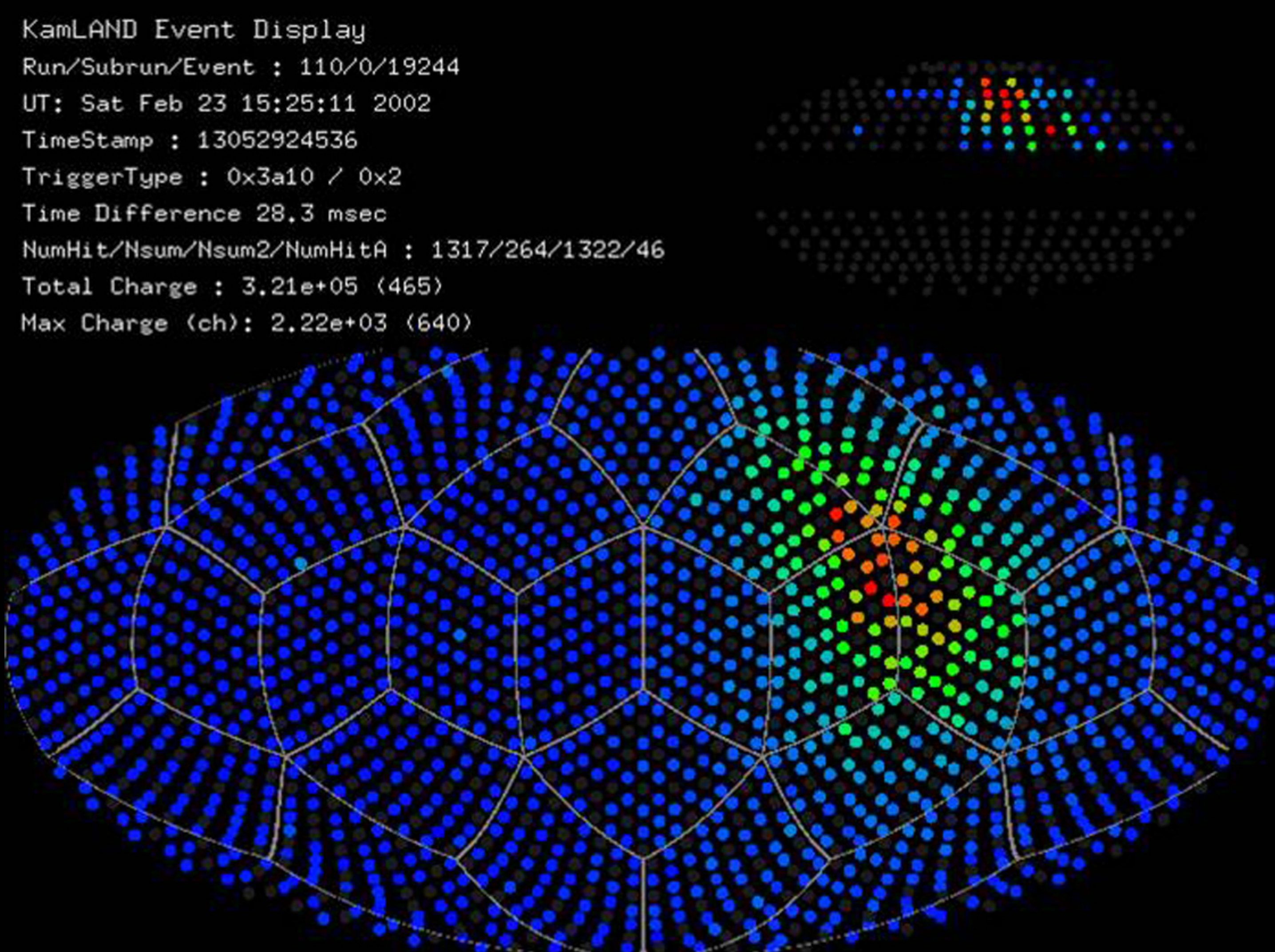
Antineutrino Detection for Nuclear Monitoring



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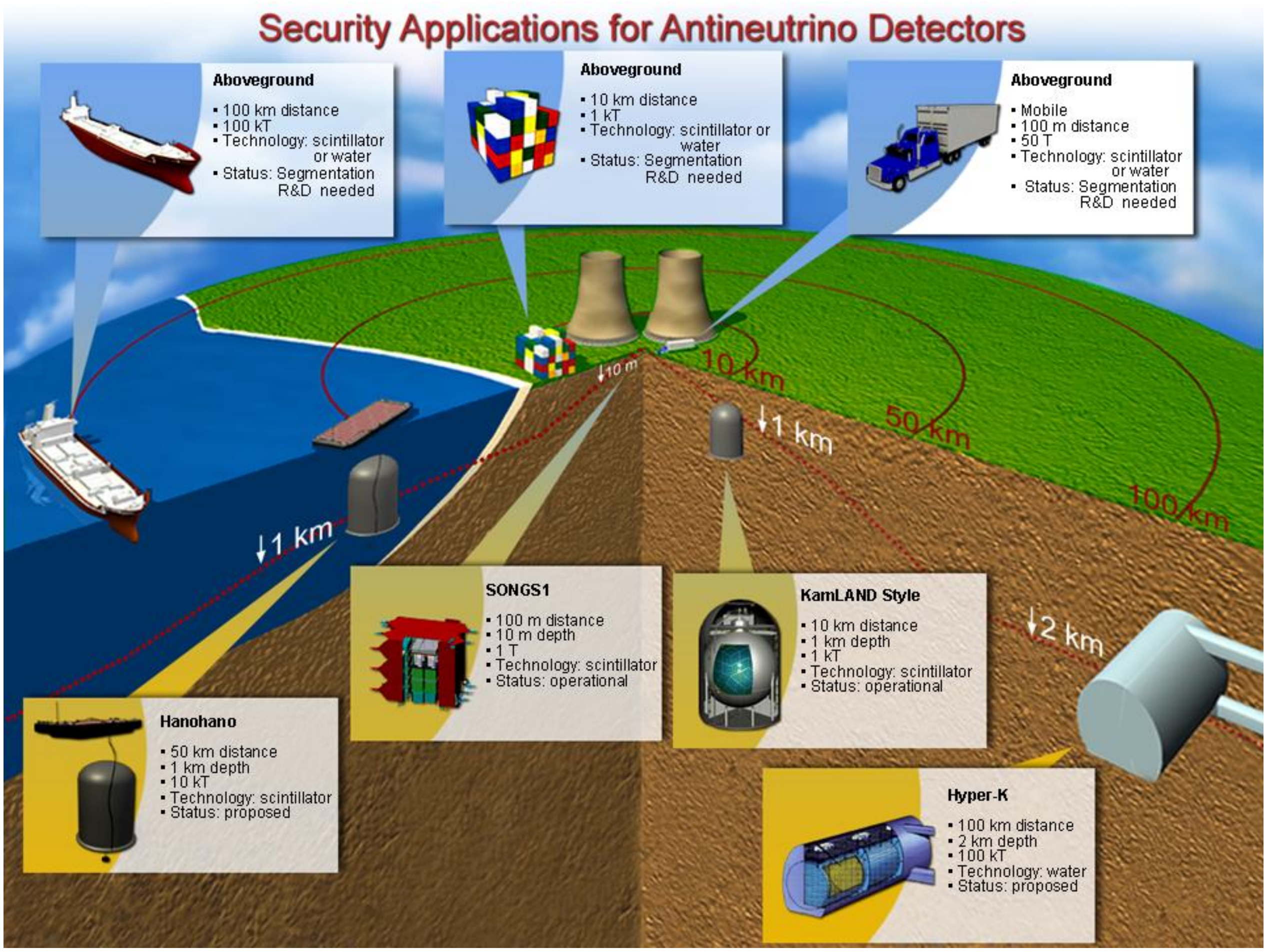


Graphic courtesy Lawrence Livermore National Laboratory

On the cover: Stopped muon in KamLAND, the largest scintillation detector ever constructed.
For more information and pictures, go to http://kamland.lbl.gov/.

FOREWORD

This draft report is the result of a productive and intensive workshop held at the University of Maryland on January 2–5, 2008, that engaged leaders in the antineutrino science and nuclear security communities. Drawing on contributions from experts in both fields, this report presents a survey of applied antineutrino physics in the areas of nonproliferation, geophysics, and particle physics. It also summarizes recent advances in the field, describes the overlap of this nascent discipline with other ongoing fundamental and applied antineutrino research, and sketches a course for research and development for future applications. It is intended to be a resource for policy-makers, researchers, and the wider nonproliferation community.

1. EXECUTIVE SUMMARY

The threat: The potential for a terrorist group to acquire or make nuclear explosives is directly proportional to the global availability of plutonium and enriched uranium. A rogue state or terrorist cell can covertly acquire these special nuclear materials from:

- Assembled weapons
- Raw uranium ore
- Enriched uranium used to fuel nuclear reactors
- Plutonium extracted from spent fuel

The technology: The antineutrino is a subatomic particle produced in all nuclear fission processes—in particular, reactors and nuclear explosions. No matter how much shielding may be provided, huge numbers of antineutrinos escape. Detecting these antineutrinos provides irrefutable evidence of a fission reaction. Triangulation from multiple detectors can even define reactor locations.

The promise: Nuclear power reactors are expected to proliferate in response to the rising cost of fossil fuels and the effects of global climate change. The increased number of reactors will strain conventional means for safeguarding these sources of plutonium and uranium. A global antineutrino monitoring infrastructure will help avert the spread of covert nuclear reactors and weapons development programs.

