50 meters water equivalent (m.w.e.), the total background from all sources is around 80 events per day using the KamLAND detector characteristics and event selection criteria. The rate drops to 0.028 per day at the actual KamLAND depth of 2700 m.w.e..

Fixing the Number of Events, Detector Size, and Test-Detector Distance

The volume of the detector can be determined directly from equation 4once the yield and number of signal events are fixed. The optimal minimum signal strength can be derived by assuming a Poisson distributed background and demanding that it produce no more than one false positive event per century. (Relaxing this strict criterion to once per year has only a modest effect on the minimum required signal level.) The calculations below use the total background estimate for a detector at a depth of 50 m.w.e. in a 10 second interval. Table 2 shows the number of events required in a KamLAND-sized (1000 ton) detector, and in a set of five such detectors (total mass 5000 tons), as well as the distance at which detectors of the given size would be sensitive to this number of events. The required number of events has been scaled upward to reflect an estimated 20 percent detection efficiency. The range for the large 5000 ton detector array could be extended to about 6.5 km with 100 percent signal detection efficiency. Relaxing the criterion to allow one false positive per year reduces the number of required events for a 1000 (5000) ton detector to 15 (20), and gives only a modest increase in the maximum distance for sensitivity to a 1 kt explosion.

Table 2: The number of raw antineutrino interactions required to guarantee no more than one background-generated false positive 1 kt event per century. Also shown is the distance from a 1 kt nuclear test at which this mass of scintillator is sensitive to the indicated number of events, as derived from equation 4. The background estimate has been scaled to a depth of 50 m.w.e.

Detector mass (tons)	Number of raw events required to guarantee less than one false positive per century	Maximum distance from a 1 kt explosion for sensitivity to this number of events
1000	20	1.5 km
5000	25	3 km

In summary, liquid scintillator detectors operating a few tens of meters below the Earth, with sizes and characteristics similar to existing detectors, could detect 1 kt explosions at a range of a few kilometers.

Antineutrino Detection in H_2O

The cut-off range for the use of scintillator is a few kilometers, due to the prohibitive cost and environmental impact of the huge amounts of scintillator required at greater distances. Beyond this range, water is probably the only suitable medium, despite its inferior sensitivity.

Because the neutron signal is normally not measured in H_2O, spatial and time correlation between the positron and neutron cannot be used for noise rejection. As a result, the background rate is high, consisting of any positron-like signal in the few MeV range. Because of the high backgrounds, water Cerenkov detectors have so far been limited to detection of neutrinos with energies above an approximate five MeV threshold. The five MeV threshold is difficult to lower, as fission burst detection would require.

Detecting a Fission Antineutrino Burst in H_20

Water detectors measure the Cerenkov light produced by the positron in the inverse beta decay process (equation 2). The positron, with a typical energy of ~2 MeV, produces about 270 Cerenkov photons in H_2O in the 350 to 550 nm range,[18] which may be detected by phototubes.[19]

As before, the detector size is set by specifying the yield, range and desired number of events. Ideally, the number of events should be optimized as a function of the background. We set the number of events to be 10, large enough so that the burst is difficult to reproduce by background fluctuations, but as small as possible to minimize the required number of modules.

Design Considerations and Array Size

Because of the small number of photons produced per event, a large number of phototubes and as hermetic a detector as possible are required for efficient recovery of the signal. For reasons of simplicity and efficiency, we consider a spherical array of phototubes surrounding a central volume of water.

The radius of the sphere is constrained by the need to reduce the spread in photon arrival times at phototubes and the effect of light attenuation on the signal. In purified water, the attenuation length for blue Cerenkov light is about 60 m. Significantly larger radius detectors would therefore result in an unacceptable loss of signal. In the following treatment we use modules with total diameters of 50 m, with events accepted from a 45 m diameter inner sphere, corresponding to a 200 ns time window for signal collection by phototubes.[20] The total amount of water in a 50 m diameter spherical module is 65,550 tons (47,712 tons in the 45 m diameter fiducial volume). This is comparable to the total mass of the SuperKamiokande detector (50,000 tons), the largest purified water Cerenkov detector ever built.

The range of a 50 m radius module for a 1 kt explosion is only a few tens of km depending on the number of events required in the signal. To reach greater distances, we must use arrays of modules. We define the signal at great distances as a single antineutrino event in each of a subset of modules in the array, all occurring within a 10 second time gate.

Assuming 50 percent phototube coverage of the detector, a typical ~2.0 MeV positron will trigger about 25 phototubes on average. Existing experiments have about 40 percent coverage.

