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United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

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Workshop Towards Neutrino Technologies

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Antineutrino monitoring at the San Onofre Nuclear Generating Station (SONGS)

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Antineutrino Monitoring at the San Onofre Nuclear Generating Station (SONGS)

A Joint Project Between
Sandia and Lawrence Livermore
National Laboratories

David Reyna
Sandia National Laboratories, CA

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

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Lawrence Livermore National Laboratory

Sandia National Laboratories

Acknowledgements and Project Team

Sandia National Laboratories

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Lawrence Livermore National Laboratory

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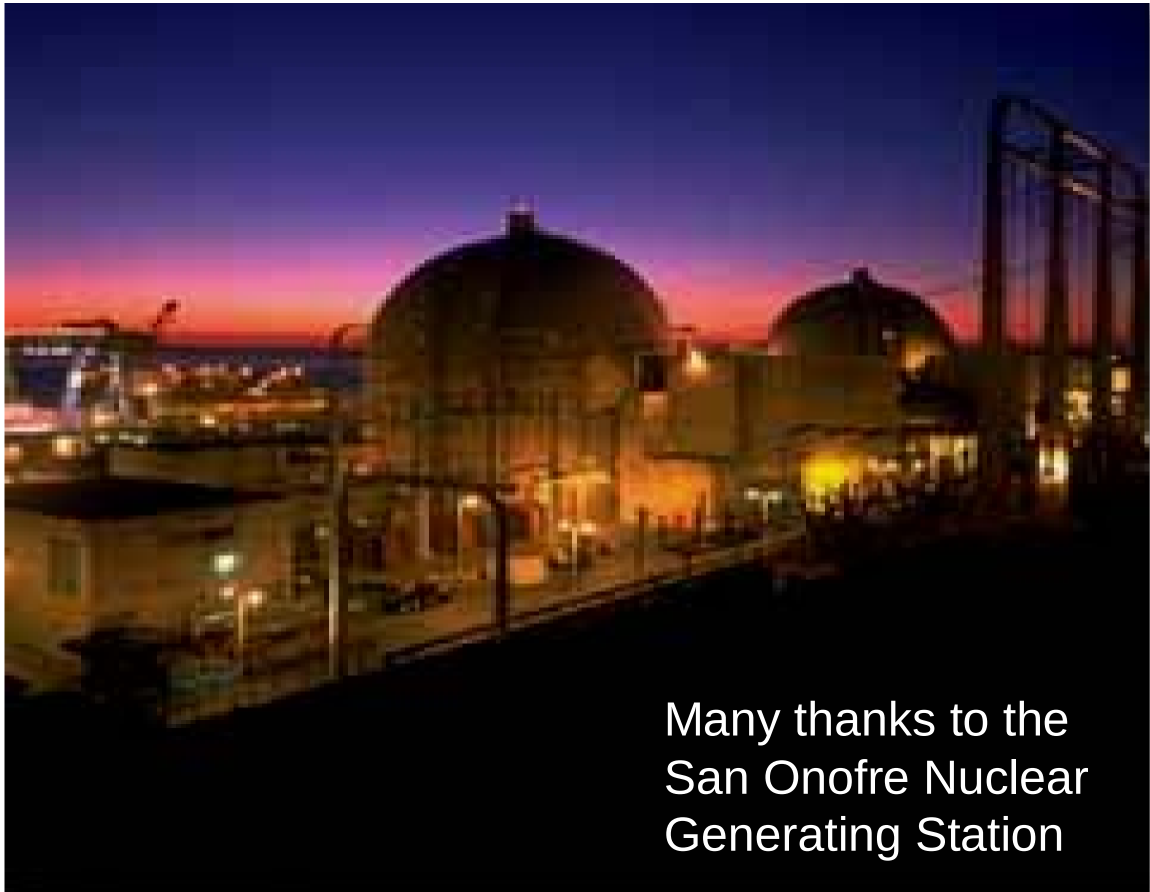
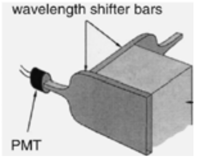
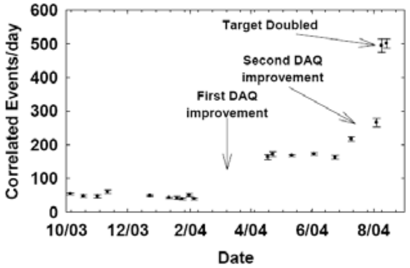
Steven Dazeley

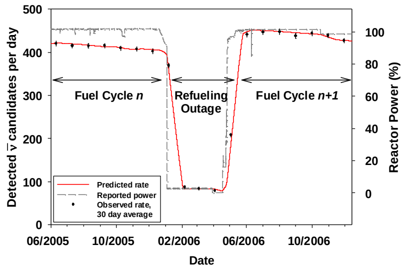


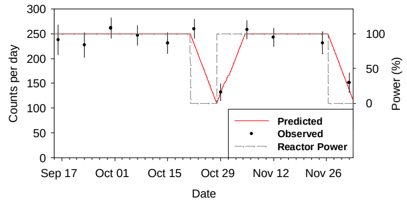
This Work is supported by DOE-NA22
(Office of Nonproliferation Research and Development)

Timeline of LLNL/SNL Presence at SONGS









Conceptual Paper,
Detector Design

First $\bar{\nu}$ observation
Large efficiency gains

Isotopic evolution
SONGS extension

Deployable Results
Detector Removal

2002

2004

2006

2008

2003

Design Refinement,
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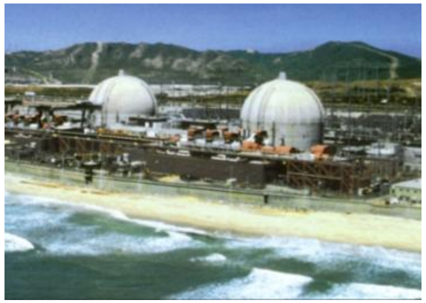

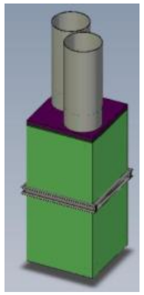

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Power Monitoring
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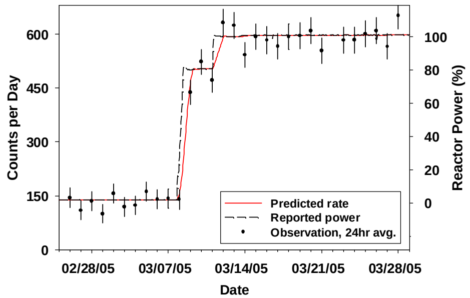


