SAND2011-4857C

Aboveground Antineutrino Detectors for Reactor Monitoring and Safeguards

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Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000

Lawrence Livermore National Laboratory

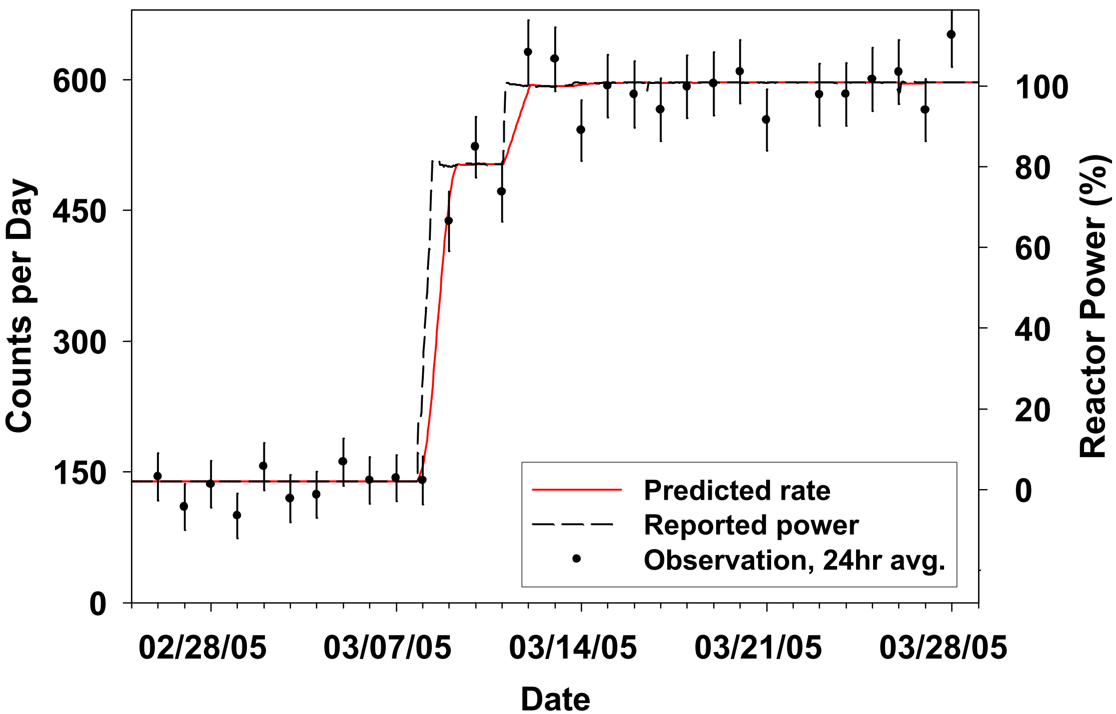
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory in part under Contract W-7405-Eng-48 and in part under Contract DE-AC52-07NA27344.

Sandia National Laboratories

A Novel Technology for Reactor Safeguards

- Antineutrino Monitoring of Reactors provides independent measurements of Thermal Power and Fissile Inventory
  - Non-intrusive with NO connection to plant systems
  - Continuous Remote Monitoring
  - Highly tamper resistant
- Potential Applications to Present and Future Safeguards
  - Independent Confirmation of Operator Declarations
  - Reduction in needed Inspector visits
  - Provide fissile content information for Next-Generation fuel cycles (MOX, Th, bulk process)

Reactor Power Monitoring using **only** $\bar{\nu}$



Timescale

1 – 3 Hours:

Sudden changes in operational status (on/off)

1 Day:

Large power changes

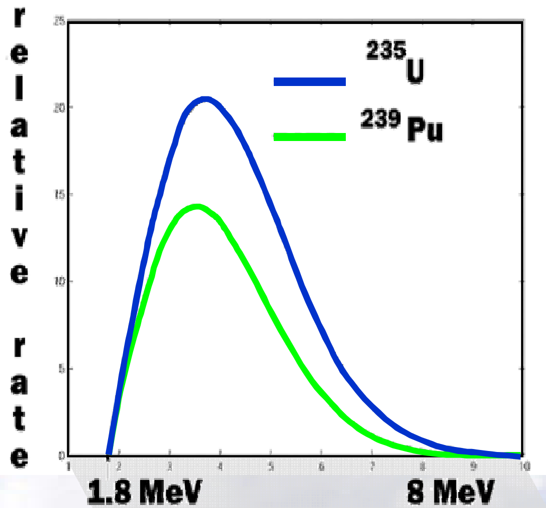
7 Days:

Relative thermal power measurement (2 – 3%)