Why now? The oncoming rapid multiplication of nuclear reactors and concomitant international security issues create more urgency for this mission. There is a time window within the coming decade during which antineutrino monitoring can be brought into common use. In order to design the needed capabilities into next-generation reactors, and the detectors best suited for monitoring these reactors, *a focused national effort needs to begin now, before the next generation of reactors is built worldwide.*

Specifically, we should …

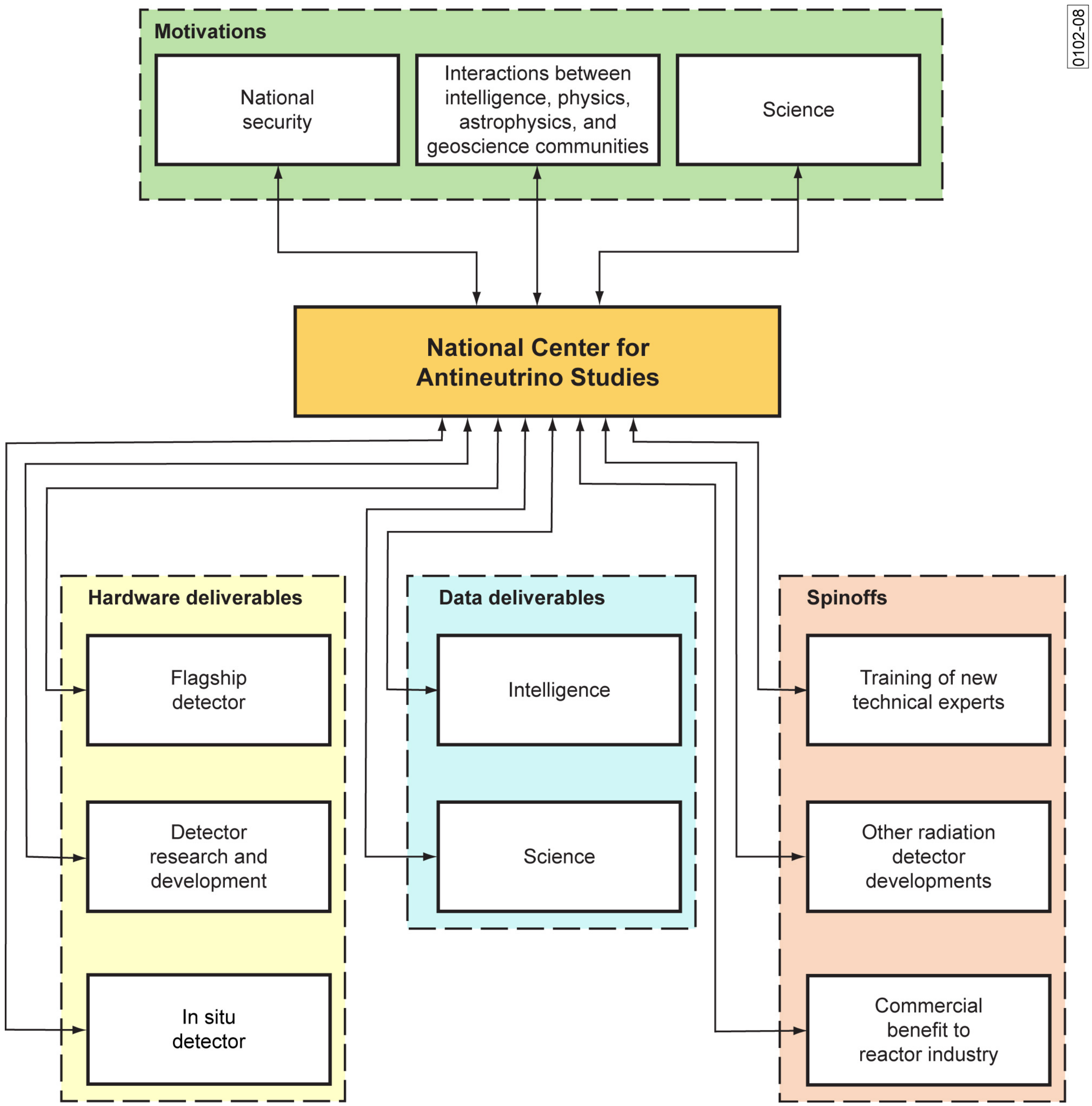
Key Recommendations

- ***Establish a National Center for Antineutrino Research to coordinate and extend national efforts aimed at deploying antineutrino detectors for security purposes***
- ***Commission a comprehensive study that addresses center functions, technology road maps, data management, sensor deployments, operating parameters, physical design, economic impact, and both physical and cyber security***
- ***Construct and deploy a remotely operated flagship antineutrino detector***

The conceptual diagram below shows the proposed National Center for Antineutrino Research. The center will provide:

- An environment that fosters the exchange of technical knowledge between the intelligence and scientific communities.
- A clearinghouse for antineutrino monitoring for national security.
- A focus for research into developing techniques to improve the performance of antineutrino detectors while reducing their cost and size.
- A framework for expert evaluation of new ideas and for steering the field forward.

The center will enhance communication and coordination between academics and national laboratory and industry personnel engaged in the construction of detectors of rather different scopes and sizes. And, by attracting promising graduate students in antineutrino detection from around the world, a byproduct will be a new cadre of experts in the field.

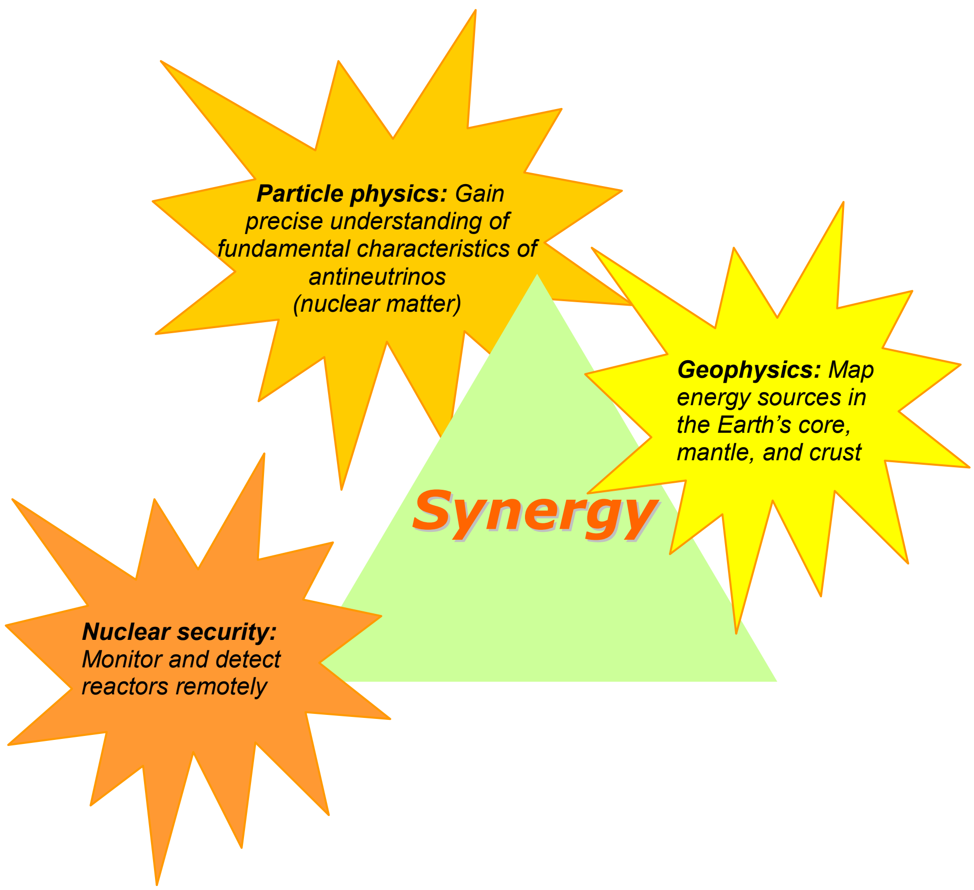


2. SYNERGY

Antineutrino signals from nuclear reactors cannot be faked or masked, so their measurement provides a unique information source for national security. Using antineutrino detectors to meet the needs of the nonproliferation community will, in turn, synergistically provide more and new data to improve the understanding of fundamental sciences.

Both the nonproliferation and science communities share an overlapping need to understand the fundamental parameters that describe antineutrino travel through the Earth, the background of neutrinos from radioactivity in the Earth, and antineutrino production from nuclear reactors. Current antineutrino detectors have measured most (but not all) of the fundamental antineutrino parameters to a little better than 10%, a necessary prerequisite before we can expect to use these antineutrino measurements and signals to provide national security and nonproliferation warnings. The better we know these parameters, the more reliably national security concerns can be met with antineutrino measurements and the more clues physicists have to finding universal governing patterns.

In the past decade we have advanced our understanding of the properties of antineutrinos substantially. This success has created a surprising synergy between three apparently unrelated areas: particle physics, international nuclear security, and geophysics.



Particle physics: Particle physicists are interested in gaining a precise understanding of the fundamental characteristics of antineutrinos, including their quantum mechanical properties. Measuring these properties provides physicists with a unique "microscope" to study the laws of nature at distances well below the size of the smallest subatomic particles). The last few years have revealed many surprises in the properties of both neutrinos and antineutrinos, particularly in their ability to "oscillate" from one type of neutrino to another and the fact that their mass is finite, albeit extremely small. These discoveries indicate that the laws of physics change at extremely small distances. With these properties of antineutrinos and their details being very actively pursued in the international research arena, we now know antineutrino characteristics well enough to consider the utility of antineutrino monitoring for the international security community.

International nuclear security: Anticipated future increases in the number and geographic spread of nuclear reactors worldwide are expected to significantly challenge the ability of both the international community and the US national security community to sustain a robust nonproliferation environment. Using antineutrino detection systems holds promise for providing a reliable, automated, and cost-effective method to address both international safeguards and US national security concerns.

The nonproliferation community has come to recognize the potential of antineutrino detectors for:

- Monitoring the operational status, power, and fissile content of operating nuclear reactors
- Detection or exclusion of the presence of reactors at a few kilometers' standoff
- Remote detection of undeclared reactors or fission explosions

Different solutions need to be perfected for the various applications, and in some instances entirely new detection mechanisms may be developed, such as so-called "coherent neutrino scattering," which employs a new and as yet undemonstrated mechanism, with great potential for reduction in detector size or increase in the detectable range of reactors for a given size detector.