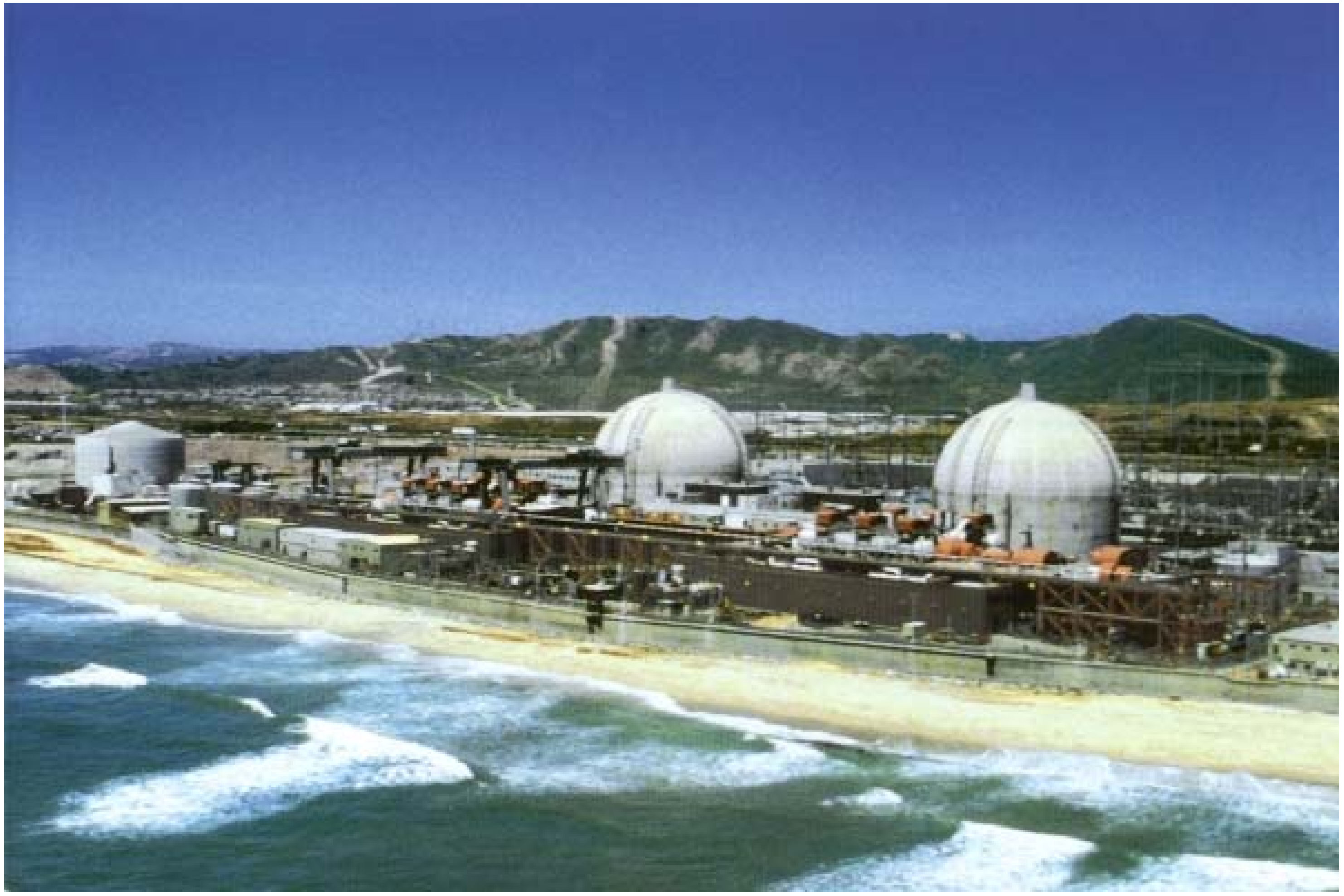
2007

Deployable Detectors Designed,
Constructed, Deployed

2009

New Deployment In
SONGS Unit-3

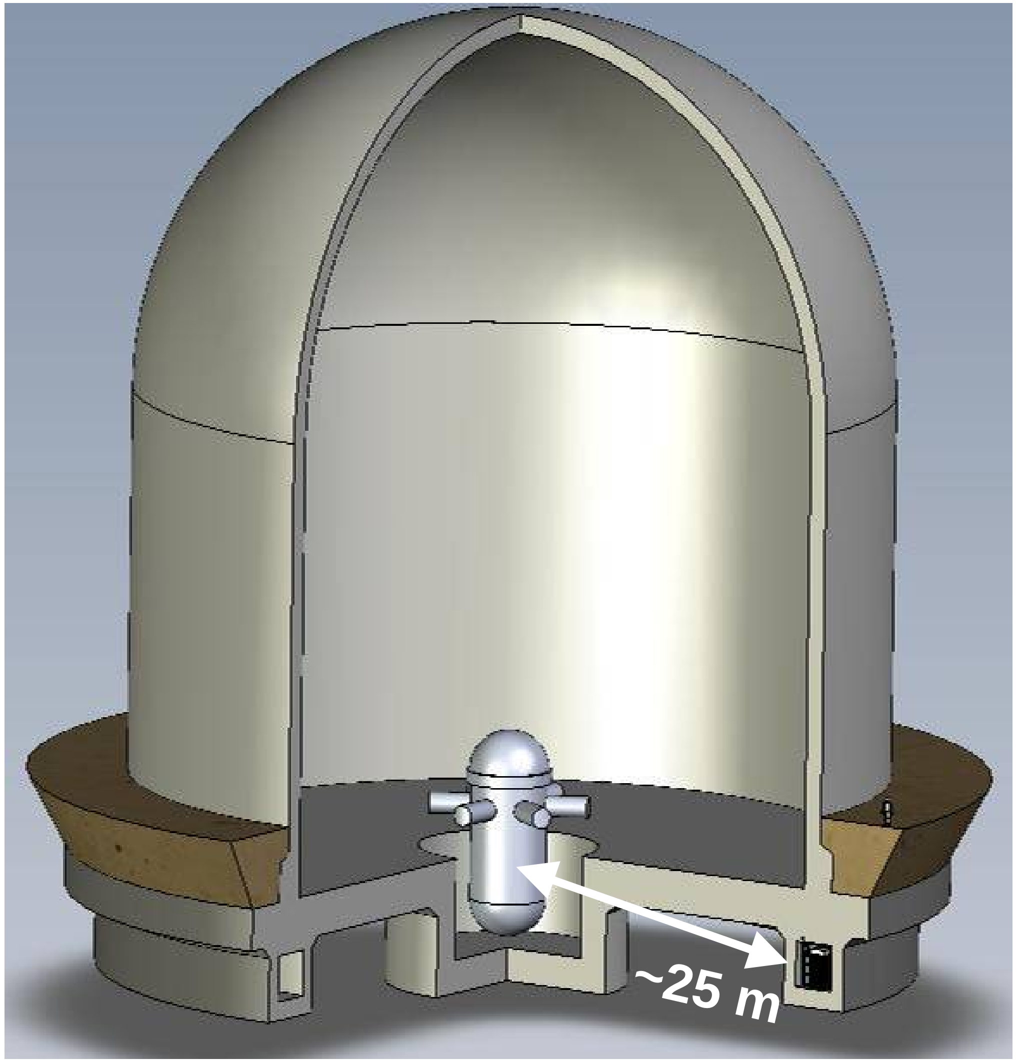
Our Past, Present and Future Home



Our long stay at SONGS is a strong validation of the non-intrusiveness of this technique.

SONGS Unit 2 Tendon Gallery

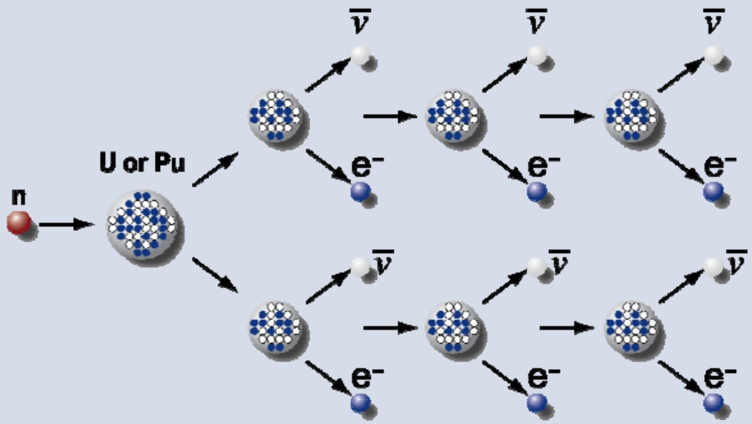
- Tendon gallery is ideal location
  - Rarely accessed for plant operation
  - As close to reactor as you can get while being outside containment
  - Provides ~20 mwe overburden



Detected antineutrino rates from reactors are reasonable for cubic meter scale detectors

Reactors emit huge numbers of antineutrinos