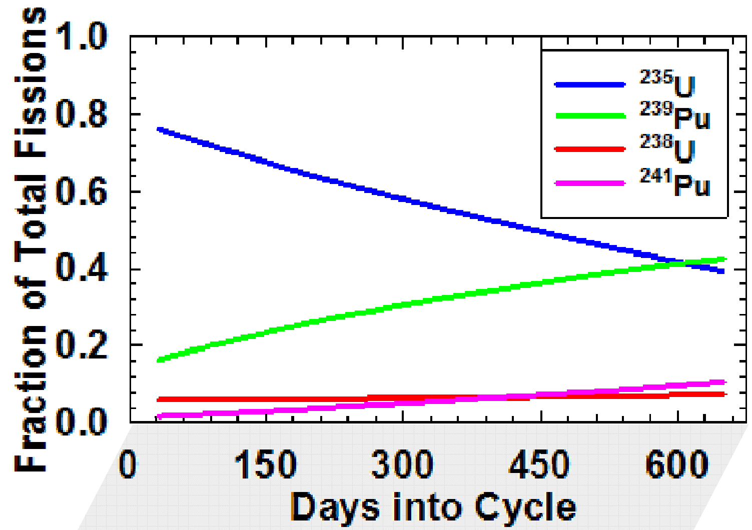
Large power changes are readily observed with no physical connection to the plant

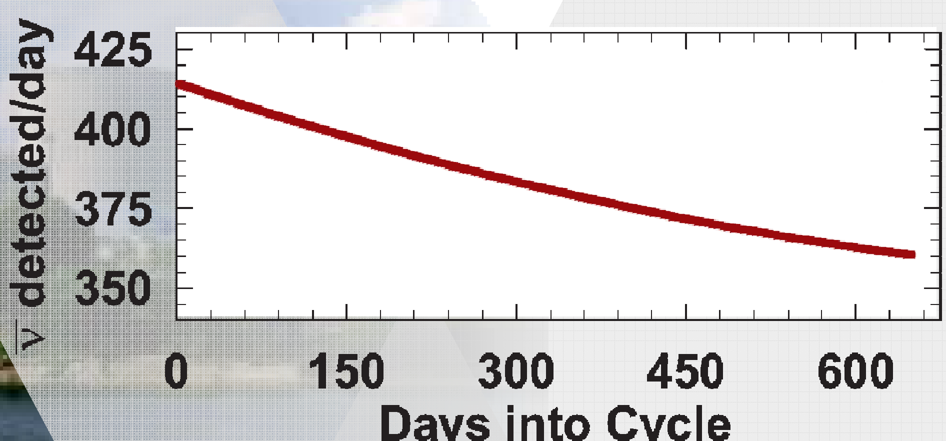
The Antineutrino Rate varies with Isotope