With this geometry and photostatistics, we can estimate the number of modules and phototubes required for sensitivity to a 1 kt test at a given distance. The tolerable noise level can then be set by demanding that a false positive occur no more than once per century. To ensure a reasonable number of photoelectrons, we demand a minimum positron energy of 2.0 MeV, resulting in a signal loss of about 38 percent. The detector volume is scaled upward to compensate for the efficiency loss.

Table 3 shows the number of modules, number of phototubes per module, and total number of phototubes required as a function of detector range. For comparison, a modern high-energy physics experiment may use as many as 10,000 phototubes. Reductions in the numbers shown in Table 3 by a factor of two or three might be possible with increases in photocathode efficiency, or with improved light collection methods such as focusing lenses.

Table 3: The number of modules of the indicated size required to detect a 10 event burst from a 1 kt explosion at the indicated distance. Also shown are the number of phototubes per module and total number of phototubes at each range.

Range (distance from test to detector, km)	Module radius (m)	Number of modules per detector	Number of PMTs per module	Total number of PMTs
10	20	1	12800	12800
100	22.5	63	16200	~10^6
1000	22.5	~6300	16200	~10^8
~12,800 (Earth Diameter)	22.5	10^6	16200	~10^{10}

Module Noise Restrictions

At distances of 100 km and above, we take the signal as a single antineutrino event in each of 10 detectors in a 10 second time gate. Actual burst-like backgrounds such as supernovae are low, while multiple events produced in a single module from muon showering would not satisfy the multiple module requirement. Therefore the only events of concern are accidental fluctuations to the event level in multiple modules within the 10 second time window.

Table 4 shows the noise rates per module which ensure that a fluctuation to the 10 event level in any 10 second period in the entire array occurs less than once per century. Comparison of these target event rates with various background estimates allows restrictions to be placed on the range, contamination levels and construction depth of fission burst detectors. Relaxing the background restriction to allow one false positive per year rather than per century has only a modest effect on the tolerable background noise level. For example, the allowable noise at 1000 km becomes 1.1 events per day instead of 0.7.

Table 4: The background rate per module required for sensitivity to 10 events from a 1 kt test in a water-based detector at the indicated distance, with the constraint of no more than one false positive per century.

Range (distance from test to detector, km)	**Noise rate per module that ensures no more than one false positive per century (events/day)**
10	5875
100	75
1000	0.7
~12,800 (Earth Diameter)	0.004

Backgrounds

Backgrounds in undoped water detectors are severe because of the absence of a coincident neutron signal. When only the positron is measured, the background consists of any event detectable by Cerenkov radiation and depositing 2 MeV or more of energy in the detector. At ranges above approximately 10 km, the currently achievable water radiopurity levels of 10^{-15} to 10^{-16} g/g for uranium and thorium result in backgrounds well above the tolerable rates just defined. Several order of magnitude reductions in impurity concentrations would be required to extend the range to 100 or 1000 km.

Addition of Dopants to Enhance Sensitivity

Backgrounds might be reduced dramatically if the neutron could be detected in coincidence with the positron. This could be done with a dopant that has a high neutron absorption probability such as gadolinium. This option is being considered for the SNO heavy water detector,[21] in which 2.5 tons of NaCl are to be dissolved in 1000 tons of D_2O. Such doping has never been done in H_2O, or on the scales contemplated here. The advantage of neutron recovery derives from the fact that only the relatively rare time-coincident backgrounds survive event selection. We use gadolinium as an example because of its high neutron capture cross-section.

Capture Time and Position Reconstruction

A 0.1 percent concentration of gadolinium in light water would give a mean neutron capture time of 24 μs. A 100 μs time gate between the positron and neutron signal would then give a 94% neutron capture efficiency. After neutron absorption, the excited Gd nucleus decays into 3-4 gamma rays with a total energy of 8 MeV. A 5 MeV detection threshold should allow recovery of this signal with good efficiency. For comparison, liquid scintillator detectors doped at the 0.1 percent level have measured neutron detection efficiencies of about 85-90 percent with a 6 MeV threshold.[22]

As in liquid scintillator, position reconstruction can be used to define a containment volume for the positron and neutron. A position for each event can be reconstructed using the difference in photon arrival times among struck phototubes. Extrapolating from the 0.5 m vertex resolution of the SuperKamiokande detector[23] to the lower energies expected here gives a crude estimate of 1 m resolution in each coordinate for a 2 MeV (25 hit PMT) positron.