- 6 antineutrinos per fission from beta decay of daughters
- 10^{21} fissions per second in a 3,000-MWt reactor



About 10^{22} antineutrinos are emitted per second from a typical PWR unattenuated and in all directions

Detected rates are quite reasonable

- 10^{17} antineutrinos per square meter per second at 25-m standoff
- 6,000 events per ton per day with a perfect detector
- 600 events per ton per day with a simple detector (e.g., SONGS1)

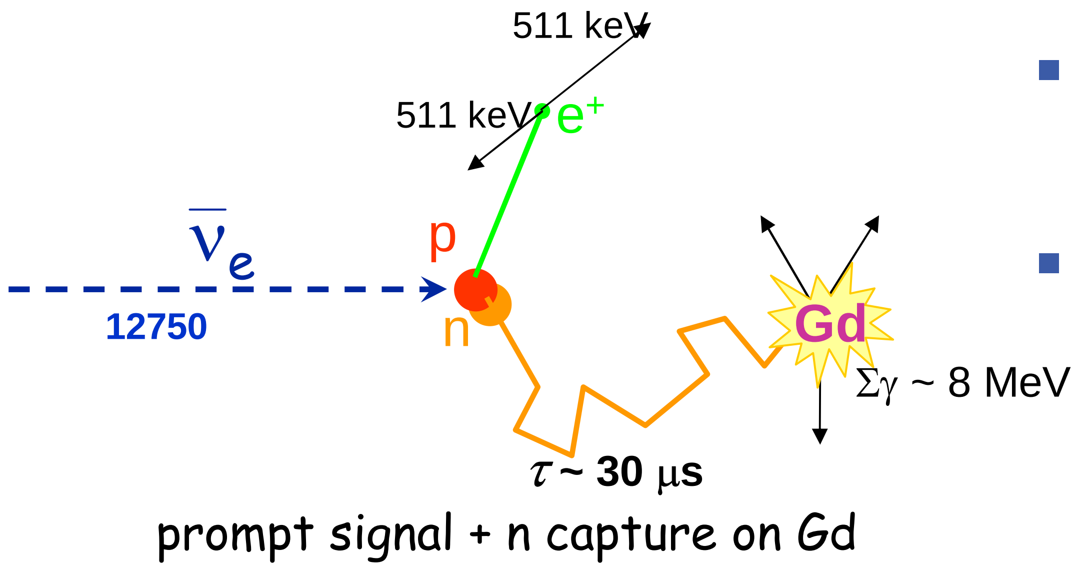
Example: detector total footprint with shielding is 2.5 meter on a side at 25-m standoff from a 3-GWt reactor

Antineutrino Detection

- **We use the same antineutrino detection technique used to first detect (anti)neutrinos:**