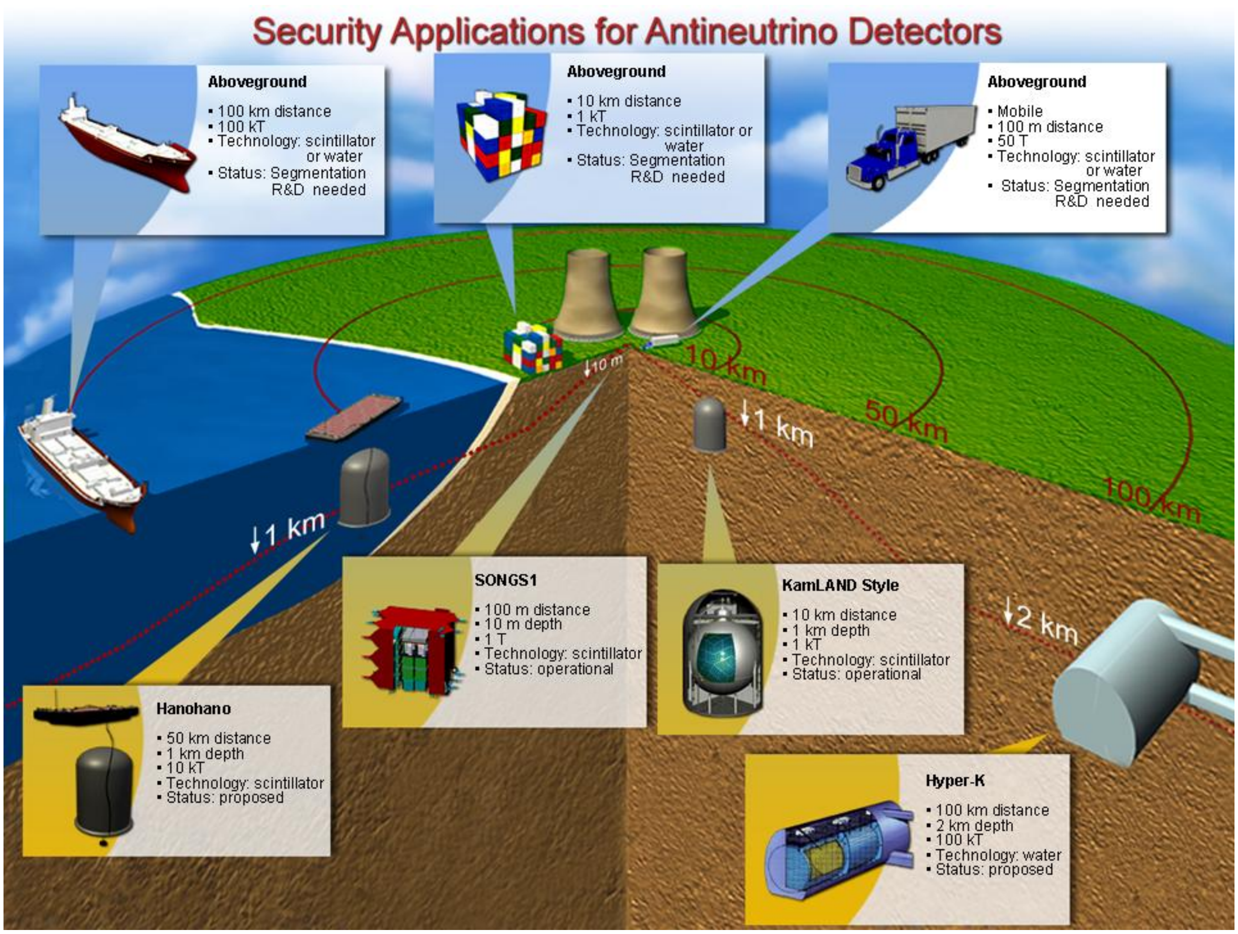
Geophysics: Coming from an entirely different scientific community, geophysicists and geochemists now recognize the power of using antineutrinos as a tool for mapping the distribution of radionuclides in the Earth's crust, mantle, and core. Antineutrinos have the potential to extend and transform our understanding of the origin and distribution of the Earth's heat sources, the forces that drive plate tectonics, and the geomagnetic field.

Geoscientists would greatly benefit from a worldwide antineutrino monitoring network, in particular from mobile detectors in the deep oceans. The observations of reactors and geoscience, as well as a range of other potential uses, such as searches for new particles of astrophysical origin and exotic rare processes are mutually compatible, simultaneous, and—because each phenomenon is a background for the others—reinforcing. The community has thus come to recognize the tremendous synergy between the needs of fundamental science and the newly appreciated nuclear security applications for antineutrinos.

3. OVERVIEW

Antineutrino monitoring systems can operate at various ranges: ease of deployment scales directly with the power and inversely with the distance from the reactor being monitored. Nearby (10–100 m) antineutrino monitoring of nuclear reactors is a realistic, near-term addition to the existing international monitoring carried out by the International Atomic Energy Agency (IAEA), which relies heavily on operator declarations of reactor power and fissile content. In order to take direct measurements, the IAEA must perform intrusive activities, such as making actual physical connections to the reactor piping. Antineutrino monitoring, in contrast, offers a continuous, near-real-time, and nonintrusive record of power production and plutonium generation of reactors. This new window into reactor cores can, in the near term, provide a reliable, independently measured benchmark for the entire reactor fuel cycle, and serve as a watchdog for a range of suspect activities, such as repeated short shutdowns for removal of plutonium-bearing fuel rods.

We have within sight the opportunity to build a worldwide network of reactor monitoring systems that covers both cooperative and uncooperative reactor operators. Such a large network could enhance the global nuclear test detection network. For example, sensing even one antineutrino event in coincidence with seismic data could—with a high degree of confidence—reveal the nature of an explosion (nuclear vs. non-nuclear) and provide an estimate of its yield.



Graphic courtesy Lawrence Livermore National Laboratory

Schematic illustration of various detector types versus distance from a reactor.

3.1 Reactor detection and monitoring

Recent scientific achievements have proven that small (1-ton) antineutrino detectors using well-developed technology can now be used to monitor nuclear reactor operations from the 10 m range. Such observations yield a measurement technique that is:

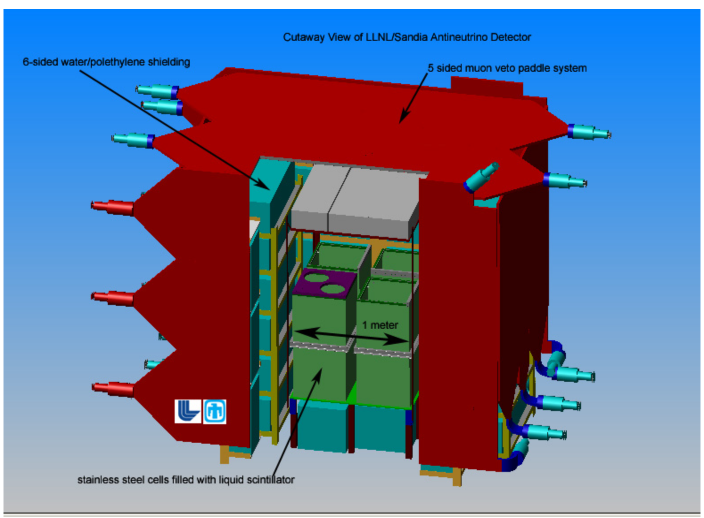
- Nonintrusive (absolutely no physical connection to the reactor is required)
- Cannot be spoofed or hidden
- Can be automated for continuous (persistent) surveillance and readout from distant centers

Such antineutrino monitoring systems benefit both the organizations responsible for safeguard monitoring and reactor operators. Monitoring organizations will realize cost savings by reducing the number of on-site inspections (if automated remote systems are deployed), while reactor operators will benefit because of the nonintrusive aspect of the automated system and access to prompt analysis of the antineutrino sensor data. The power and fissile content measurements may have the additional benefit of providing useful feedback to operators interested in tracking fuel consumption and power production in their reactors. This power-monitoring capability thus has the potential to be the first direct commercial spin-off of this technology. Reactor safety can potentially be enhanced as well.

To obtain the maximum benefit from this new technology, the following system characteristics need to be incorporated:

- An effective antineutrino sensor system must be designed into new construction or a cost-effective system that can be deployed (above ground) near the reactor site must be developed.
- The system should operate via remote communications continuously, producing a near-real-time measurement of reactor operations.
- The system should be capable of resolving the antineutrino energy spectrum well enough to effectively monitor reactor core burn-up.

The national security community has a recognized need for both on-site and standoff antineutrino reactor monitoring. The feasibility of small on-site antineutrino monitoring has been demonstrated during the past year at the San Onofre Nuclear Generating Station (SONGS) in California. Key remaining desirable characteristics for on-site monitoring are now being pursued, including further miniaturization, improved energy resolution, detector efficiency improvements, use of nonhazardous materials, and background signal rejection.



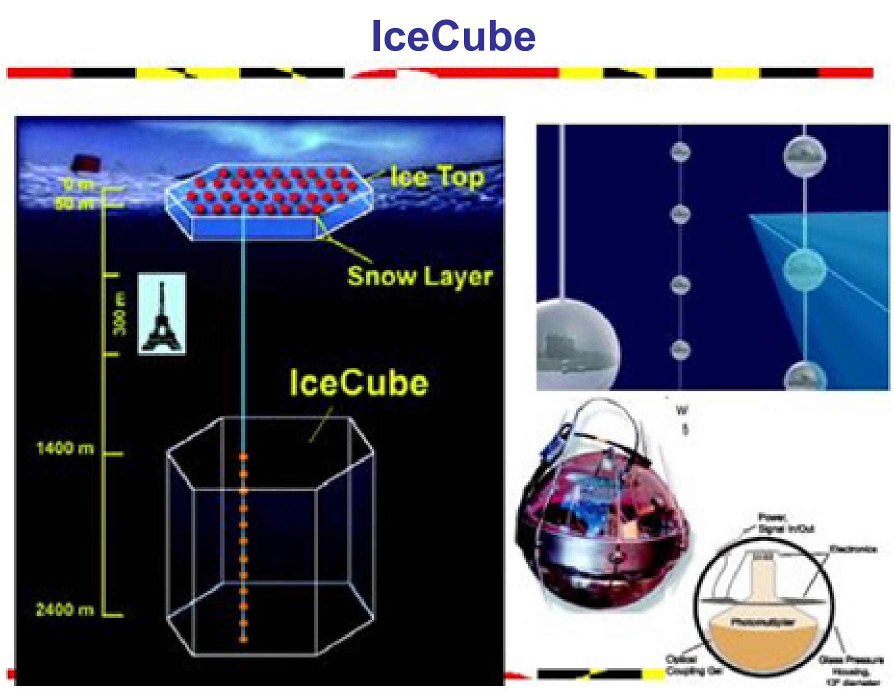
Graphic courtesy Lawrence Livermore National Laboratory

The SONGS1 prototype reactor monitoring detector. The active antineutrino detector is one cubic meter, with neutron/gamma shielding of approximately 0.5 meters on all sides.

Current detectors are located beneath a few meters of concrete shielding from the background produced by cosmic rays. Detectors that can operate just outside the reactor containment building, and without large amounts of shielding, are just starting to be developed and will require new and heavily segmented technology. We envisage surface detectors on the scale of tractor-trailers being operated as near as possible to a reactor.

Standoff antineutrino reactor monitoring is feasible but can greatly benefit from more fundamental antineutrino research and collaboration with other research efforts, for example, physics, astrophysics, and geophysics that focus on measurements of antineutrinos generated at short and long ranges. Current research assumes that detection range increases can be achieved only with concomitant increases in size and complexity of the detector system. Some improvements can be realized by technology developments in background rejection and improved understanding of antineutrino propagation characteristics. But the major issue for longer-range detection is the development of new materials and sensor technologies (e.g., new-generation photosensors) that can drive down the cost of these inescapably large instruments.

Existing prototypes include the 1000-ton KamLAND liquid scintillation detector, which senses reactors from around Japan at a typical range of 200 km, and the 50,000-ton SuperKamiokande water-based detector. Credible scientifically driven proposals exist for deep underground million-ton antineutrino detectors. A billion-ton detector called IceCube is being built at the South Pole. Although its energy threshold is much too high to observe reactor antineutrinos, it does set a scale precedent.



Graphic courtesy University of Maryland

The gigaton IceCube detector, under construction at the South Pole. Note its size in relation to the Eiffel tower shown at the left-hand side of the figure.

