Outline

A. What are we trying to accomplish?
   1. By 2016, demonstrate 1-25 km standoff sensitivity to a reactor using a 1000 ton detector.
   2. Ultimately: Demonstrate $O(500)$ km sensitivity to a small reactor with a Megaton-scale detector

B. KURF background experiments that help us prepare for A.1.

C. Choosing a suitable deployment location for the 1000 ton detector
**Ultimate goal:** find or exclude hidden 10 MWt reactors at a distance - a hard problem

<table>
<thead>
<tr>
<th>Goal</th>
<th>Detector mass</th>
<th>standoff</th>
<th>Required reduction in bg rate relative to KamLAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 events in 1 year from a 10 MWt reactor, (25% accurate thermal power)</td>
<td>10 kiloton</td>
<td>~40 km</td>
<td>10x</td>
</tr>
<tr>
<td></td>
<td>1 Megaton</td>
<td>~400 km</td>
<td>100x</td>
</tr>
</tbody>
</table>

http://arxiv.org/abs/0908.4338  
*Science & Global Security, 18:127–192, 2010*

Gadolinium-doped (light) water is the most viable option for scaling to the largest sizes

Global reactor antineutrino fluxes
Interim goal: sensitivity at 1-25 km with a kiloton mass Gd-water detector

- Remote reactor monitoring demonstration in the NNSA Strategic Plan

- O(50 M$) project, 4-5 year duration

- NNSA lead with support from DOE Office of Science
WATCHMAN (WATer Cherenkov Monitoring of ANtineutrinos) is now in its first phase in the United States – 2.5 years, NA-22 funded

- **Overall Project Goal**: demonstrate sensitivity to reactor antineutrinos using a gadolinium-doped (light) water detector at ~1 kilometer standoff from a 10-150 MWt US research reactor, or up to 25 kilometers from a 3000 MWt scale US commercial power reactor.

**First Phase, 2012-2014:**
- measure backgrounds
- identify site
- develop a design/ cost envelope for the detector
Complementary experiments worldwide

**EGADS** - 200 ton deeply buried detector to evaluate Gd-doped antineutrino detection
- backgrounds
- materials
- energy thresholds

*This detector volume is too small for direct demonstration of sensitivity*

- **HyperKamiokande**
  - 560,000 ton multipurpose water detector being planned by Japan
  - Time scale: ~12 years
  - Interest in U.S. science community in participation will lead to further R&D in this area
  - Gd an option but not guaranteed

*Our demonstration would give strong confidence for exercising the Gd option*
The WATCHMAN Collaboration

A. Bernstein, N. Bowden, S. Dazeley, D. Dobie
P. Marleau, M. Gerling, K. Hulin, J. Steele, D. Reyna
K. Van Bibber, C. Roecker, T. Shokair, S. Asghari
R. Svoboda, M. Bergevin, M. Askins
J. Learned, S. Dye, J. Maricic, J. Murillo
M. Vagins
B. Vogelaar, S.D. Rountree, C. Mariani

Current Phase: Two U.S. National Laboratories, 6 Universities, 2.25 years
WATCHMAN has five phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Activity</th>
</tr>
</thead>
</table>
| I - Now | - measure backgrounds  
- identify site  
- develop a design/cost envelope for the detector |
| 2014-2015: | Sponsor approval of large detector deployment |
| II | Design and site licensing |
| III | Construction |
| IV | Deployment |
| V | Data-taking and demonstration to end users |
Antineutrino signal and background

Backgrounds:
1. Real antineutrinos
2. Random event pair coincidences
3. Muon induced high energy neutrons
4. Long-lived (~ 1 sec) radionuclide decays

Signal in 1 kiloton of water

- Exactly two Cerenkov flashes
- Within ~100 microseconds
- Within a cubic meter voxel

‘The antineutrino heartbeat’
Step 1: Measuring backgrounds

- **Shallow Depths** (100-600 meters): not well known, measure as a continuous function of overburden at the KURF

  Based on recent survey and muon data at KURF, **300 400 and 600 mwe** appear to be viable measurement locations

- **Pre-existing Mine**: (1 km) reasonable extrapolations from past and ongoing experiments (KamLAND, Soudan mine water detector)
(Relatively) Shallow depth Background Measurements at KURF

- Drive in access
- Can deploy from 100 feet to 1400 feet of overburden
- Use of the same detector at multiple depths ensures reliable comparison of results
- First-ever continuous measurement as a function of depth
What will we actually measure at shallow depths

1. The energy spectrum of muogenic fast neutrons as a function of depth below the Earth’s surface
   - Allows us to model double-neutron antineutrino-like backgrounds in a kiloton scale detector

2. The rate of muogenic radionuclides such as $^9$Li
   - Allows us to set an upper limit on the contamination of our signal by these antineutrino-like backgrounds
Fast Neutron Spectrometer

- Plastic scintillator/Gd doped paint detectors sandwich ~4 tons of lead.
- Direct interaction with scintillator for $E < \sim 100$ MeV.
- Neutron multiplication off of the lead for $E > \sim 50$ MeV.
- Expect 3000-5000 events per month at 100 m.w.e.
Fast Neutron Spectrometer with muon veto on platform

- Detector + muon veto + data acquisition and peripherals are less than 9 tons.