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

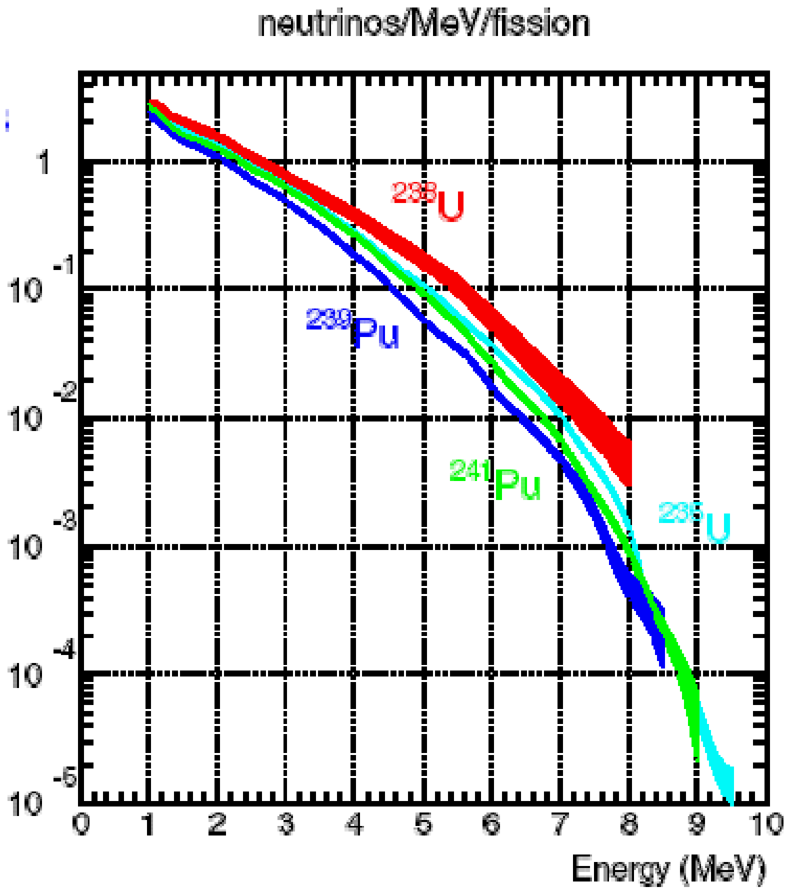
  - **inverse beta-decay produces a pair of correlated events in the detector – very effective background suppression**
- **Gd loaded into liquid scintillator captures the resulting neutron after a relatively short time**

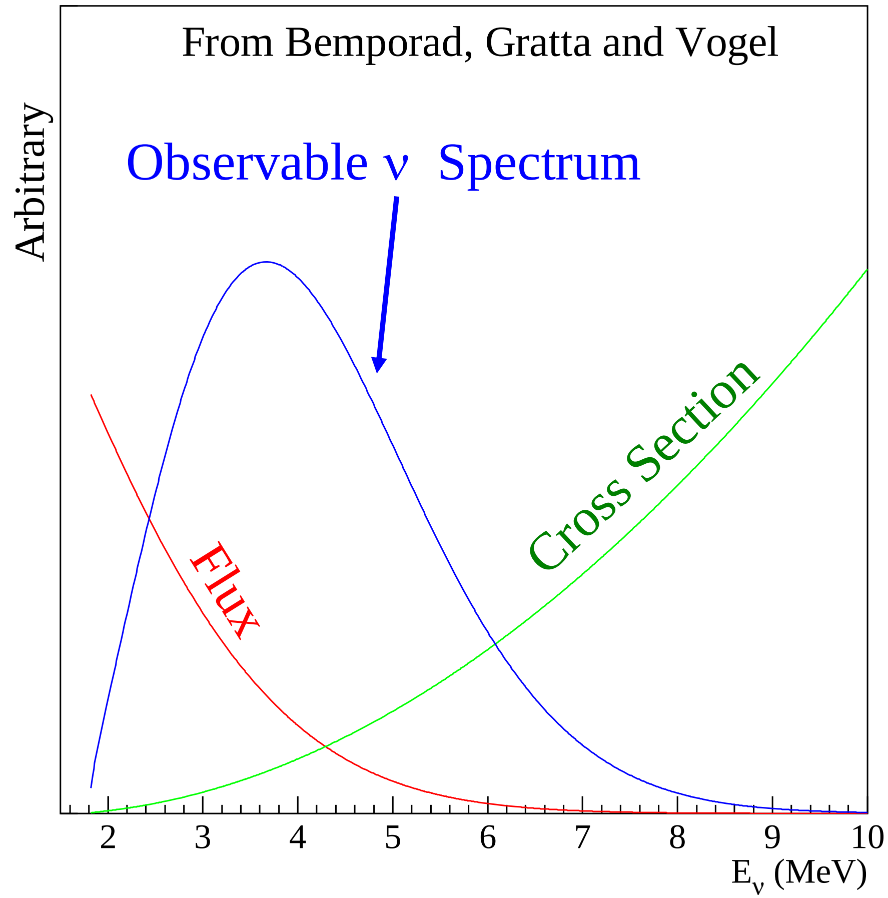


- **Positron**
  - **Immediate**
  - **1- 8 MeV (incl 511 keV γs)**
- **Neutron**
  - **Delayed (τ = 28 μs)**
  - **~ 8 MeV gamma shower**

(200 μs and 2.2 MeV for KamLAND)