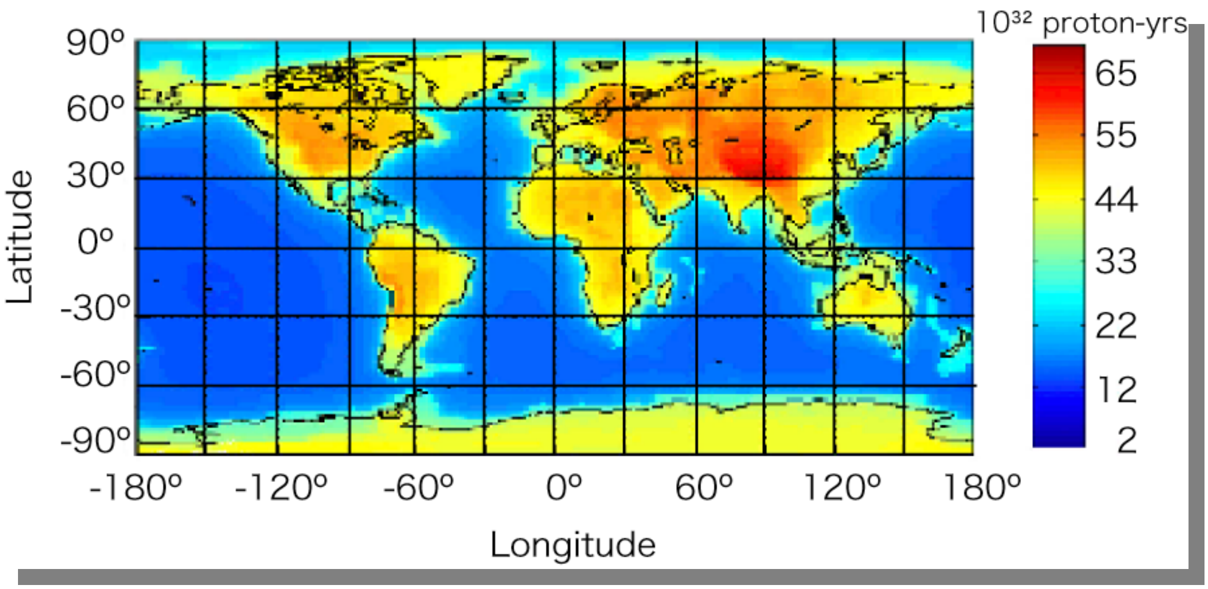
In any event, economy-of-scale improvements for materials and readout methods are needed in order to build antineutrino detectors sufficient to constitute a long-range reactor (and weapons testing) network. Concentrated research and development can drive the costs into more practical ranges. A first-step 10-kiloton liquid scintillation detector, described in more detail in Section 5, has been proposed for deployment in the deep ocean.

Such large detectors, or their successors, can be used in concert with small, close-in antineutrino monitors, as discussed above, to create a network with multiple capabilities. Specific situations have different needs. With a partially cooperative nation, for example, we could deploy a network of modestsized instruments to guarantee that no hidden reactors are being operated. In another scenario, we could mount a large surface detector on a ship in international waters to monitor uncooperative facilities along a coastline. Or in yet another scenario, a large detector could be deployed invisibly underwater off the coastline. In all such cases the undeclared facility would be revealed by a deviation from the anticipated antineutrino flux at the detector.

3.2 Real-time confirmation of nuclear weapons detonation/covert test

Although we have known for a long time that fission weapons could *in principle* be detected and even measured in yield by observation of their huge few-seconds burst of antineutrinos, the problem is daunting. However, with the growth of a reactor-monitoring network of large detectors, weapons testing enters into the mix. The same countries that may be under close observation for reactor utilization are likely to be the same candidates for an underground weapons test, so there is an automatic synergy between these monitoring goals.

Traditional test detection, accomplished via seismic or other means, has its limitations. Events that were unquestionably explosions can be ambiguous with respect to the nature of the explosion (e.g., was it chemical, a fake, or an accident). Detecting even one antineutrino in coincidence with such an event could yield unique and crucial information. Detecting 10 such events gives us a 30% estimate of the yield.



Graphic courtesy University of Hawaii

Predicted antineutrino detection around the world. The color scale indicates the rate of events that would be detected at that location by a detector of 10^{32} protons observing for one year, or about that from a kiloton-sized instrument per year. Most of the flux will be due to continental crust, particularly over the thick Himalaya region, except in the deep oceans. (Note: Data is modeled, not actual)

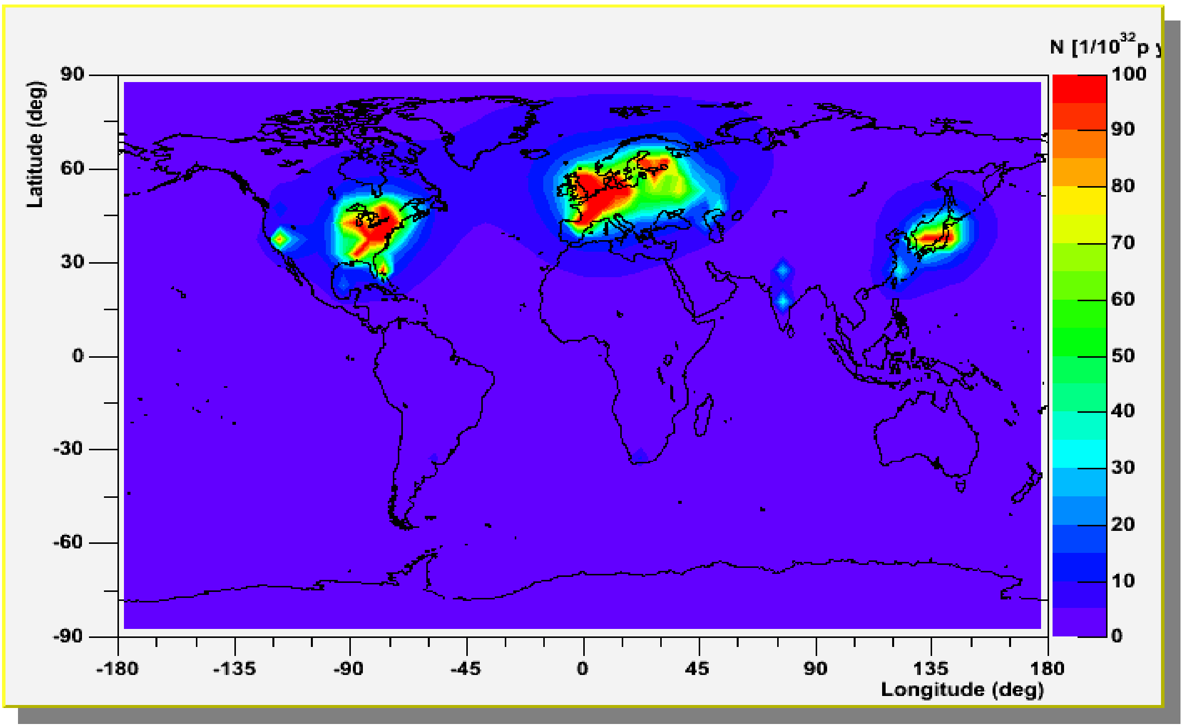
3.3 Fundamental science—the time is right

Fundamental science in the fields of geophysics, astrophysics, and basic antineutrino physics is ripe for exploration with the detectors and arrays of instruments under discussion. The lower-energy regime—appropriate to reactor neutrinos, solar neutrinos, neutrinos from natural radioactivity throughout the Earth, and neutrinos from supernovas—constitutes a special class on which the center should focus.

Geophysics: transformative scientific discoveries. There are large uncertainties in our understanding of the Earth system, which hinders our progress on establishing the underlying geophysical principle of how the Earth operates. Counting the Earth's antineutrino emission will lead to transformative scientific discoveries in basic geosciences. Data from these experiments will provide insight into the Earth's energy budget, and will provide fundamental information on the forces that drive plate tectonics and that generate the Earth's protective magnetic field.

The strength of the antineutrino signal from Earth is directly proportional to the abundance of thorium, uranium, and potassium within it. These radioactive elements provide the nuclear fuel that drives the Earth's engine. Knowing the absolute abundance of the radioactive elements in the Earth tells us about the temperature structure of the interior of the planet; from these insights we can begin to understand the Earth's thermal evolution.

The first results from the KamLAND antineutrino detector demonstrated that it is possible to detect geoneutrinos and thus establish limits on the amount of radioactive energy produced in the interior of our planet. Measurements have become increasingly more precise since.



Graphic courtesy University of Hawaii

Average antineutrino flux around the world due to nuclear reactors, showing the antineutrino interaction rate per 10^{32} protons per year, or about that in 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. (Note: Data is modeled, not actual)

Portable, ocean-based antineutrino detectors, deployable on the sea floor, would enable us to measure antineutrino signals on a global scale. Such detectors could be deployed close to a nuclear reactor, or out in the deep ocean, far removed from the continents and nuclear reactors, in order to assess the ambient background signal from within the Earth.

Particle physicists are only a decade or so away from implementing experiments that will allow more precise determination of the Earth's structure. This would appreciably improve on the precision of global seismological models. This work directly relates to climate change because an accurate determination of the deep location of the radioactive elements thorium and uranium would allow for better interpretation of the temperature gradient measured near the Earth's surface, which includes hundred-thousand-year-scale information on local temperature history.

Astrophysics. Remote reactor sensing detectors will have new capabilities to detect astrophysical events such as the neutrino burst from gravitational collapse supernovas. Current detectors can sense events out to a bit beyond our galaxy and nearest neighbors. Larger arrays begin to enable the possible detection of other types of objects at cosmic distances, most notably neutrinos from gamma ray bursts. These still-enigmatic objects, which may momentarily appear as bright as the entire universe and are powerful enough to affect terrestrial radio communications, have unknown driving mechanisms and remain largely a mystery. Operating such detectors while making other astronomical observations simultaneously might prove key to arriving at a new understanding of physics.

Basic neutrino science. Unique antineutrino parameter measurements can be made from a distance of 50 to 60 km offshore from a nuclear power reactor complex. With larger instruments, we can accomplish studies of high importance with a high-power neutrino beam or from a neutrino factory. Within a few years experiments now under way will better chart the possibilities for this work, but the potential of discovering the origin of matter over antimatter keeps a significant fraction of the high-energy physics community up at night. Antineutrino physics may hold the key to this mystery. In this rapidly evolving field, the goals shift with time. With mobile antineutrino detectors one can "follow the physics."

3.4 Matching nonproliferation antineutrino applications to physics applications

The antineutrino detectors used to monitor the world's nuclear reactors would be transformational to the field of geophysics, would vastly expand neutrino astronomy, and would improve the measurement of the fundamental neutrino parameters by an order of magnitude, enabling discrimination between competing fundamental theories of physics. A broad range of basic physics opportunities can be pursued by using detectors that are also used to monitor and detect nuclear reactors. A brief overview of possible applications is shown in the table below.