- Platform is a standard trailer outfitted with power and AC.

- Platform now deployed and taking data at Level VI (No pictures or data yet !)
Simulation of detector response trigger on recoil and multiplicity trigger logic:
Neutron recoil: > 8.5 MeV
AND
Neutron Gd-capture: >3 events, 1-8.5 MeV
AND
no muon (defined by veto)

Reconstructed spectrum based on multiplicity and recoil information

<table>
<thead>
<tr>
<th>Depth (m.w.e.)</th>
<th>Events in 3 Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>18293</td>
</tr>
<tr>
<td>200</td>
<td>8303</td>
</tr>
<tr>
<td>300</td>
<td>4854</td>
</tr>
<tr>
<td>400</td>
<td>3393</td>
</tr>
<tr>
<td>500</td>
<td>2473</td>
</tr>
</tbody>
</table>

Integral number of events versus depth
Radionuclide Background Detector

- 3.5x3.5 meter detector with 1.5x1.5 meter active inner volume.
- Four optically segmented volumes with 0.1% GdCl₃ doping.
- Three inner volumes define a muon ‘telescope’
- The central volume is the search region.
- The outer volume is the muon/neutron veto.
Radionuclide detector installation

Top of detector vessel

Inside the vessel

Assembling the inner detector

Inner detector PMTs installed
Step 2: Choose a location suitable for nonproliferation demonstration

1. Detect as few as ~1 but no greater than 10 signal events per day.

2. Three sigma detection of the presence of the reactor in <~1 month.
   • For 1 signal event per day → tolerable background is ~2 events per day.
   • Greater standoff can be compensated by greater overburden

3. Overburden:
   • Existing or shallow overburden preferred (cost savings)

4. Reactor Power:
   • A small reactor is preferred, (greater similarity with the ultimate intended use)
Map of US Power Reactors
Map of US Reactors + Active Mines
One US deep site: Perry Nuclear Generating Station

Perry Reactor Nuclear Generating Station to IMB cavern in the Fairport Salt Mine (Ohio)
- 1570 m.w.e.
- cavity was 18m x 17m x 22.5m
- ~13 km standoff
- 3875 MWth

Pros
- Existing cavern in active mine (IMB).
- Large depth for low background (more physics overlap).

Cons
- Large stand-off will give low signal rate (0.5-1.0 per day).
- Old cavern likely to require renovation.
**Shallow sites: Oak Ridge High Flux Isotope Reactor and Idaho Advanced Test Reactor**

**INL – ATR**
- Very attractive power and duty cycle - ~2:1
- ~150 MW\text{th}

**ORNL - HFIR**
- 50% duty cycle –
- 85 MW\text{th}

Both offer highly enriched $^{235}\text{U}$ fission sources

1000 ton det. target mass
S = 13 events per day
B = 164 events per day @100 m
10 days ON and OFF to detect @ 3 sigma

Initial estimate: 10-15 M$ for tunnel/cavern
WATCHMAN as a US Water Testbed

- New PMTs (ADIT, ANL prototypes..)
- WLS plates (CSU, UC Davis)
- Water Based Liquid Scintillator (BNL)
- Gd-recirculation (UC Davis) *

WATCHMAN lets the US water detector community make major contributions to the design and understanding of the next large water detector, wherever it is built ... HyperK, LBNE, LAGUNA, etc..
At any depth, WATCHMAN will be one of the world’s largest supernova watch detectors

- A kiloton detector even with moderate overburden (few 100 m.w.e.) could detect ~700 events from a supernova at the galactic center. Any detector capable of detecting reactor antineutrinos can do this by default.

WATCHMAN would see antineutrinos from a supernova like 1987a, shown here in the visible

A synoptic view of neutrino fluxes. (from ASPERA roadmap)
Conclusions

- both the nonproliferation and scientific communities are working towards building giant water detectors that are sensitive to low energy antineutrinos

- A kiloton scale Gd-water detector is a logical next step towards these large, low threshold detectors

- Deployment of such a detector at intermediate depths is a cost-effective approach to demonstrating sensitivity to reactor antineutrinos

- The KURF deployments will help us establish the minimum tolerable overburden for such a deployment
Possible Additional Physics at a Deep Site

Boulby Mine in Northern England

Currently this option is beyond scope in NA planning, but the Fairport Salt Mine near the Perry reactor remains a possibility.
Physics reach at Boulby

- Potential for precision $\theta_{12}$ measurement (LS or Water-based LS)

- Potentially sensitive to mass hierarchy (if can at 30 km with 5 ktons LS)

- Supernovae sensitivity (water, LS, WbLS) (like other sites)
82.2% of antineutrino flux is from Hartlepool (if detector at 25 km distance at Boulby).