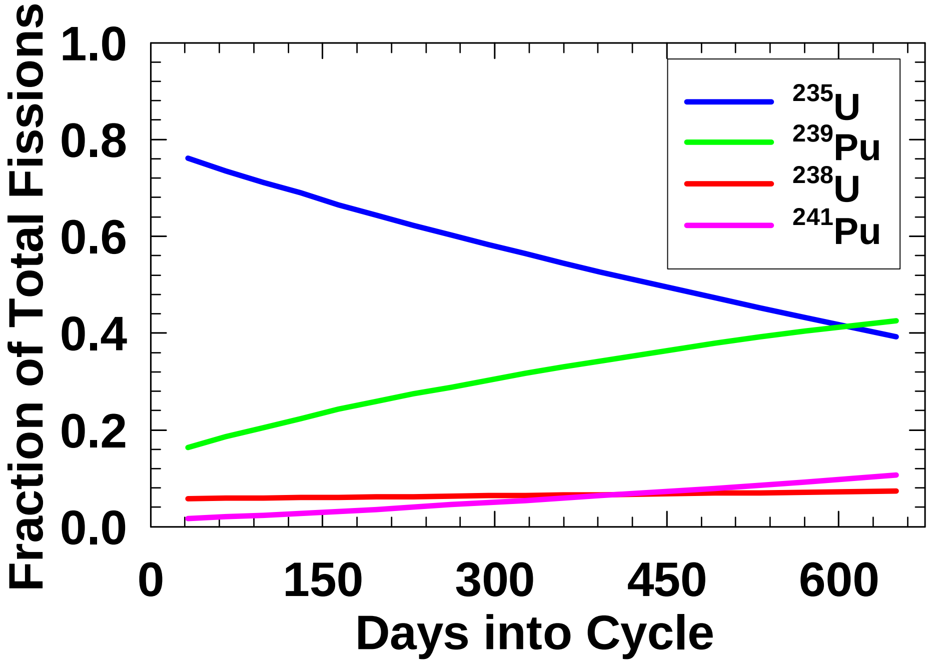
Neutrino Energy is Sensitive to Isotope



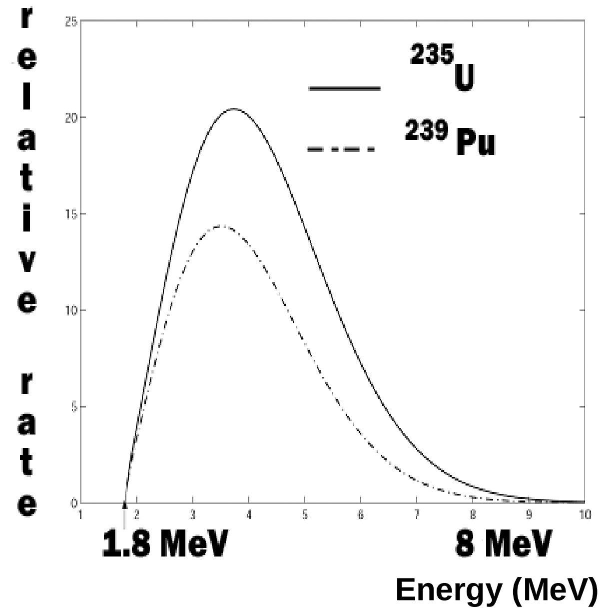


The Antineutrino Production Rate varies with Time

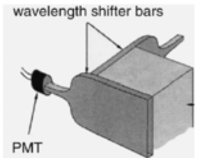
The fuel of a reactor evolves under irradiation: ^{235}U is consumed and ^{239}Pu is produced

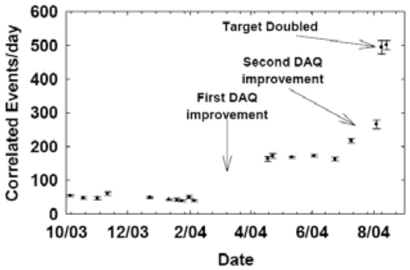


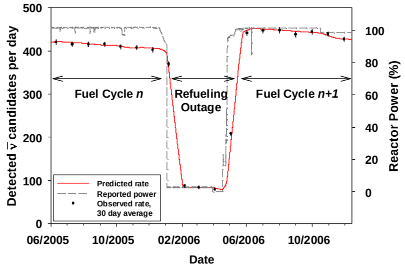
The energy spectrum and integral rate produced by each fissioning isotope is different

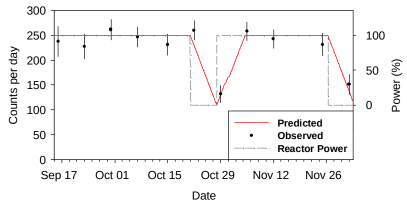


Timeline of LLNL/SNL Presence at SONGS









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Isotopic evolution

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Detector Removal

2002 **2004** **2006** **2008**

2003 **2005** **2007** **2009**

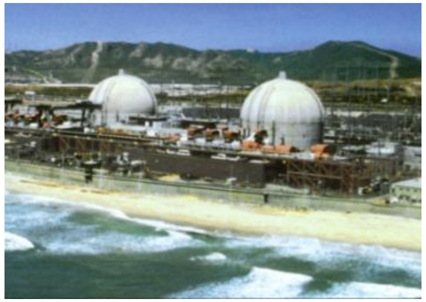
Design Refinement, Deployment at SONGS

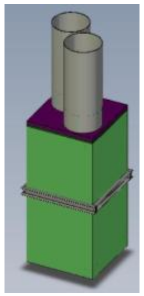
Power Monitoring

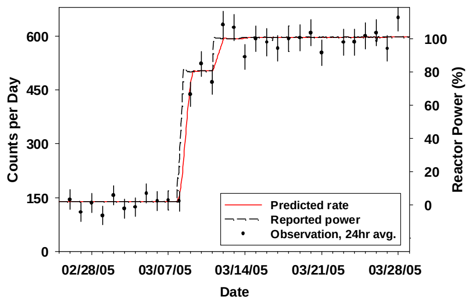
Detector Stabilisation

Deployable Detectors Designed, Constructed, Deployed

New Deployment In SONGS Unit-3

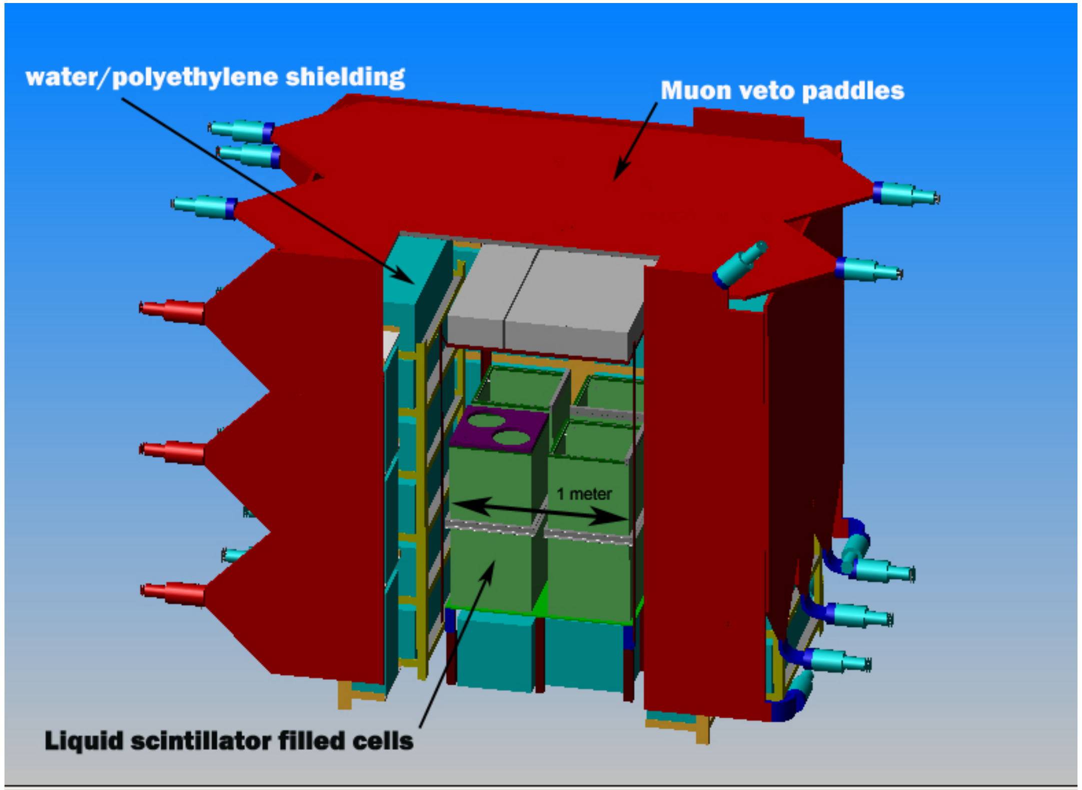






Sandia/LLNL Antineutrino Detector (SONGS1)