The energy spectrum and integral rate produced by each isotope is different



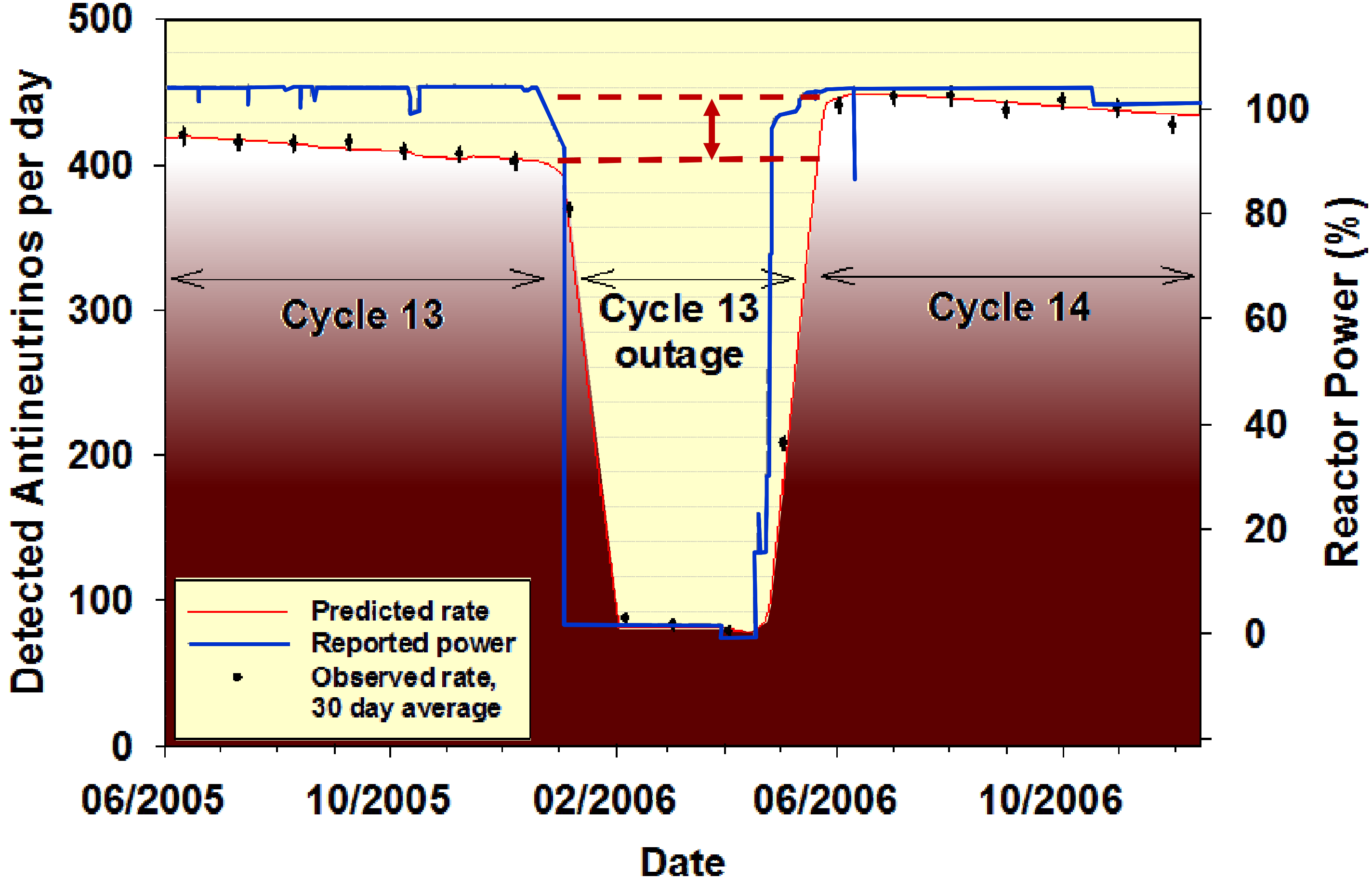
The fuel of a PLWR evolves under irradiation: ^{235}U is consumed and ^{239}Pu is produced





$\overline{\nu}$ Provides Information on Fuel Composition

Standard Refueling is Clearly Visible

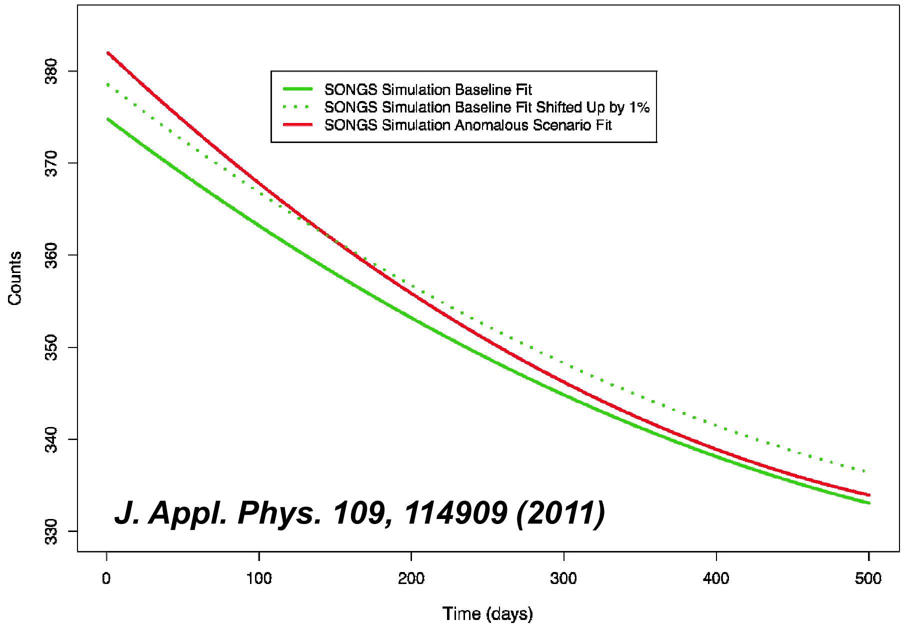


Sensitive to undeclared removal of 70 kg ^{239}Pu

Core and Assembly Level Verification Studies

Replace 10 once burnt assemblies — **70 kg Pu239 in removed assemblies**

With 10 fresh assemblies — **Replacement keeps thermal power constant**



The antineutrino rate evolution throughout the cycle is affected by the change in initial fuel loading