11.5% from other British reactors. This is dominated by Haysham 1&2, which is 148 km distant and accounts for 8.4%.

4.9% from France
1.4% from Belgium, Netherlands, and Germany
Potential for Measurement of $\theta_{12}$

A: $E_{vis}$ spectrum showing effects due to "theta12" oscillations (overall suppression) and theta13 (small wiggles). Resolution is 3%/sqrt(E). Distance is 25 km.

B: Ratio showing low energy suppression due to theta12. Error bars assume 20 kton-yr exposure at Boulby. The theta12 sensitivity comes from the low energy shape.

C: With pure water, this is still there but much less apparent due to 20%/sqrt(E) resolution and Cherenkov threshold.

Studies to determine the exact sensitivity for theta12 are still underway.
Nonproliferation, Technical and Scientific objectives are all met by WATCHMAN

**Nonproliferation**
- First ever demonstration of sensitivity to reactor antineutrinos at appreciable standoff from a reactor using a gadolinium-doped water detector – probably the only scalable technology choice
- A concrete example to policy makers of a reliable low event rate antineutrino-based measurement system, with unambiguous detection of only a few events per day

**Technology**
- Detection efficiencies and backgrounds for large Gd-WCD detectors
- Well-benchmarked detector and background simulation tools
- Experience with gadolinium-doped water handling, purification monitoring in order to scale to next generation experiment

**Fundamental Physics**

**Kiloton detector:**
- Core-collapse supernovae in this galaxy

**100 kiloton- 1 Megaton**
- Megaparsec supernovae detection
- Diffuse supernova neutrino detection
- Proton decay
- Long baseline neutrino CP phase and mass-hierarchy experiments
- 60 km standoff mass hierarchy measurements at reactors
DOE Office of Science High Energy Physics Strategic Planning

- For the first time, Neutrinos and Nonproliferation are two explicit elements in the HEP Long Range Strategic Planning Process –
  - Bernstein chair of the relevant subgroups
- 5 whitepapers on
  - Coherent scatter
  - Spectral measurements for SBL and for fissile inventory estimates
  - WATCHMAN for LBL and reactor exclusion prototype demonstrations and for supernovae search
- NNSA-NA Office plan/goal is to seek FY15 funding for this project
Applied Antineutrino Physics – a growing global community with strong ties to Dark Matter and Neutrino Science

Neutrinos and Arms Control Workshop

5-7 February 2004, University of Hawaii

Neutrino Sciences 2005

Neutrino Geophysics

Honolulu, Hawaii

AAP 2006

WORKSHOP
SEPT 24-26
LIVERMORE, CA

AAP-2009
V Applied Antineutrino Physics Workshop

The meeting will be dedicated to discuss applications of antineutrino detection in the field of non-proliferation, geophysics and other applied areas.

AAP 2010

仙台 SENDAI

The 6th International Workshop on Applied Anti-Neutrino Physics
Advantages of antineutrino detection for remote discovery and monitoring of reactors

1. Cross border detection – ultimate limit is perhaps ~800 km
2. Continuous surveillance
3. Constraints on power and plutonium production rate
4. With long range capability, no cueing information required
5. Eventually: Reactor localization with improved directionality or spectral measurement

My own guess at the most likely use: cooperative deployment to confirm absence of reactors in a prescribed wide area
Boulby headframe 25 km from Hartlepool. Distances of up to 30 km available in the very extensive (~900 km) network of underground workings.
Cross-border reactor monitoring is going on right now – but only for GWt reactors and with a technology that is difficult to scale

\[\text{Per month:} \]
- 16 reactor antineutrinos
- 1 background event
From 130 GWt of reactors

\[\text{~3\% of signal from South Korean reactors} \]
\[\text{@ 400 km standoff} \]
Why is Boulby an interesting site?

- Event rate meets our detection goal
- Depth suppresses most backgrounds
- Relatively large standoff provides a convincing demonstration
- Mature, well-run, well supported underground science infrastructure
- Excavation costs lower than 'greenfield' options
- Recent mine activity allows for larger cavern (15x15x15 m)
- International cooperative deployment underscores and reinforces nonproliferation commitments of all participants
- World-class science and a path towards very large detectors
A deep site: the Boulby mine, 1000 meter depth

- 1000 ton detector target mass, 2.5 m water shield
- Power = 1570 MWth (2 cores)

\[ S^B = 0.6 \text{ events per day} \]

50 days (ON and OFF) to detect @ 3 sigma

(mine extends under North Sea)
Other Options – Ocean deployment off SONGS

- Under water options (Hanohano type deployment) near reactors off California.

- San Onofre Nuclear Generating Station (SONGS) - two 3.4 GWth reactors.

- Mobile detector may offer benefits.

Ocean bottom topography off SONGS (~700 mwe at ~12 km is possible)