- 640 liters Gd doped liquid scintillator readout by 8 x 8" PMTs
- 6-sided water shield
- 5-sided active muon veto

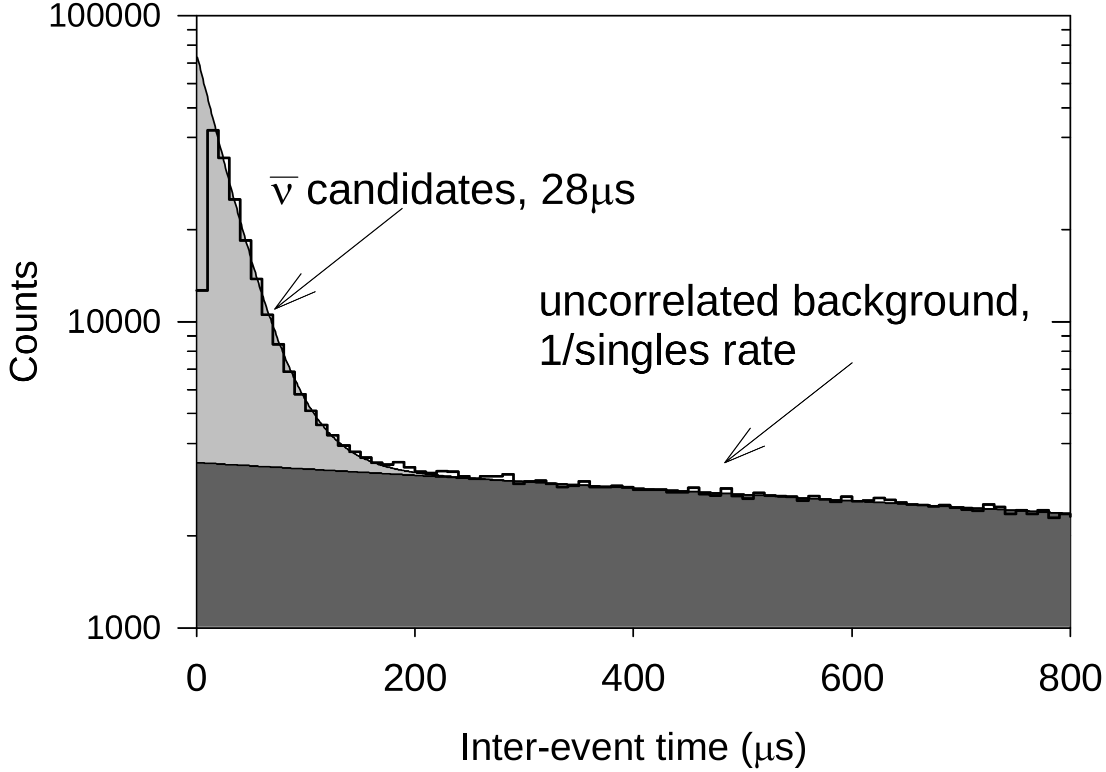


Candidate event extraction

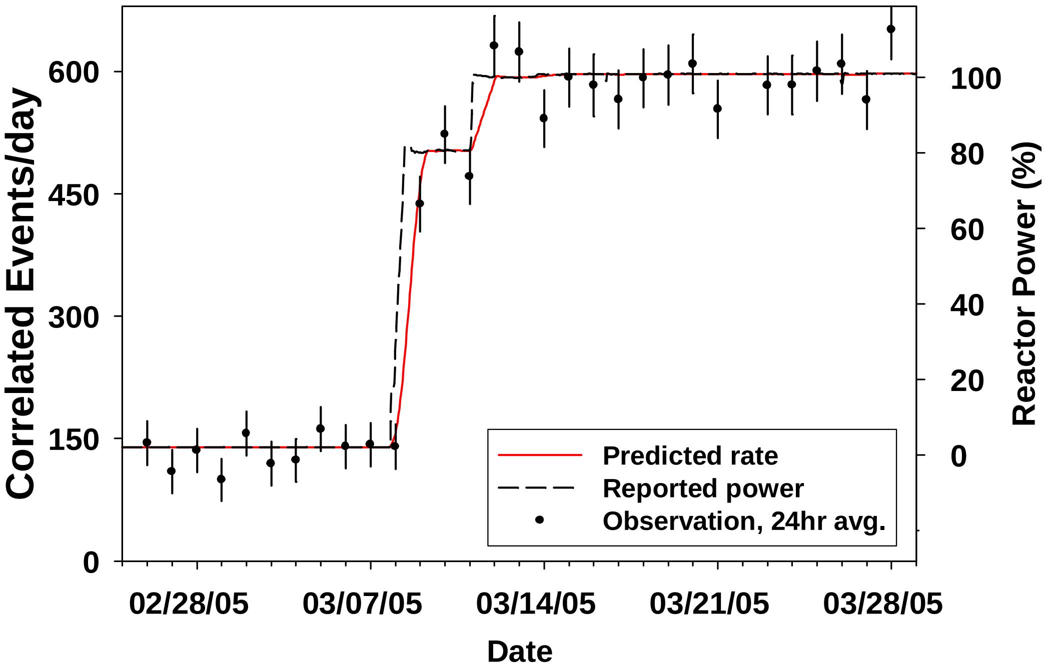
- **We record ~30 million events per day, only a handful of which are antineutrino interactions**
- **An automatic energy calibration is performed using background 2.6 MeV gamma**
- **Cuts are applied to extract correlated events:**
  - **energy cuts**

    >2.5 MeV prompt

    >3.5 MeV delayed
  - **at least 100μs after a muon in the veto detector**
- **Examine time between prompt and delayed to pick out neutron captures on Gd**