Over time, a statistical test detects the anomalous fuel loading

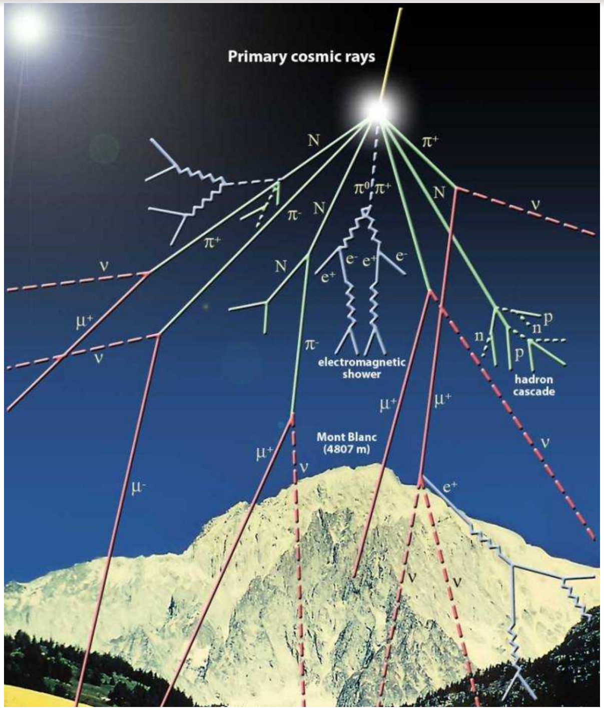
Event statistics, misreporting of thermal power are the dominant effects

	2000 cts/day
90 day acquisition	0.95 True Positive
90 day acquisition - thermal power shift	0.23 True Positive
500 day acquisition - thermal power shift	0.99 True Positive

Studying additional capabilities to verify individual assemblies, in conjunction with modern evolution codes

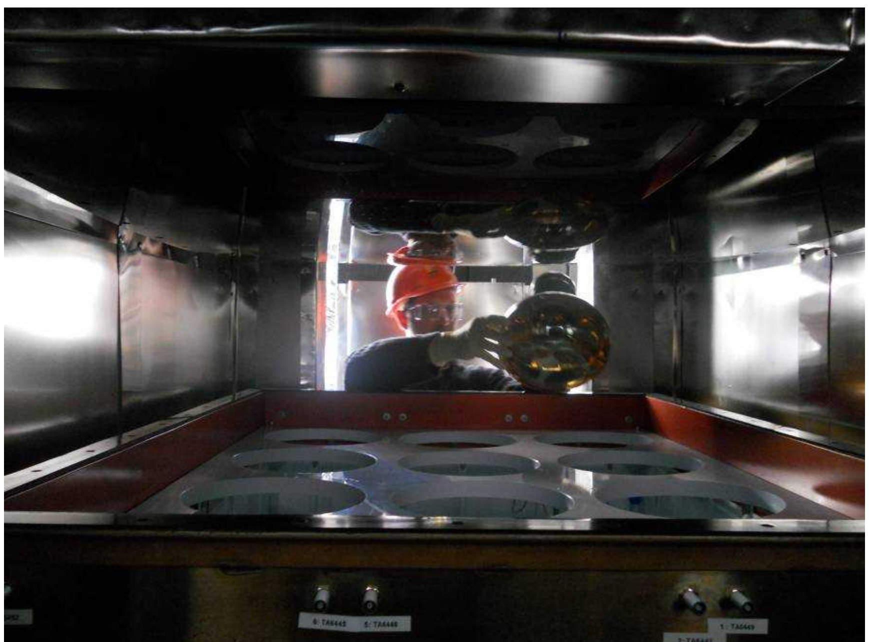
Aboveground Challenge: Increased backgrounds

- Without overburden, an aboveground detector is exposed to:
  - An increased muon rate
  - Hadronic showers
  - Electromagnetic showers
  - Secondary particles produced by all of the above in the detector and its surroundings
- Belowground (only a few meters) many of these cosmic backgrounds are significantly reduced
  - SONGS1 design would not have survived aboveground backgrounds
- A shield can control backgrounds more simply than detector design
  - Need to reduce neutron impact is severe
  - Constructed a high-quality shield within a transportable 20' shipping container



Next Stop….San Onofre

Final Deployment at SONGS



2 Detector Technologies: Different Methods of Background Rejection

The "Smart" (complex) Detector: Segmented Scintillator with Particle Identification (PID)

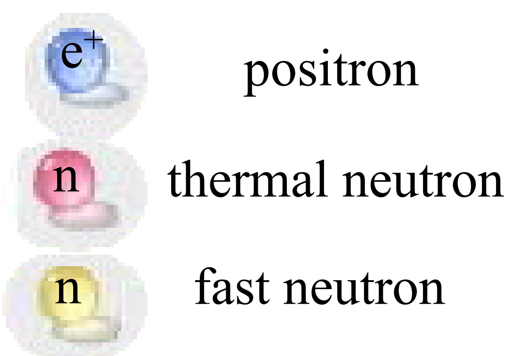
Identify and reject:
- Fast neutrons
- Gamma-rays

