THE WATCHMAN DEMONSTRATION:
REMOTE REACTOR MONITORING USING A GADOLINIUM-DOPED WATER CHERENKOV DETECTOR

TEAL PERSHING (UC DAVIS)
FOR THE WATCHMAN COLLABORATION
TAUP 2017
NEW TECHNOLOGIES PARALLEL
JULY 27TH, 2017
ANTINEUTRINOS FROM NUCLEAR REACTORS

\[ \sim 6 \times 10^{21} \rightarrow 10^{22} \rightarrow \sim 3 \]

Antineutrinos per nuclear fission \( \times \) Fissions per second in a 3 GWt reactor \( \rightarrow \) Antineutrinos per second from a 3 GWt reactor (all directions) \( \rightarrow \) Antineutrino interactions per day (per 1 kton volume, at \( \sim 25 \) km standoff)

Distance to detector, small interaction cross section

With the right detector configuration, antineutrinos could be used to monitor/exclude the existence of reactors at tens to hundred of kilometers
ANTINEUTRINO DETECTORS: AN EXAMPLE

- Already a scintillator-based detector measuring reactor antineutrino fluxes remotely
  - Detection made primarily measuring inverse beta decay (IBD) events
- Large standoff/single reactor monitoring and discovery presents additional requirements
  - Easily scalable & affordable
  - Low environmental impact
- Gadolinium-doped water Cherenkov detectors meet the criteria for this end goal

Per month:
- 16 reactor antineutrinos
- 1 background event
From 130 GWt of reactors

Approximately 3% of signal from South Korean reactors @ 400 km standoff

THE WATCHMAN COLLABORATION

32 collaborators
10 Universities
4 National Laboratories

Co-spokespersons:
Adam Bernstein, LLNL
Mark Vagins, UC Irvine/Tokyo University
THE WATCHMAN DEMONSTRATION

- Primary goal: Actively monitor an operating reactor plant installation from 10-25 km standoff
  - Demonstrates the reactor monitoring capability of a ~kton volume Gd-water detector
  - Paves the path for operating 0.1-1 Mton volume Gd-doped detectors
    - Could actively monitor reactors at ~100 km standoffs

Potential upgrades:
- ~Installation of 100 fast photosensor units (i.e. Large area picosecond photodetectors)
- WbLS fill following Gd-H₂O

HARTLEPOOL REACTORS (UK)
- 2 cores
- 1570 MWt per core
- 25 km standoff

WATCHMAN DETECTOR
- 1 kton, ~3000 HQE photomultiplier tubes
- Water Cherenkov detector, doped with gadolinium
- Antineutrinos detected via IBD signal

PERRY REACTOR (US)
- 1 core
- 3875 MWt
- 13 km standoff

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**DETECTING IBDS WITH GD-DOPED WATER**

- **IBD interaction:** \( \bar{\nu}_e + p \rightarrow e^+ + n \)
- **Delayed coincidence signal**
  - Prompt light from positron’s Cherenkov light
  - Delayed signal (~30 µs) gamma cascade after Gadolinium capture of neutron
    - Average energy release of Gd capture above most natural backgrounds

\[ n + ^{155,157}\text{Gd} \rightarrow ^{156,158}\text{Gd} \rightarrow ^{156,158}\text{Gd} + \gamma + s (8 \text{ MeV}) \]

**Well counter (top and schematic)**

**Neutron capture energy spectrum in SuperK**

**Gd signal source geometry (deployed in SuperK)**

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WATCHMAN – DOMINANT BACKGROUNDSS

1: long lived radionuclides
2: fast neutrons
3: coincidences of:
   - single gamma-rays,
   - neutrons,
   - muons,
   - radon...

Fast neutron rates are measured by MARS

The long lived radionuclide event rates are measured by WATCHBOY
FAST NEUTRON MEASUREMENT - MARS

- Multiplicity and Recoil Spectrometer (MARS)
- Fast neutrons incident on lead target induce multiple neutron products
  - Fast neutron incident energy determined with neutron multiplicity
- First variable depth measurement made with one detector
  - Paper submitted to PRL May 2017

Fast Neutron Flux vs. Energy, measured at the Kimballtont Underground Research Facility (KURF)

Fast neutron (~200 MeV)
LONG-LIVED RADIONUCLIDES WITH WATCHBOY

• WATCHBOY – Gd-doped water detector designed to measure the $^9\text{Li}$ production rate following cosmic muons
  - $^9\text{Li}$ signal: two flashes (prompt beta and delayed neutron) following a muon event
• Set a limit on $^9\text{Li}$ production rate at 400 m.w.e. depth at KURF
  - 90% CL: $1.9 \times 10^{-7} \mu^{-1} g^{-1} cm^2$
  - Determined radionuclide production is a subdominant background
• Results published in NIM Phys. R. A in June 2016

All Li-9 Candidates following muons in WATCHBOY (207 live-time days)


- 36 10” outer volume PMTs in a water volume for muon ID
- 16 10” PMTs in Gd-doped water region
MONITORING OF REACTOR STATES - STUDY

- Boulby Mine (UK) and Fairport (USA) two main potential sites for WATCHMAN Gd-doped water Cherenkov detector