Nonproliferation Physics Synergy

Monitoring Distance	*Possible Monitoring Applications*	*Possible Physics Applications*	*Detector Scale*
Short-distance <100 m	• Logging operational uptime and thermal power • Fuel monitoring and characterization	• Investigate new antineutrino interactions	<1 ton
Medium-distance 100 m–10 km	• Logging operational uptime • Exclusion/detection of undeclared reactors of >10 MW	• Investigate antineutrino properties	10 tons–10 ktons
Long-distance >10 km	• Logging operational uptime of multiple reactor facilities • Exclusion/detection of undeclared reactors of >100 MW	• Investigate Earth's structure • Investigate antineutrino properties • Detect supernovas • Search for exotic interactions	10–1000 ktons

Near-distance monitoring (<100 m). Monitoring antineutrinos at short distances is generally accomplished by using small, compact detectors less than a few meters on a side. Such detectors are deployed within a reactor complex and require the cooperation of the reactor operators for access. National security interests in such monitoring range from the simple logging of reactor operational uptime to the careful determination of thermal power and fuel composition. There is a potential that a high-precision thermal power monitor could be adopted by the nuclear reactor industry or the NRC to improve operational efficiency and safety. A mobile version of such a detector could even be used to diagnose a critical failure or reactor meltdown such as Chernobyl.

Intermediate-distance monitoring (100 m–10 km). Antineutrino monitoring at intermediate distances is usually performed by detectors in the 10 ton–10 kton range. These detectors require shielding from cosmic radiation, which is usually satisfied by installing the detector 50–500 m underground or under at least a few hundred meters of water, as with the antineutrino detectors monitoring the Chooz power plant in France. In addition to being able to simply log the operational uptime of reactors within this distance, such monitoring can also be used to establish the existence or absence of any reactor with a power of 10 MW or greater. A properly located detector of this scale could be sensitive to the passage of a nuclear submarine within a few kilometers. Such speculations certainly warrant further study.

Graphic courtesy Sandia National Laboratories

The French nuclear power plant Chooz will have a 5-ton detector that lies 110 m underground and another detector at 2 km distance

Long-distance monitoring (>10 km). Detectors used for long-distance monitoring are generally characterized by their large size. Such detectors require significant passive shielding, needing to be at least a kilometer underground or under water. These detectors can monitor the operational uptime of multiple reactor facilities within a zone of several hundred kilometers. For example, the existing KamLAND detector, at only 1 kton, has shown sensitivity to the integrated operational power level of all nuclear reactors in Japan—distributed an average of 180 km from the detector location.

A well-distributed array of large detectors could provide comprehensive remote monitoring of an entire country. The basic physics applications for such large detectors are varied. Originally designed to provide new information on the antineutrino oscillations discussed above, KamLAND, the largest existing antineutrino detector, has already provided the first-ever measurement of antineutrinos produced from the radioactive composition of the Earth. Very recently KamLAND also established the first experimental limit in the power of a hypothetical nuclear reactor in the Earth's core, directly demonstrating the possibility of long distance monitoring (although for the time being with modest sensitivity). Having additional detectors distributed at other locations—preferably with higher accuracy for geoneutrino measurements—would be truly transformative.

Such large-scale detectors can also provide long-term search for more exotic processes, such as the interactions of dark matter or the decay of protons. Acquiring antineutrino data over large distances by these large detectors would provide a veritable antineutrino map of the Earth. The more accurately we are able to map out the distribution of geoneutrinos and other background sources, the more accurately we can visualize plutonium production around the world—locations that would stick out as high-intensity antineutrino hot spots.

3.5 Compatible detector designs

The nuclear nonproliferation community's practical need for many detectors, precise detectors, and larger detectors might, in parallel, generate a windfall of scientific data. The feasibility of detecting nuclear reactors at distances between 20 m and 150 km has already been demonstrated. Improving the antineutrino detection technology in terms of making such detectors with improved economies of scale, more specific and robust, and more compact both enhances their suitability for national-security applications and their suitability for scientific applications.

One of the major cost factors for large detectors is efficient, low-noise detection of very low levels of light emitted by scintillators used for the detection of antineutrinos by means of photo multiplier tubes. The development of novel, simplified, and more compact solid-state light detection devices would thus serve the needs of both the national security and the scientific community.

Development of novel detection technology requiring less shielding would allow compact detectors to be more robust against background radiation when near the surface and enable reactor monitoring at intermediate distances, perhaps in a clandestine way to detect undeclared reactors or undeclared reactor uptime. This goal overlaps with the desire of the antineutrino community to develop detectors with a more specific detection signature. A center for antineutrino studies would help coordinate such development efforts and avoid duplication of efforts.

Decreasing the size of antineutrino detectors also benefits both communities. Coherent scattering of antineutrinos off atomic nuclei is an uncontroversial but technically difficult technique that would offer a 100–1000 times enhancement in antineutrino detection efficiency, and ultimately enable much more compact antineutrino detectors. The development of compact and perhaps concealable antineutrino detectors would thus naturally overlap with this research and development thrust within the scientific community.

4. SUGGESTED TECHNOLOGY IMPROVEMENTS

Some specific technological areas could profit from a more focused approach on the specific needs of national security antineutrino detectors. In broad strokes, these developments attempt to solve three basic problems (summarized in the table below): improve economies to make production of larger detectors more practical; develop compact antineutrino detector materials to make smaller detectors; and improve methods of identifying background signatures.

Detector Technologies

Detector Need	**Technology Means**	***Technology Transfer***		
		National security/ Intelligence	*Medical*	*General industrial potential*
Economies of scale	Improved photon detection (PD):	X	X	X
	• Solid-state PDs			
	• PD wallpaper			
	New detector media:	X	X	X
	• Amplify light			
	• Water-soluble scintillator			
	• Wavelength shifter			
	• New scintillators			
Compact	• Germanium	X	X	X
	• Silicon	X	X	X
	• Noble gases	X		X
	• Bolometers	X	X	X
Background rejection	• Directionality	X	X	X
	• Imaging	X	X	X
	• Segmentation	X	X	X
	• Signal processing	X	X	X
	• Fast electronics	X	X	X
	• Inorganic scintillation	X	X	X

4.1 Evolution of existing technologies

Amazingly, the antineutrino detection technologies most in use today still rely on techniques developed in the 1950s. Making progress depends largely upon improving the capabilities and cost-effectiveness of existing methods. One method, discussed below, holds potential for greatly reduced detector size for near-reactor measurements. But largely we cannot escape the huge sizes needed for remote detectors—simply due to the small antineutrino interaction probability with matter.

To expand our options, evolutionary improvements to existing technologies such as the following are required:

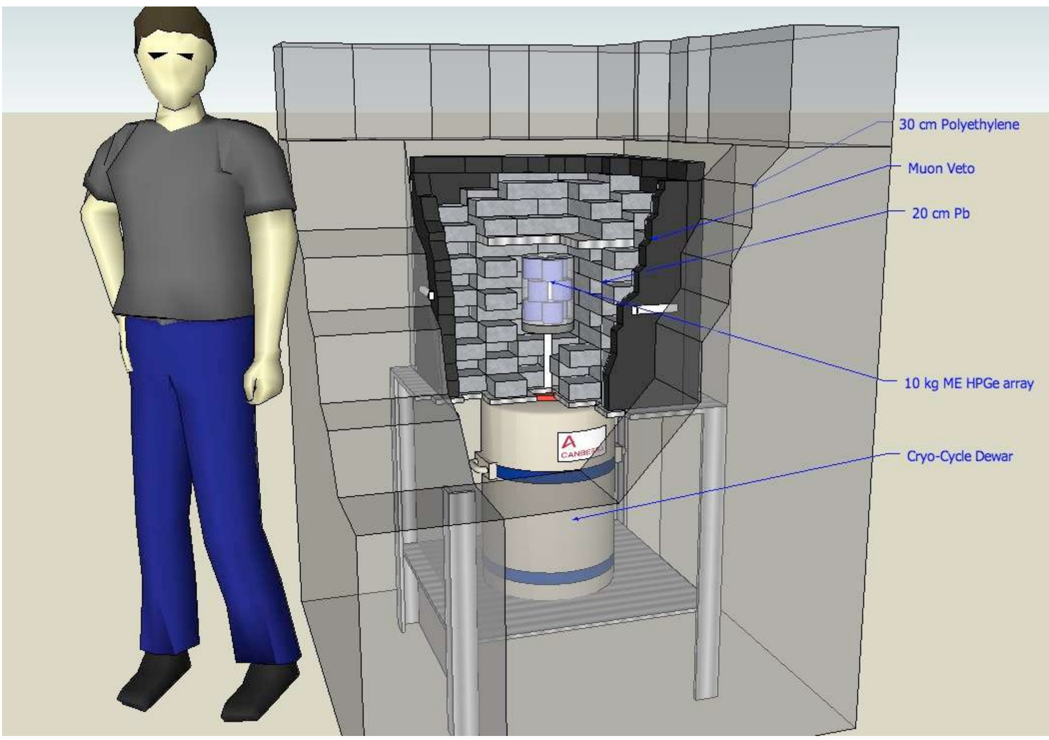
- ♦ Improve scintillator materials either by increasing light yield, improving safety, stability, and transparency, or by combining inorganic materials to these existing scintillators to increase final-state sensitivity.
- ♦ Develop better water-based detectors; this would significantly reduce the hazardous material in these detectors, thus increasing the overall safety of the deployment apparatus.
- ♦ Devise methods for handling the high background event rates associated with detector operation above ground, where cosmic rays are not as well shielded.

We also need to reduce costs. The cost driver in large antineutrino detector designs is photodetection. All current instruments employ the venerable glass bulb photomultiplier. These devices—while providing good sensitivity and low noise—are not only expensive, but difficult to handle. It is time to press on to

21st-century photodetection technology. This is an area of study that could definitely stimulate industrial development.

4.2 Novel technologies

Novel technologies—those considered to be truly transformative—involve developing completely new materials or establishing new methods of detection. A good example would be the current focus on attempting to create detectors from materials such as high-purity germanium or silicon crystals that are sensitive to an antineutrino interaction called coherent neutrino scattering. This process is very difficult to use, but provides the potential for a 500–1000 times greater rate of antineutrino interactions. Such a detector would allow a significant reduction in size, requiring a few *kilograms* of detector material—rather than a few *tons*—to satisfy the near-distance monitoring needs discussed in the previous sections.



Graphic courtesy University of Chicago

Artist's rendering of compact, widely deployable reactor model showing requirements for shielding 10 kg of germanium

5. THE NEED FOR A NATIONAL CENTER FOR ANTINEUTRINO RESEARCH

Over the last 10 years the international landscape has changed greatly—in a way that presents new challenges to US security. With the emergence of international terrorism and our increasing need for energy, verification of the nuclear fuel cycle worldwide, and close tracking of the global flows of fissile material must become a heightened national priority. The price of ignorance and inaction is high.

Over the same time period US scientists have come to understand that antineutrinos can play an important role in nuclear security applications. Until very recently, this science has been pursued for the sake of pure knowledge, but new applications to geophysics and national security have emerged with the construction of kiloton-scale low-energy antineutrino detectors, and smaller detectors built for the express purpose of monitoring individual reactor cores.

Assimilation of these related but disparate sets of data is needed to develop and build an integrated picture of various international nuclear programs. In order to build on this trend, we need a center to bring together national security experts and scientists. Such a center will foster communication between different areas of research, enhance the ability to perform R&D on nuclear technologies, and facilitate building a suite of initial experiments addressing long-distance detection as well as in situ measurements.