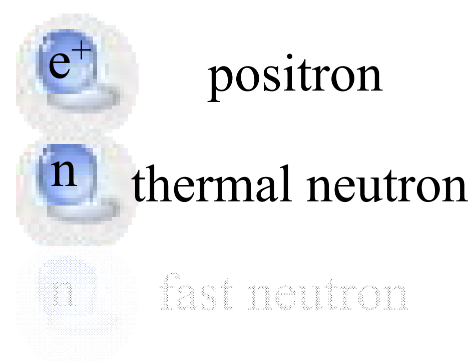
Explicitly tag final state products:
- Positron
- Thermal neutron (capture)

The "Dumb" (simple) Detector: Gd-Doped Water Cerenkov

Indifferently sensitive to:
- Positron
- Neutron (captures)
- Gamma

Insensitive to an important class of background:
- Fast neutron recoils



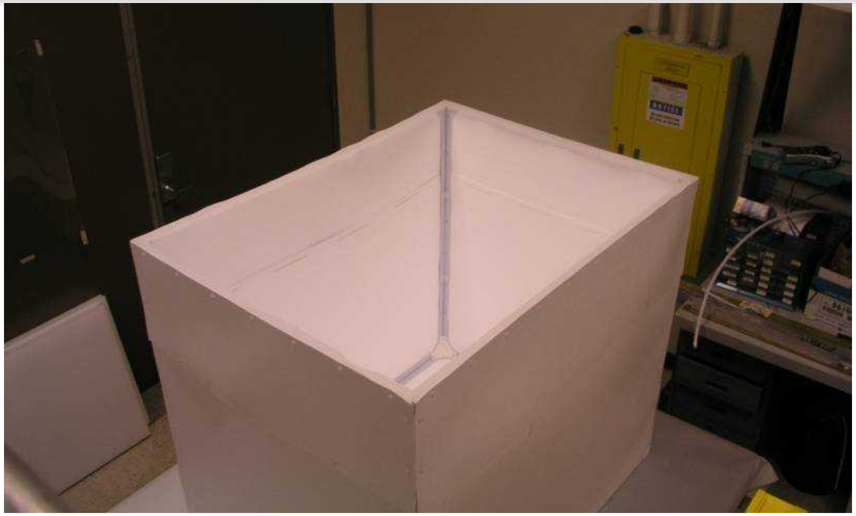


First Try: No Particle Identification, Just Physics

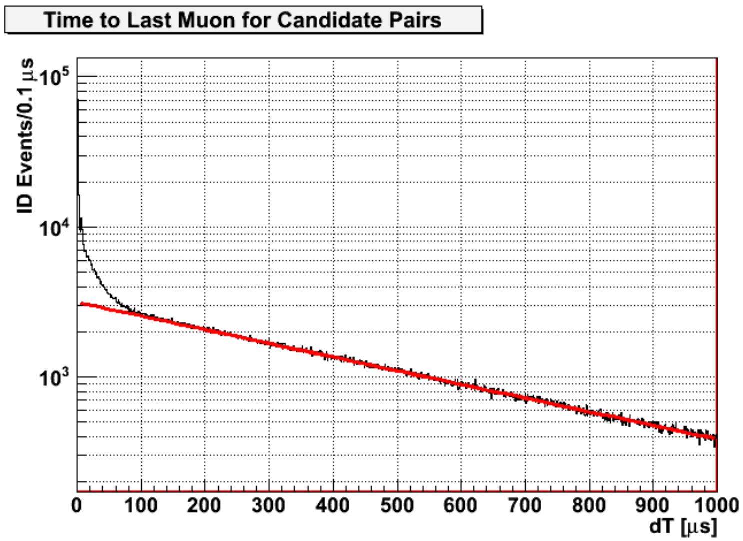
A Water Based Antineutrino Detector

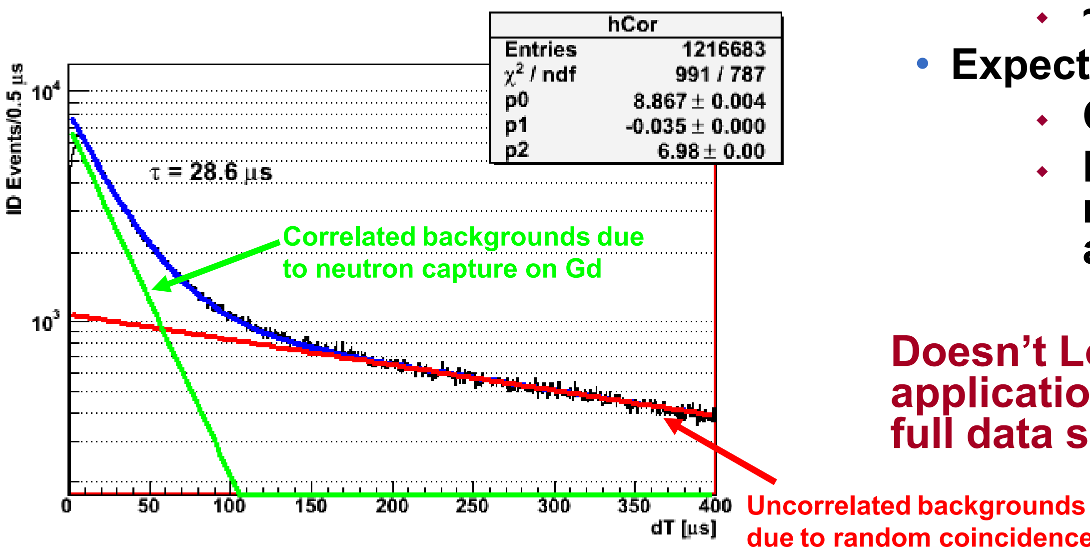
- Water Cerenkov used for *neutrino* detection
  - Deployability – Environmentally safe
  - Reduced sensitivity to fast neutron backgrounds
  - Poor energy resolution, due to:
    - Directionality of photons
    - Low number of photons
    - Minimum electron/positron energy required to produce any photons