Summary of Backgrounds in Doped Water Detectors

To calculate sensitivity in the presence of a dopant, we require estimates of three backgrounds beyond those for undoped detectors:

- uncorrelated backgrounds produced by the overlap of positron and neutron-like signals within the 100 μs coincidence gate and the event containment volume;
- real antineutrino backgrounds; and
- correlated backgrounds, from fast neutrons that thermalize after having struck proton targets to mimic the positron signal.

Reference 14 provides rate estimates. The total background rate from all sources is close to 1 event per day per module, assuming uranium and thorium concentrations of 10^{-16} g/g, and modules buried at a depth of 3000 m.w.e. Referring to Table 4, this gives a limit of around 1000 km for sensitivity to 10 events produced by a 1 kt test using a doped detector. Even if backgrounds could be further reduced, the reactor background is persistent, allowing extension of the range to only about 1200 km for a perfectly quiet detector sized for 10 events.

Conclusions

The above analysis shows that the immediate prospects for detection of antineutrinos from low yield tests are limited, for both on-site and remote applications. The prospects in different media at various ranges are summarized below.

On-site Liquid Scintillator Detectors

Within a few kilometers of a test site, possible applications of interest are:

- cooperative monitoring of a restricted region of an existing nuclear test site for 1 kt explosions;
- cooperative monitoring of a sensitive area designated by the host country to reduce the likelihood of CTBT on-site verification inspections; and,
- verifying that sub-critical tests are not in fact low yield super-critical explosions nor being used to mask such explosions.

Existing liquid scintillator detectors constructed about 50 m.w.e. (20 m of rock) below the surface could detect 1 kt tests a few kilometers from a source and therefore could be useful for the first two applications. The utility of such a detector ultimately depends on trade-offs between cost and the desire by states for a non-intrusive local nuclear monitoring system.

Monitoring sub-critical tests is much more difficult. For example, an array of about 30 50,000 ton doped water modules (i.e., 30 SuperKamiokande sized detectors) would be required to detect 10 events from a 5 kilogram yield test 100 m distant. Such applications might be of interest only if a detector array were built for other purposes, such as physics research or for longer range monitoring of higher yield tests.

Water Detectors

Water detectors without dopants are not feasible at ranges greater than a few tens of kilometers because of the overwhelming backgrounds from ambient radioactivity. Dopants that enable neutron recovery could help reduce the background rate dramatically. Gadolinium is too expensive (~ $100 per gram) to be feasible for large arrays: detectors using chlorine salts would be less expensive.

If dopants can be used, detection of 1 kt tests at the 100 km range up to about 1000 km is limited primarily by three engineering obstacles. First, the cost of photomultiplier tubes is now around $1000 per tube, while the number of tubes required for remote detection ranges from 10^5 to 10^9 or more. Collection and detection efficiencies of the phototubes, set in our study to 50 percent and 20 percent respectively, may increase no more than threefold overall, with a similar cost decrease. The second obstacle is maintaining radiopurity. Purification levels of $\sim 10^{-16}$ g/g are just within reach of current technology, but the amount of water treated would have to be scaled up at least two orders of magnitude for remote applications. The third obstacle is the requirement of deep burial to screen out cosmic backgrounds. At a sensitive range of around 1000 km, 6300 modules would have to be built about 1100 m below ground for sufficient screening. Examples of large-scale projects approaching this size and depth are nuclear waste repositories. For instance, the Yucca Mountain repository will consist of several miles of tunnels 5 to 10 m in diameter, ~300 m below ground.

Beyond approximately 1000 km the reactor antineutrino background imposes a physics limitation. Even absent other noise, the rate in a single module from reactors is about 0.5 events per day in the world's most remote regions, which, interpolating in Table 4, gives a range of no more than 1200 km for a 1 kt explosion. This limit can be evaded by requiring more than 10 signal events. However, this would require even larger detector arrays.

Taking all of these factors into account, the greatest range that seems possible in the next decade is a distance of 100 km from a 1 kt test, requiring about 60 50,000 ton water modules. This is 60 times larger than the largest neutrino detector now in operation. In short, while antineutrino detectors are in theory very attractive for CTBT verification, engineering difficulties and ultimately physics limitations severely proscribe actual applications. Table 5 summarizes our findings.

Table 5: The applications and feasibility of antineutrino detection at various ranges from a 1 kt fission explosion.