The same countries that may be under close observation for reactor utilization are likely to be the same candidates for a buried weapons test, so there is an automatic synergy between these monitoring goals. Further studies are assuredly needed, particularly with trial cases. We envisage this as part of the ongoing role of the center, involving personnel from a range of scientific, intelligence, technology, and policy areas.

Raw, unprocessed, antineutrino data, made openly available through the center, would provide a common basis of work. The database would also amplify the capabilities of both communities, providing them access to data from their own instruments as well as instruments built by others. Now both communities can accomplish much better their own missions by leveraging the worldwide neutrino detection assets. A centralized data storage and handling structure, overseen by the center, would exploit overlap between the two communities. By providing and managing a set of analysis tools the center would further avoid duplication of effort. Questions of appropriately protecting proprietary information (e.g., fuel burn-up data provided by reactor operators or the IAEA versus requiring a degree of transparency at nuclear reactor sites) will have to be addressed in the exploratory study.

5.1 Benefits

A National Center for Antineutrino Research is required to ensure that US national security goals will be attained. Detectors optimized for pure science applications are not necessarily optimal for intelligence gathering. Such a center will, therefore, provide an environment that fosters the exchange of technical knowledge between the intelligence and scientific communities. The center will provide:

- A clearinghouse for antineutrino monitoring for national security.
- A focus for research into developing techniques to improve the performance of antineutrino detectors while reducing their cost and size.
- A framework for expert evaluation of new ideas and for steering the field forward.

The center will enhance communication and coordination between academics and national laboratory and industry personnel engaged in the construction of detectors of rather different scopes and sizes. And, by attracting promising graduate students in antineutrino detection from around the world, a byproduct will be a new cadre of experts in the field.

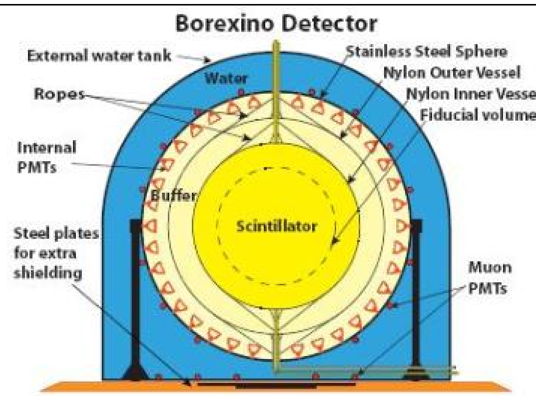
Current and past successful antineutrino detection projects

Kamioka Liquid Scintillator Anti-Neutrino Detector (KamLAND): Buried 1 kilometer under Earth, in an old mine northwest of Tokyo, KamLAND (Kamioka Liquid Scintillator Anti-Neutrino Detector) is the largest scintillation detector ever constructed. KamLAND researchers came from Japan, China, France, and institutions throughout the US. Their first experimental goal, measuring the antineutrino flux from reactors in Japan and Korea, has been achieved. More recently KamLAND also detected neutrinos from uranium and thorium decay inside the Earth and set limits on the power that could be produced by a reactor in the Earth's core, demonstrating that detection with very large standoff is possible.

Graphic courtesy Lawrence Berkeley National Laboratory

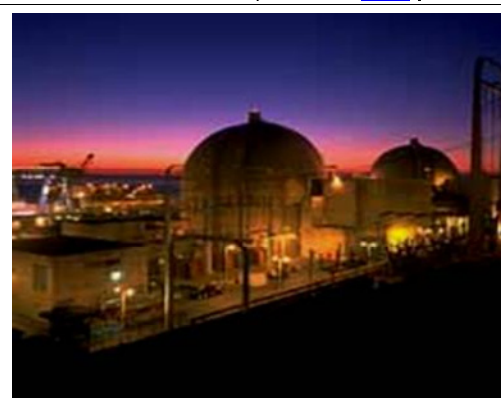
Borexino: An international team of more than 100 researchers used the huge Borexino detector to detect low-energy solar neutrinos for the first time. These results confirm scientists' theories that neutrinos oscillate between three types: electron, muon, and tau neutrinos.

The Borexino detector used for these discoveries is located near L'Aquila, Italy. It is an 18-meter-diameter dome placed more than a kilometer underground to block interferences with cosmic rays.

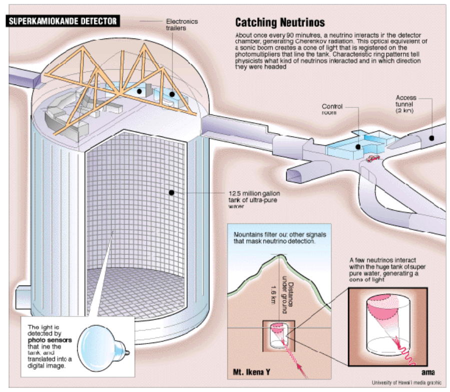
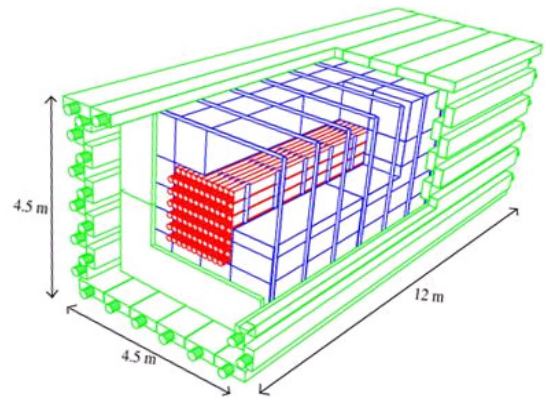


Graphics from arXiv {0708.2251}

San Onofre Nuclear Generating Station: The feasibility of small-scale on-site antineutrino monitoring has been demonstrated during the past year at the San Onofre Nuclear Generating Station (SONGS) in California. Key remaining desirable characteristics for on-site monitoring are now being pursued, including further miniaturization, improved energy resolution, detector efficiency improvements, use of nonhazardous materials, and background signal rejection.



Graphic courtesy Lawrence Livermore National Laboratory

Super-Kamiokande, or Super-K for short, is a joint Japan-US large underground water Cherenkov detector in Japan. The observatory was designed to search for proton decay, study solar and atmospheric neutrinos, and keep watch for supernovas in the Milky Way Galaxy. Super-K is located 1,000 m underground in the Mozumi Mine (Kamioka Mining and Smelting Co.), Gifu Prefecture, Japan. The detector consists of a cylindrical stainless steel tank 41.4 m tall and 39.3 m in diameter, enclosing 50,000 tons of ultra-purified water.	 *Graphic Courtesy University of Hawaii*
Palo Verde Antineutrino Detector: a segmented detector capable of detecting antineutrinos from nuclear reactors with a standoff distance of 750 m with modest cosmic ray shielding. The detector was built by a team of about 15 scientists and located in a shallow underground site to observe the antineutrinos produced by the Palo Verde Nuclear Generating Station, 50 miles west of Phoenix, AZ. The segmentation in 66 cells, the use of gadolinium-loaded scintillator and a rather sophisticated trigger system made up for the limited (~10 m thick) Earth shielding, providing a specific signature for the antineutrino interactions. The success of the Palo Verde detector demonstrates that advanced techniques may enable reactor monitoring from moderate distances with limited or, perhaps, no cosmic-ray shielding.	 *Graphic courtesy Stanford University*

Another important benefit of the center is that it will provide a universal framework for the management and administration of projects of various sizes and duration, with substantial concomitant improvement in their efficiency. Some of the roles of the center will be to formulate and possibly manage large projects, to interface with government agencies, and to interface intelligence and scientific components with various funding agencies. Because projects have varying lifetimes, it is likely that better efficiency and economy for the government will be achieved with a single partner in the center. Staff can simply be transferred from one project to the next and administrative functions such as payroll, contract management, and so on will be concentrated in one place.

Lastly, the center will generate a vast amount of prestige for the community in which it is located and discoveries are made. The national intelligence, economic, and scientific benefits of the center will vastly outweigh the expense of its creation.

Economic impact. In the long run this program will result in the construction of a suite of mobile detectors of unprecedented size, requiring a substantial staff. This highly educated workforce will require housing, schools, and other infrastructure. Because center personnel will have close connections to industry, various corporate representatives will also be visiting the community on a regular basis and will require temporary accommodations and meals. Thus the center will generate revenue for the community in which it is located.

Industry will be called upon to build and improve detectors that require series production. It is also quite likely that entirely new industries will be created for the construction of future very large detectors initially devised by center scientists and researchers. Some of the monitoring techniques developed by the center will also result in substantial savings for nuclear reactor operators, with obvious advantages for the energy industry.

Physical and virtual facilities. We envisage that most of the detectors used in this program will be deployed around the world. Therefore, some of the functions of the center may have to be virtual rather than physical. We expect that the physical portion of the center will include laboratories, conference rooms, and computing facilities, as well as administrative offices. In addition, it is expected that the center will sponsor R&D on various aspects of neutrino detection at universities and laboratories external to the center. Such studies are ongoing at the University of Hawaii, the University of Maryland, the University of Alabama, Stanford University, and the University of Chicago, for example. These would serve as virtual centers with respect to the physical one. Decentralized R&D is essential, as much of the expertise and creativity required for the advancement of the field is, by nature, distributed across not only the United States but the world. Tapping into this asset by providing remote collaboration is an essential function for the center.

Data analysis will be provided at the center for both national security as well as science applications. While much of the center's physical areas will have to be completely open to encourage the free exchange of ideas on detection technology, it is expected that the center will have designated areas that are closed and available for restricted activities. This, too, is a topic that should be addressed in the initial study.