- Addition of a neutron capture agent (~0.2% $GdCl_3$) allows for antineutrino detection via inverse beta decay
  - Previous small-scale test showed promise so we have improved it



Preliminary Water Detector Analysis



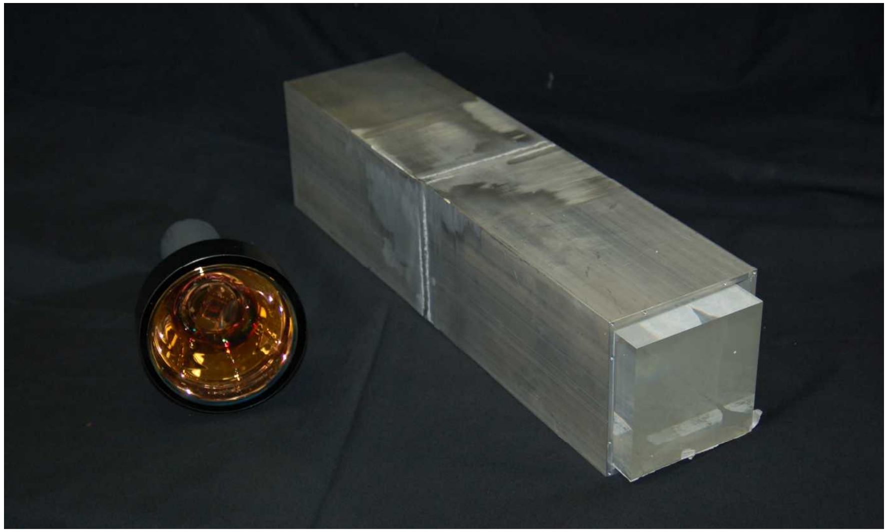


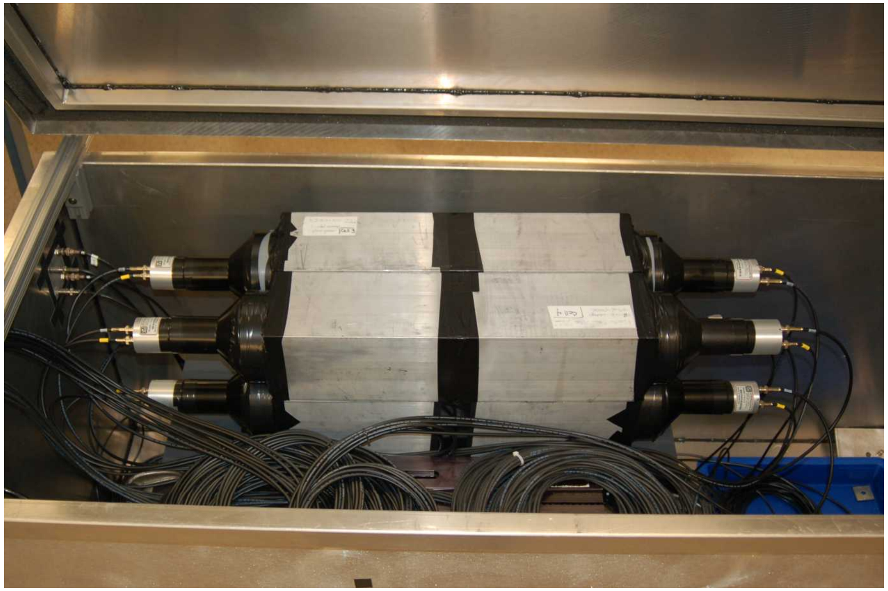
- **Initial operation of muon system looks good**
  - **>98% efficiency to detect muons**
  - **100 µs veto around muon detection eliminates most cosmic induced showers**
    - **Gives 21% deadtime**
- **Clean separation of correlated events from uncorrelated backgrounds through timing**
  - **Time constant of ~28 µs for neutron capture on Gd**
- **Preliminary Analysis**
  - **Correlated background: ~40,000 ev/day**
    - **~90,000 without muon veto**
  - **Expect ~100 $\bar{\nu}_e$ events/day**
    - **Could get 2 sigma in 14 days**
    - **Need at least a factor 4 further rejection of backgrounds to achieve our original goal**