Range (1 kt, 10 events)	Applications	Feasibility
10 km	Cooperative monitoring of few sq. km areas of former test sites Cooperative monitoring to create CTBT on-site inspection "exclusion zones"	Possible with current liquid scintillator detectors built at depths of 50 m.w.e.
100 km	Detection of 1 kt tests over entire test sites Cooperative monitoring of subcritical tests placed near the detector array See over borders for larger tests	At limits of current technology: • Must recover neutron signal through doping • Cheaper photodetection would help (current phototube noise acceptable)
1000 km	See over borders Cover entire countries/ regions of interest	Significant advances needed beyond current technology • Lower cost photodetection • Improvements in large scale water purification • Recovery of neutron signal • New detection methods/ways to reduce background
10,000 km	Remote monitoring of 1 kt tests	Impossible for this design type and number of events due to irreducible reactor backgrounds

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NOTES AND REFERENCES

1. http://www.ctbt.rnd.doe.gov/ctbt/introduction/onsite_inspections.html.

2. See for example, T. Bowles and M. Silbar, "The Neutrino in 1980," *Los Alamos Science*, (1981): 2:1, 94.

3. Information about SuperKamiokande can be found at http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/super-kamiokande.html, while the cubic kilometer ice detector is described at http://amanda.berkeley.edu/km3.

4. The CTBT includes provisions for post-event On-site Inspections, which can include the use of specified sensing equipment sometimes referred to as "On-site Technologies." The use of these sensors is intended to resolve ambiguous events detected in other systems (e.g. the remote sensing systems). In this paper, we use the term "On-site Technologies" in a more generic way to refer to *any* sensor deployed within a short distance of a suspected test site for the purpose of registering a signal from a nuclear event. Since there are no provisions in the CTBT for monitoring with this larger class of sensors, permission to use them would have to be granted by separate bilateral agreements.

5. Given this technical limitation in the current international monitoring system, on-site inspections (OSI) will be relied upon to gather evidence on ambiguous or suspect events.

6. The third false positive occurred in Pakistan on April 28, 1991. Pakistani scientists incorrectly suspected that the event was an Indian nuclear test. Gregory van der Vink and Terry Wallace, "The Political Sensitivity of Earthquake Locations," *IRIS Newsletter*, (1996): 20-23. Gregory van der Vink and Terry Wallace, "Response to Comments by M. Henger, K. Koch, B. Ruud, and E. Husebye," *IRIS Newsletter*, (1997): 16:2, 21-22.

7. Seismologists have incorrectly classified nuclear explosive tests as earthquakes before. See S. Arora and T. Basu, "A Source Discrimination Study of a Chinese Seismic Event of May 4, 1983," *Tectonophysics*, (1984): 109, 241-251.

8. WJ. Hannon, "Seismic Verification of a Comprehensive Test Ban," *Science*, (1985): 227: 4684, 251-257.

9. http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/super-kamiokande.html,http://amanda.berkeley.edu/km3, op. cit.

10. Pulsed reactors could produce weak antineutrino bursts with a variety of time

scales.

11. The signal is described in more detail in reference 14.

12. Other detection methods, which rely on radiochemical conversion of nuclei by neutrinos, have cycle times that are too slow to be useful for detecting fission explosions in real time.

13. We take five interactions as the minimum number for detection of two events with 96% confidence.

14. Adam Bernstein, Todd West, Vipin Gupta, *An Assessment of Antineutrino Detection as a Tool for Monitoring Nuclear Explosions*, SAND99-8497 (Livermore CA: Sandia National Laboratories, June 1999), 13. This expanded version of the current article contains more detail on backgrounds and detector design.

15. Gadolinium has a neutron capture cross section of about 49,000 barns, compared with 0.328 barns for hydrogen.

16. Detector parameters are taken from F. Suekane, "Status of the KamLAND Experiment," Talk presented at Europhysics Neutrino Oscillation Workshop, (Now'98) 7-9 September 1998, Amsterdam, the Netherlands.

17. We neglect the small amount of Cerenkov light arising from Compton scattering of the positron annihilation photons.

18. http://www.lngs.infn.it/lngs/htexts/lvd/.

19. At the ten kilometer range, a slightly smaller 40 meter diameter module.

20. Cerenkov light is a coherent electromagnetic shock wave emitted when a charged particle travels through a medium at speeds greater than the speed of light in the medium.

21. H.H. Chen, "The Sudbury Neutrino Observatory," *Nuclear Instruments and Methods in Physics Research* A264, (1988): 50.

22. H. de Kerret et al., "Proposal to Search for Neutrino Vacuum Oscillations Using a 1 Km Baseline Reactor Neutrino Experiment," (1993), http://www.hep.anl.gov/NDK/Hypertext/chooz.html, 74.

23. T. Yamaguchi, *Study of Solar Neutrinos at Super-Kamiokande*, Thesis, University of Tokyo, (April. 1988). http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/pub/index.html, 75. This extrapolation is treated in more detail in reference 14.