<table>
<thead>
<tr>
<th></th>
<th>Option 1</th>
<th>Option 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Location</td>
<td>Perry, Ohio, United States</td>
<td>Hartlepool, England, United Kingdom</td>
</tr>
<tr>
<td>Thermal Power (MWt)</td>
<td>1 x 3875</td>
<td>2 x 1500</td>
</tr>
<tr>
<td>Detector Location</td>
<td>Morton Salt/IMB mine</td>
<td>Boulby underground science lab, Boulby, England</td>
</tr>
<tr>
<td></td>
<td>Painesville, Ohio</td>
<td></td>
</tr>
<tr>
<td>Standoff</td>
<td>~13 km</td>
<td>~25 km</td>
</tr>
<tr>
<td>Overburden (mwe)</td>
<td>~1500</td>
<td>~3000</td>
</tr>
<tr>
<td>Signal Events</td>
<td>110 per month</td>
<td>11 per month</td>
</tr>
<tr>
<td>Background Events</td>
<td>50 per month</td>
<td>20 per month</td>
</tr>
</tbody>
</table>

- For Fairport’s expected signal vs. background rates, how many days would WATCHMAN need to run to see a clear 3-sigma deviation between the “reactor on” data set and “reactor off” data set?
  - Assume we have the proposed reactor operation schedule at either site
  - WATCHMAN detector performance simulated using RAT-PAC
  - Boulby study still ongoing
**REACTOR ON/OFF TRANSITIONS - FAIRPORT**

- At the Fairport site, WATCHMAN would observe the Perry power plant’s on/off cycle in less than 3 months
  - Statistically generated 100,000 experiments to set confidence levels on the day of observation
  - Fairport assumed schedule: Core off for 40 days, on for 700 days

- Blind confirmation studies (i.e. no prior knowledge of the schedule) the next task
CONCLUSION

- Gadolinium-doped water Cherenkov detectors are a competitive detection medium for reactor monitoring
  - High IBD detection efficiency
  - Scalability to 100 kton – 1Mton scales
- Potential testbed for additional detector technologies in a ~kton scale detector
  - Fast photosensors
  - Water-based liquid scintillators
- New physics measurements already made on the path to the WATCHMAN demonstration
  - Fast neutron flux vs. depth
  - First Gd-water demonstration at ~ton scale
- Sensitivity to confirming a reactor plant’s given operation schedule at Fairport site investigated
  - Studies on measuring deviations from a given schedule upcoming
  - Boulby study and optimization underway
- Currently proposed to start WATCHMAN in 2018
RESOURCE SLIDES
AVERAGE IBDS/DAY FOR EACH SITE AS SIMULATED IN WATCHMAN

Values used in preliminary study shown
Values generated using WATCHMAN’s RAT-PAC as of June 2017

Boulby Site Values

```json
{
  "Photocoverage_Cases": [
    {
      "Photocoverage": 0.25,
      "Signal_Contributions": {
        "Core_1": 0.3699,
        "Core_2": 0.3699,
        "Other_Reacs": 0.1073,
        "Accidentals": 0.0996,
        "Fast_N": 0.0832,
        "Radionuclides": 0.0145
      }
    }
  ]
}
```

Fairport Site Values

```json
{
  "Photocoverage_Cases": [
    {
      "Photocoverage": 0.20,
      "Signal_Contributions": {
        "Core_1": 3.69,
        "Other_Reacs": 0.1845,
        "Accidentals": 0.4333,
        "Fast_N": 0.8554,
        "Radionuclides": 0.1896
      }
    }
  ]
}
```
The WATCHMAN Demonstration
Teal Pershing (UC Davis)

UNCERTAINTIES FOR ON/OFF CYCLE CONFIRMATION

For either the “both cores on” or “one core off” data set...

\[ \Gamma_{IBDS}(t) = \frac{N_{IBDS}}{t} \]

\( \Gamma_{IBDS} \) – Average IBDs/Day according to all data taken up to that day (cores + background)
\( t \) – time in days of data collected for this data set

At any day in the experiment, the uncertainty in this average is:

\[ \sigma_{\Gamma} = \Gamma_{IBDS} \sqrt{ \left( \frac{\sigma_{N}}{N} \right)^2 + \left( \frac{\sigma_{t}}{t} \right)^2 } \]

\[ \sigma_{\Gamma} = \Gamma_{IBDS} \left( \frac{\sigma_{N}}{N} \right) = \Gamma_{IBDS} \left( \frac{\sqrt{N_{IBDS}}}{\Gamma_{IBDS} \times t} \right) \]

\[ \sigma_{\Gamma} = \frac{\sqrt{N_{IBDS}}}{t} \]

“Confirmation” of the reactor cycle is claimed when:

\[ \Gamma_{ON} - \Gamma_{OFF} > 3 \sigma_{TOT} \]

is true for 14 days in a row. \( \sigma_{TOT} \) is the “ON” and “OFF” data set average uncertainties added in quadrature
GADOLINIUM PURIFICATION USING EGADS

- Gadolinium-doped water has been investigated for potential addition to Superkamiokande
- Evaluation of Gadolinium Action on Detector Systems (EGADS) developed in Kamioka mine
  - 200 ton Gd-doped water Cherenkov detector
  - $Gd_2(SO_4)_3$ diluted in DI water
  - Gd-compound + water purification system
- Separation of gadolinium compound and DI water for purification of water performed
  - 99.9% recovery of Gadolinium compound achieved in system
- Continuous operation and purification of Gd-doped water system ongoing
  - Will give a final benchmark on purification performance on longer timescales

**THE IBD SIGNAL, NO GADOLINIUM**

- Delayed coincidence signal
  - Prompt light from positron Cherenkov radiation
  - Delayed (~100 μs later) 2.2 MeV signal from neutron capture
    - For water Cherenkov detectors, this energy range has numerous natural backgrounds

$$\nu_e + n + p \rightarrow 2 H + \gamma (2.2 \text{ MeV})$$