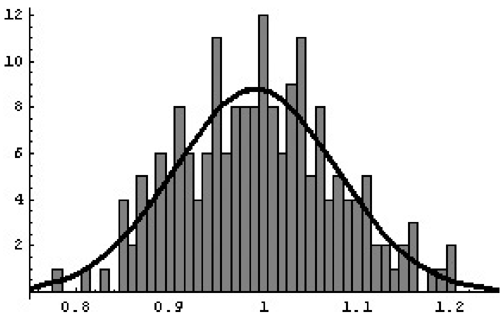


Reactor Power Monitoring using only $\bar{\nu}$

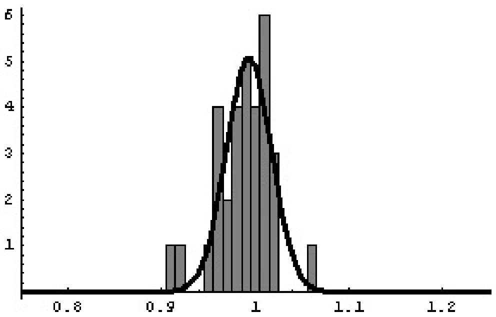


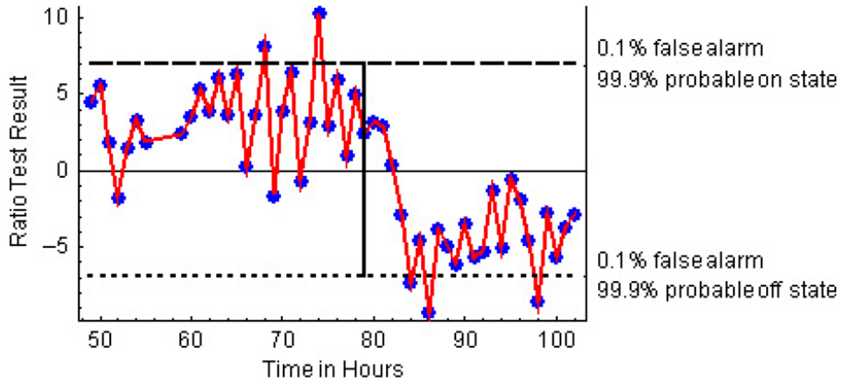
- In this example, we integrated for 24 hrs. The reactor is restarted after unscheduled maintenance
- The reactor off period allows us to measure the correlated background rate
- Large power changes are readily observed with no connection to the plant except antineutrinos
  - Daily Avg: 8% relative precision
  - Weekly Avg: 3% relative precision
- With a one hour integration time, sudden power changes can be seen

Daily Average: 8% Relative Uncertainty

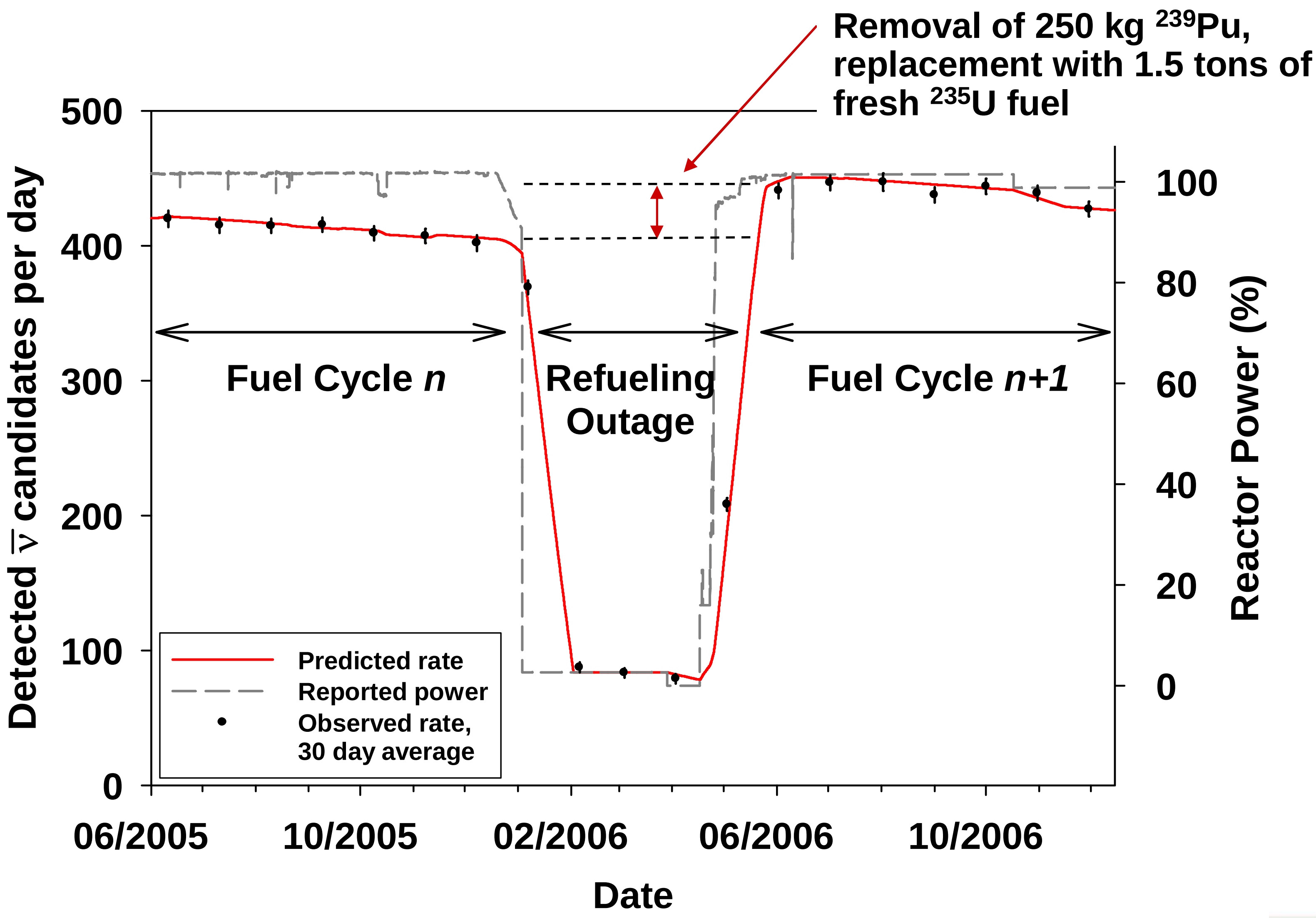


Weekly Average: 3% Relative Uncertainty





Long Term Monitoring – Fuel composition



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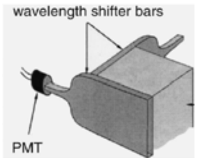

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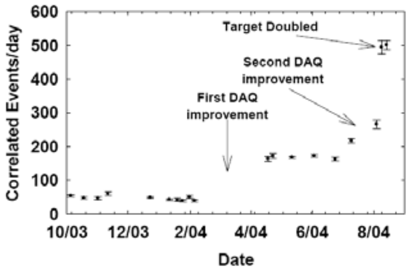