Doesn't Look so good for Aboveground application….but we are still analyzing the full data set

Second Try: PID with Segmented Scintillator Detector

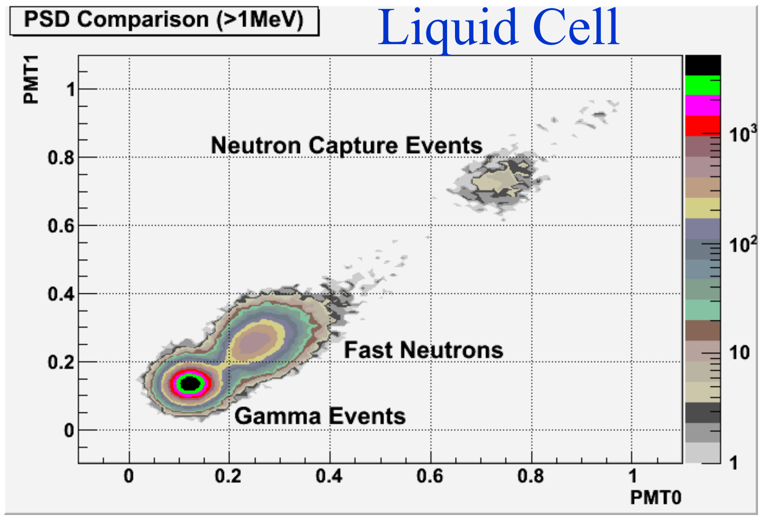
- **Individual Segments contain organic scintillator with ZnS:Ag/^{6}LiF screens on outer surface**
  - **3 cells with Plastic scintillator**
  - **1 cell with Liquid scintillator**
- **Use of ZnS:Ag with ^{6}LiF allows identification of neutron capture**
  - **ZnS:Ag is sensitive to alpha from n-capture on Li**
  - **Very slow scintillator time constant (~100ns) allows pulse shape discrimination to separate n-capture from γ events**
- **With Liquid Scintillator, proton recoils are also easily identified**
  - **Allows a comparison to test need for additional rejection**
- **Ultimate design would be for 16 cells but this 4-cell prototype was sufficient for first testing**

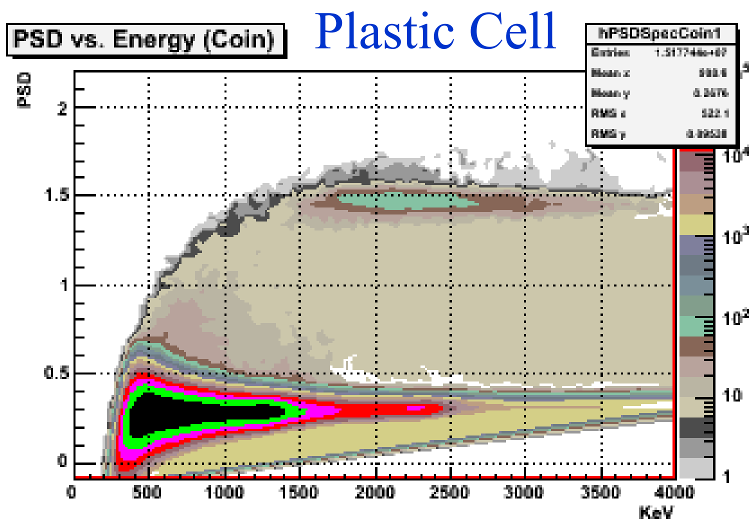




Particle Identification (PID)