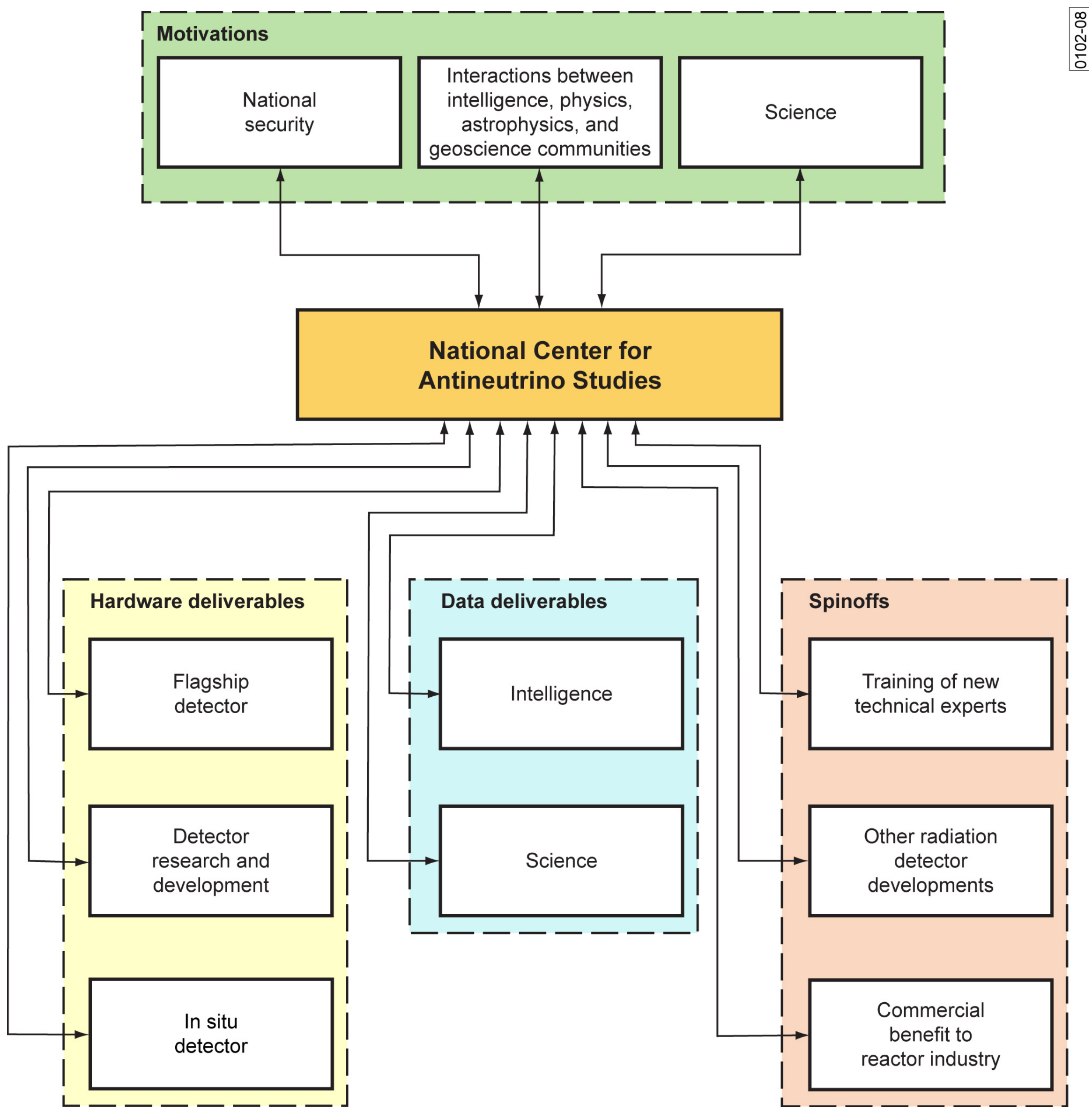
Establishing a National Center for Antineutrino Studies will concentrate attention on this dynamic field and the important role it can play in national security.

5.2 Initial study to develop center

Before the National Center for Antineutrino Research is established, an initial study must be funded to address the following issues:

- The location of the physical core, administrative and computing facilities, and classified areas.
- Whether such facilities should be established inside an existing national laboratory or university or whether the center should be a stand-alone entity.
- The mechanisms for funding the center and for distributing resources to the different research activities.
- The interfaces (physical and virtual) between unrestricted activities and restricted ones.
- The relationship between the different projects and detectors within the center and the center itself.

In addition, the initial study will clarify the exact functions of the center and its relationship with existing efforts in pure antineutrino science. A conceptual view of the center is shown below.



5.3 Initial activities of the center

We assume the center will be developed over a period of approximately 2 years. In the interim, while plans for organizing, building, and staffing the center are in the works, some ongoing R&D projects should be supported so that momentum is not lost. Many such R&D projects are already under way at universities. Providing a small but expanding funding source from the Center for Antineutrino Studies would start the process of moving current university and national lab R&D towards technologies that can be produced at lower costs on a larger scale, and thereby serve the needs of both the nonproliferation and science communities. Another initial activity could be to issue a request for proposals to engage the commercial sector. Some of the scale-improving technology likely exists in the commercial sector, but is not perceived as a need due to the low numbers of antineutrino detectors being built.

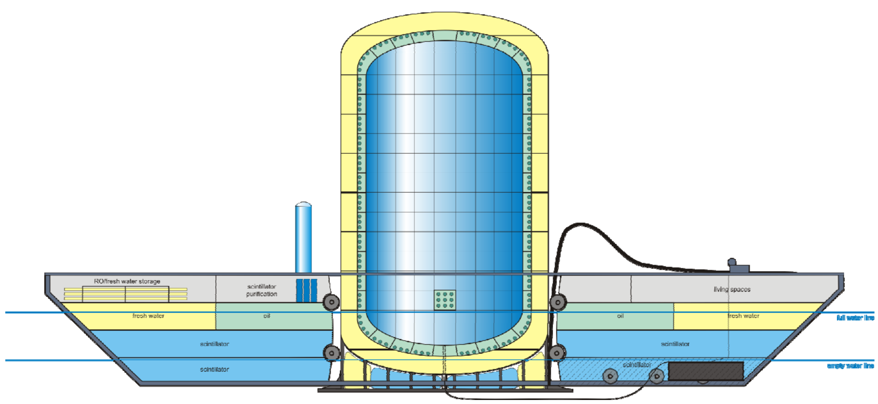
A *flagship detector,* discussed below, would serve as a focal point for initial activities: the relationship between the Advanced Photon Source and the visiting science facility at Argonne National Laboratory is one possible model. A *global array* of smaller, cooperatively deployed antineutrino detectors in close proximity to nuclear power sources is a second important focus. Lawrence Livermore National Laboratory has successfully developed and deployed detectors of this nature.

5.3.1 Flagship prototype detector

A first-class scientific project with broad multidisciplinary interest, called Hanohano, can make the first steps in realistic long-distance (~100 km range) reactor monitoring. While most of the technology exists and has been demonstrated in mine-based detectors (e.g., KamLAND and Borexino), it remains to be brought into practice for portable application in the world's oceans. Hanohano would do this, and in so doing would accomplish transformative geological science and unique neutrino physics and astrophysics measurements.

Geologists do not know well the content of the inner Earth, below a few kilometers, from the mantle on down through the outer and inner core. The only direct measurements we have are from seismic studies, but these yield only sound velocity and character. The composition must be guessed at, based upon meteorite and solar analogs and the crust, which we can directly observe. There have been long-standing debates about the content of the core, the mechanisms for heat transport, and the heat balance of the Earth. Measuring the electron antineutrino flux from uranium, thorium, and potassium—the major sources for internal heating—can help resolve these vital geological questions.

The Hanohano Collaboration proposes to build a 10-kiloton liquid scintillator–based antineutrino observatory, designed for use in the (5 km) deep ocean, and connected by optical cable to shore. The design of this instrument has already been studied, and the proposed configuration is as shown below, a large cylindrical tank transported via special barge, and multiply deployable to the deep ocean. This instrument, which will be assembled, tested, and serviced after recovery at pier-side, can achieve laboratory-scale reliability and functionality.



Graphic courtesy University of Hawaii

Cross section of proposed oceangoing 10-kiloton Hanohano antineutrino detector. The detection cylinder is deployed (and recovered) from the 113-m-long barge, and remains for periods of typically one year at a deep ocean observation station.

The current antineutrino physics goal involves standing off from a reactor complex by about 50–60 km and recording a signal of about 4700 antineutrino interactions per year from the San Onofre power reactor complex (or another site). This data will permit some important neutrino studies (oscillations and masses), the results of which are needed for later reactor monitoring efforts as well.

As the prototype remote reactor monitoring detector, Hanohano can measure the reactor power level from a distance of 55 km offshore on a daily basis, and one-day shutdowns can be very clearly detected. The average plutonium mix of the reactor complex can be determined as well. Aside from this remote reactor monitoring demonstration, the project will measure background, which is necessary information for later remote-monitoring instruments. The project will also train and focus the efforts of scientists who will be needed to bring world reactor neutrino monitoring to fruition.

The Hanohano Project is already in motion (initial design study completed 2007), although not yet funded, and will be independent until the National Center for Antineutrino Research comes into being, at which time they will become closely linked (by intention of all parties).

5.3.2 Flagship Near-Reactor Detector Array

A second important focus for the center, building on recent technology developments and demonstrations in the United States and abroad, is to work towards the widespread adoption of small, low-cost, near-reactor monitoring systems at dozens of the many hundred power reactors that exist worldwide. The purpose of this array is to enhance the existing reactor safeguards regime, providing real-time operational status, power, and fissile content information for use by inspection agencies to verify normal operations of civil reactors. The power and fissile content measurements may have the additional benefit of providing useful feedback to operators interested in tracking fuel consumption and power production in their reactors. This power-monitoring capability thus has the potential to be the first direct commercial spinoff of this technology.

The cubic-meter-scale SONGS1 detector, described and pictured in section 3.1 above, serves as a proof of principle for a wider deployment. The key factors to be considered are a survey of reactor sites to determine suitable deployment locations, additional engineering work to make the detectors as transportable and easy to use as possible, and a secure system for remote data uplink to the inspection agency.

Beyond the direct impact on IAEA safeguards, widespread deployment of dozens of antineutrino detectors in a cooperative context would have indirect but important and immediate benefits. First, the publicity that would attend such a deployment would help foster a positive public impression of the international safeguards regime. In a similar way, deployment would make the public aware, in a concrete way, of the direct benefits that can accrue from pursuit even of apparently esoteric fundamental phenomena such as antineutrino detection. Third, the wealth of data and technology available from the dozens of deployed detectors could be made available to students from the graduate school to high school level, with myriad opportunities for understanding of both basic science and of the importance of nonproliferation, and the synergies between them. The Center for Antineutrino Research—overseen, of course, by the appropriate national security stakeholders—could serve as a clearinghouse and gatekeeper for this information. The information could even be used by states as a real-time check on the operational status of power plants, such as is now mandated by law in California (California Public Utilities Code Section 352.5 requires the independent System Operator to make publicly available daily a list of all power plants located in the state that are not operational due to a planned or unplanned outage).

We also want to highlight other applications related to antineutrino monitoring, which we hope will be pursued even as the center is still in the birthing stage. As we have emphasized, there is an opportunity to exploit antineutrino monitoring within the next few years and momentum should not be lost. Our high-priority list of activities includes:

- In situ/reactor monitoring detectors (e.g., SONGS1)
- Basic research and development in:
  - Coherent scattering detector
  - Directional studies
  - Tracking antineutrino detectors
  - Shieldless portable detectors
  - Detector array studies
  - New photodetector technology development
- Data management for reactor antineutrino monitoring worldwide

6. SUMMARY AND RECOMMENDATIONS

There is a natural compatibility between the technology and data collection objectives of the national security community and those of the antineutrino science communities. This report has shown that significant areas for shared investments exist. Advances in antineutrino detection technologies will not only help meet nonproliferation challenges and advance fundamental science, but will also spill over to improve the current industrial base of the nation and may even give birth to entirely new industries. Driving the technology frontier often has unquantifiable and unpredictable benefits.

Easily foreseeable benefits to industry exist in national security, intelligence, and medicine. Advances in scintillators and low-light, low-noise photon detectors benefit homeland security technologies. Neutron detectors are used to search border portals for nuclear material and use many similar components. Some medical devices use scintillators with low-light detectors and similar physical mechanisms. Improvements would lead to better resolution and sensitivity. Developments in germanium detectors overlap with telecommunications industries. These are only some of the possible spinoffs.

An expanded use of antineutrino detectors further benefits our workforce. Pressing industries to meet the scale of antineutrino detectors that would protect against nonproliferation requires additional training of scientists, geologists, astronomers, and engineers. A center for collecting data from worldwide antineutrino detectors would provide an incubator for the next generation of nonproliferation experts and scientists.

Antineutrino monitoring has the potential to be a major tool in world efforts to control nuclear proliferation. There is great synergy with emergent antineutrino science and technology, and wide interest in the scientific community. A major effort to coordinate and stimulate antineutrino detection will have wide-reaching benefits to both the science and nonproliferation communities. We strongly recommend the commissioning of a comprehensive study that reaches out to a wide array of stakeholders in the particle physics, geophysics, and national security communities.

The proposed National Center for Antineutrino Research will coordinate and extend national efforts related to deploying antineutrino detectors for security purposes, as well as to enhance basic science and technology in the field. The center will facilitate collection and coordination of data from different remote and near-source antineutrino detectors as they come online, advocate for improved detection technologies, provide a nexus for domestic and international cooperation, and report on global antineutrino activities.

To ensure a truly national perspective, we further recommend commissioning a comprehensive study that reaches out to a wide array of stakeholders in the particle-physics, geophysics, and national-security communities. This study should address center functions, technology road maps, data management, sensor deployments, operating parameters, physical design, economic impact, and both physical and cyber security. Finally, the study should address an implementation plan and a development budget for the five-year defense plan (FYDP) for 2010–2014.

We also recommend construction and deployment of remotely operated flagship antineutrino detectors. The development of a single 10 kton submarine antineutrino detector is envisaged; this detector will remotely operate at far-field (>10 km) locations and is capable of multiple deployments for monitoring and deciphering natural background signals from land-based reactor fuel cycles. The center could also promote the development and distribution of near-field (<1 km distances) 1-ton detectors that can be located near recognized reactor sites.

7. CONTRIBUTORS

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Adam Bernstein (Ph.D., Physics, Columbia University) is a Staff Physicist and Group Leader for the Advanced Detectors Group at Lawrence Livermore National Laboratory. He develops neutron and gamma ray detectors for applications in fundamental science and nuclear nonproliferation. He has pioneered the use of antineutrino detectors as a practical means for real-time monitoring of fissile content and power levels in nuclear reactors.

Peter F. Bythrow (Ph.D., Space Plasma Physics, University of Texas) is Chief Scientist Defense Intelligence Agency. His early career as a Strategic Air Command pilot (1971–1975) was spent in part preparing for the delivery of nuclear weapons. He currently directs a broad-ranging research and development program that addresses—among other issues—the proliferation of nuclear weapons and the capacity to produce them. Dr. Bythrow's publications address topics that vary from *The Spokes in Saturn's Rings* to *Aluminum Gallium Nitride for 'solar blind' ultraviolet detectors*. He has been program scientist for several Department of Defense space programs, including the use of Soviet-era TOPAZ reactors for nuclear electric propulsion.

Rick Carlson (Ph.D., Earth Sciences, Scripps Institution of Oceanography) is a staff research scientist at the Carnegie Institution of Washington's Department of Terrestrial Magnetism who specializes in the application of isotope and trace element measurements used to decipher the chronology and processes of chemical differentiation of the terrestrial planets. His work has focused on the early history of the solar system, initial crust-forming events on the Earth and moon, and the mechanism of continent formation on Earth.

Juan Collar (Ph.D., Physics, University of South Carolina) is an Associate Professor at the Enrico Fermi Institute, University of Chicago. He works on the development of specialized detectors for non-accelerator particle physics (e.g., dark matter, neutrino, axions, etc.). Dr. Collar has a broad interest in radiation detection in general, for both fundamental physics and applications. He is the spokesperson for COUPP (Fermilab experiment E-961). Dr. Collar and his collaborators are trying their best to detect reactor antineutrinos via coherent nuclear scattering during 2008.

Steve Dye (Ph.D., Physics, University of Hawaii) is a physics professor at Hawaii Pacific University and an affiliate to the graduate physics faculty at the University of Hawaii. His research in neutrino detection spans 25 years, focusing initially on astrophysical and atmospheric neutrinos using the water Cherenkov technique. His current research effort targets the measurement of geoneutrinos by adapting the scintillating liquid technique for use in the deep ocean.

Jordan Goodman (Ph.D., Physics, University of Maryland) is a professor and former chair of the Department of Physics at the University of Maryland. He works in the field of experimental particle astrophysics. He has worked on neutrino physics experiments such as the Super-Kamiokande neutrino experiment and he is currently working on the IceCube neutrino observatory at the South Pole. In addition, Jordan is the spokesman for the Milagro gamma-ray observatory currently in operation at Los Alamos and is PI of the proposed high altitude water Cherenkov gamma-ray observatory in Mexico.

Giorgio Gratta (Laurea in Fisica, University of Rome, 1986) is a professor of Physics at Stanford University. He currently leads an advanced neutrinoless double beta decay experiment (EXO) utilizing techniques in nuclear, particle, and atomic physics to measure neutrino masses using tons of isotopically enriched Xe-136. Dr. Gratta is also US co-spokesman for the KamLAND detectors that for the first time observed neutrino oscillations using reactors and detected neutrinos from the interior of the Earth. In the past, Dr. Gratta has worked for Caltech, SLAC, and CERN (Geneva, Switzerland), where he investigated the Z-Boson produced by the LEP and SLC high-energy colliders.

Deborah Hanchar (Ph.D., Nuclear Engineering, Massachusetts Institute of Technology) currently serves as the Senior Technical Advisor to the Director of Science and Technology for the Director of National Intelligence. She led the Central Intelligence Agency's (CIA) nuclear research program in the Directorate of Science and Technology, which included investigating new methods and phenomenologies for detecting, identifying, and characterizing nuclear proliferation activities. Prior to that, she was a senior nuclear weapons analyst in the CIA's Directorate of Intelligence, responsible for advanced concept nuclear weapon designs, as well as various proliferant countries' nuclear weapons development programs.

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David Lambert (Ph.D., Geochemistry, Colorado School of Mines) currently serves as the Acting Head of the Deep Earth Processes Section of the Division of Earth Sciences, National Science Foundation (NSF). Prior to this appointment, he was the Director of the Instrumentation & Facilities Program at NSF. His responsibilities cover a wide range of academic and interagency activities relating to research infrastructure. He manages 15 national, multiuser facilities for the Division of Earth Sciences, and oversees the infrastructure investment portfolio of the Division.

John G. Learned (Ph.D., University of Washington), Professor of Physics at the University of Hawaii, has long studied neutrinos, initiated some of the most successful neutrino projects to date, and participated in the recent discoveries of neutrino mass and mixing. His publications and interest range through astrophysics, particle physics phenomenology, and hardware development. His 2003 white paper considering the potential for neutrino applications in long-range neutrino monitoring of reactors and nuclear weapons testing led to the present series of workshops on the subject.

Bill McDonough (Ph.D., Geochemistry, Australian National University) is a Professor of Geology at the University of Maryland. He is the Director of the Plasma Laboratory at the University of Maryland, a mass spectrometry center for chemical and isotopic analyses of materials. Dr. McDonough has derived compositional models for the planet and the Earth's core and mantle; these models predict the budget and distribution of radioactive elements in the planet.

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Richard J. O'Connell (Ph.D., Geophysics, Caltech) is a Professor of Geophysics at Harvard University. His work addresses large-scale tectonics and the thermal and chemical evolution of the Earth and terrestrial planets (now including extra-solar planets). He has also studied the elastic and rheological proporties of minerals and rocks at high pressure.

John L. Orrell (Ph.D., Physics, University of Washington) is a Research Scientist in the Radiation Detection and Nuclear Sciences group at Pacific Northwest National Laboratory. His background is in neutrino physics, though current work is focused on radiation detection for national security applications. Dr. Orrell's research interests include pulse shape analysis of germanium gamma-ray spectrometers, data analysis of multi-element detection systems, and statistical analysis of sparse data samples.

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Leslie Pitts (Ph.D., Physics, Georgetown University) is the Program Manager for two research areas in the Office of Proliferation Detection (NA-222) in the National Nuclear Security Administration (NNSA): the 235U Production Detection Program and the Plutonium Production Detection Program. Projects in these portfolios consist primarily of efforts funded at the DOE/NNSA laboratories to contribute technology-based solutions to meet national security needs.

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David Reyna (Ph.D., Physics, American University) is a Staff Physicist in the Radiation and Nuclear Detection Systems Group at Sandia National Laboratories. While having made significant contributions to the fields of medium-energy nuclear spin-physics and high-energy collider physics, he is primarily known for his work in the field of neutrino oscillation research. He is currently dedicated to the design and development of new detector technologies for the detection of neutrinos from nuclear power reactors. These developments will likely lead to a practical technology for real-time monitoring of the production of nuclear materials as well as open new avenues for fundamental neutrino research.

Mario Serna (M.S., Physics, Massachusetts Institute of Technology, M.S. Electro-Optical Engineering, University of New Mexico) is an active duty Major in the US Air Force. His current AF assignment has him finishing his Ph.D. in Particle Physics at the University of Oxford. His experience in neutrino physics involves calculations of the day/night effect predictions for Super-Kamiokande detector for his M.S., and current theoretical models for the origin of neutrino mass and mixing. Previous assignments were at the Air Force Research Lab at Kirtland AFB, NM and serving as Assistant Professor in Physics at the US Air Force Academy, CO.

Jim Siegrist (Ph.D., Physics, Stanford) is Associate Laboratory Director of Lawrence Berkeley National Laboratory (LBNC) and Physics Division Director. He serves on the lab oversight committee for US participation on the Daya Bay neutrino project. His personal research areas include collider physics at the ATLAS experiment at CERN, and instrumentation development. He is co-PI on the Berkeley Department of Homeland Security (DHS) Domestic Nuclear Detection Office (DNDO) academic research center, specializing in electronics and instrumentation.

David Simpson (Ph.D., Australian National University) is President of the Incorporated Research Institutions for Seismology (IRIS), a consortium of more than 110 US universities and 80 foreign affiliates. With funding from the National Science Foundation (and in collaboration with the USGS, other federal agencies, and many international partners) IRIS is responsible for the development and operation of facilities to support research and education in seismology. These facilities include a global network of 130 permanent observatories, more than 1000 portable instruments for temporary use in individual research experiments, and a data management system for real-time data collection and archiving of all data. As part of the NSF Major Research Equipment and Facilities Construction (MREFC) funded EarthScope project, IRIS operates USArray, with an emphasis on seismological facilities for exploration of the structure and evolution of North America. Dr. Simpson was a research scientist at the Lamont Doherty Earth Observatory of Columbia University, with interests in triggered earthquakes, monitoring of nuclear explosions and the tectonics of central Asia.

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