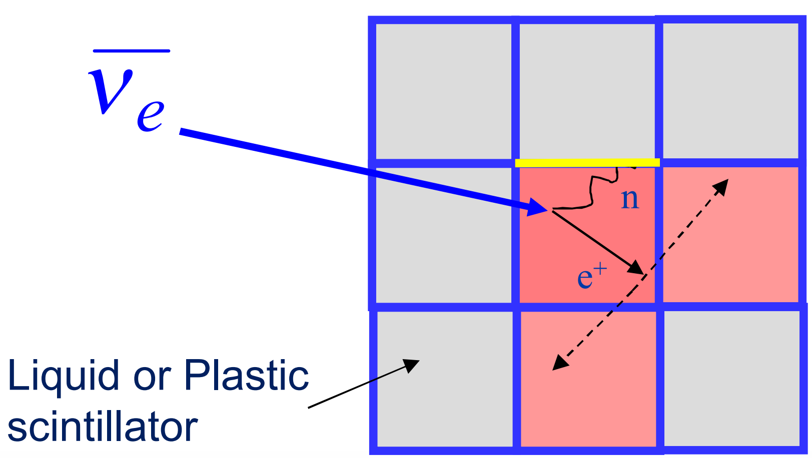
Neutron identification through Pulse Shape Discrimination (PSD)



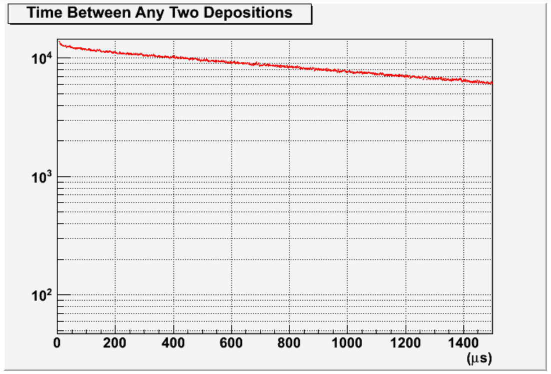


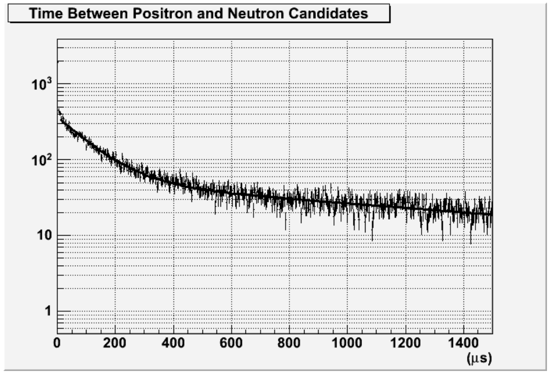
Positron Identification through Topology

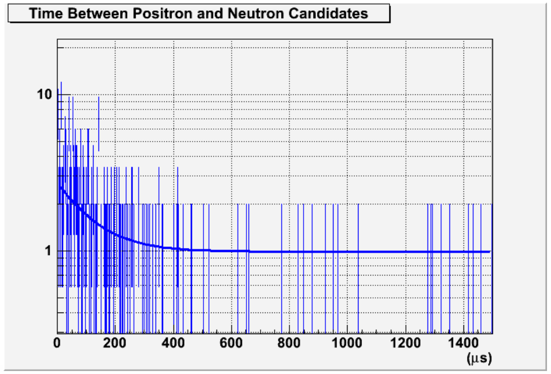
- **Positrons are rare in nature**
  - **Deposit most of their kinetic energy very quickly through standard ionization losses**
- **Positrons will annihilate into two back-to-back 511 keV gammas**
  - **Very distinctive signature**
  - **Gammas will travel ~2-5" through most scintillators**



First Analysis of Reactor Off Data







No PID
225,200 ev/day

Only Neutron PID
1,830 ev/day

Max PID info
23 ev/day

- **Detector Performance looks stable**
  - Detector efficiencies look reasonable
    - N-capture efficiency of 18%
    - Positron efficiency 2—87%
- **Background rates are reasonable for a possible observation of reactor transition**
  - 2 – 4 orders of magnitude rejection
  - 2 methods of analysis agree
- **Based on expected $\overline{\nu}_e$ signal, expect 3 sigma detection in 4 – 6 weeks**
  - Expect 1 – 37 ev/day
- **Very encouraged by technology performance**

Conclusion

- **Previously demonstrated short and long term relative monitoring of power operational status, and fissile content in reactors**
- **This project aims to expand the range of utility by enabling above ground deployment**
- **We have examined several powerful tools to achieve the required ~3-5 orders of magnitude suppression of background**
- **The hoped for demonstration of both water and scintillator paths will permit design trade-offs for end users**
- **Very encouraged by performance of Segmented Scintillator prototype**
  - **Scaled up to 16-cells, this would almost reach SONGS1 performance**