First $\bar{\nu}$ observation

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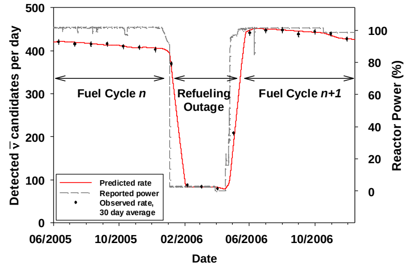

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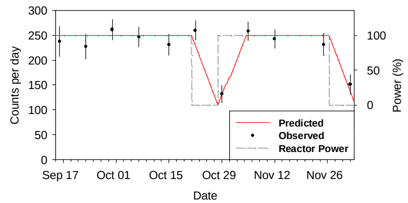

Deployable Results

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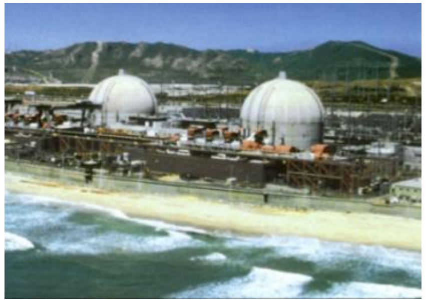
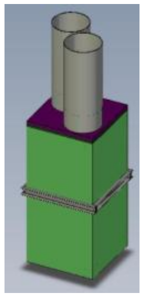

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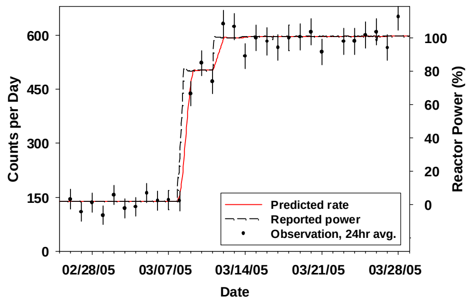
Power Monitoring

Detector Stabilisation



2007

Deployable Detectors Designed, Constructed, Deployed


2009

New Deployment In SONGS Unit-3

SONGS1 was very successful, but….

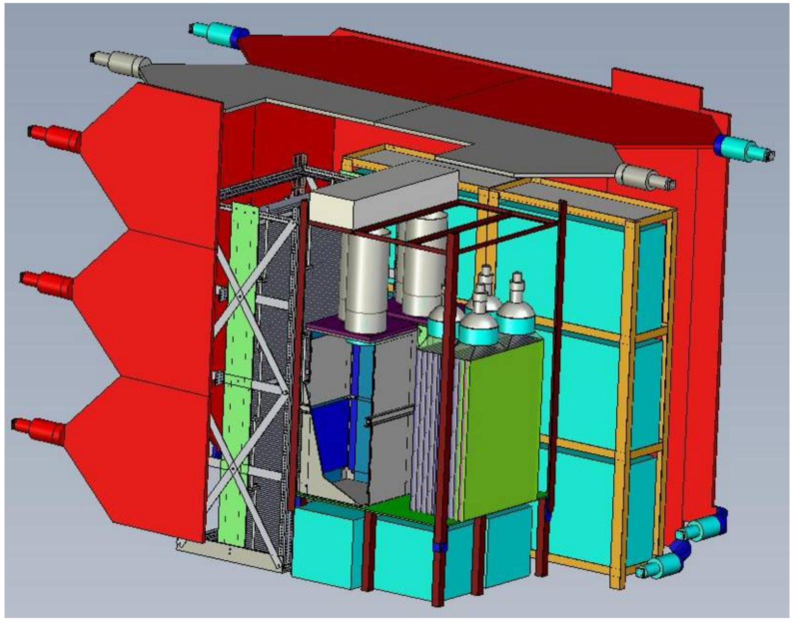
- …the liquid scintillator
  - is slightly flammable, combustible
    - Note: newer formulations are much safer (similar to plastics)
  - requires extra precautions to exclude the possibility of any liquid spillage
- With the SONGS1 run completed, we leveraged installed infrastructure to investigate several paths to more deployable detectors:
  - Use of less combustible, more robust, plastic scintillator
  - Use of doped water Cerenkov detectors instead of scintillator

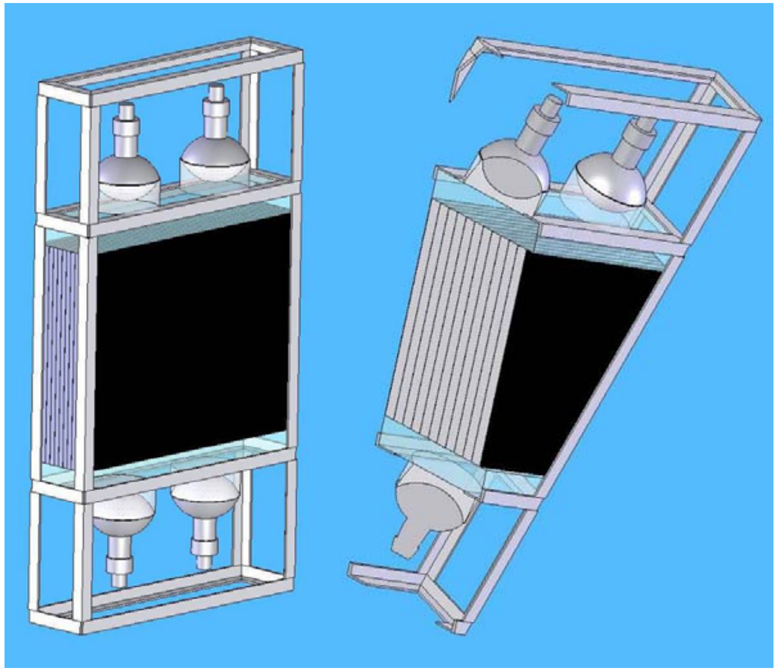
In Pursuit of Other Technologies

- Plastic Scintillator
  - Solves hazardous material problem
  - Able to be preassembled and easily transported
  - Difficulty to include neutron capture
  - Include dead material in fiducial volume
- Water Cerenkov
  - Cheap materials
  - No hazardous material issues
  - Insensitive to backgrounds from proton recoil
  - Very low light-yield $\Rightarrow$ poor efficiency
- Germanium
  - Non-hazardous materials
  - Much higher cross-section $\Rightarrow$ compact size
  - Cryogenic system
  - Increased need for shielding

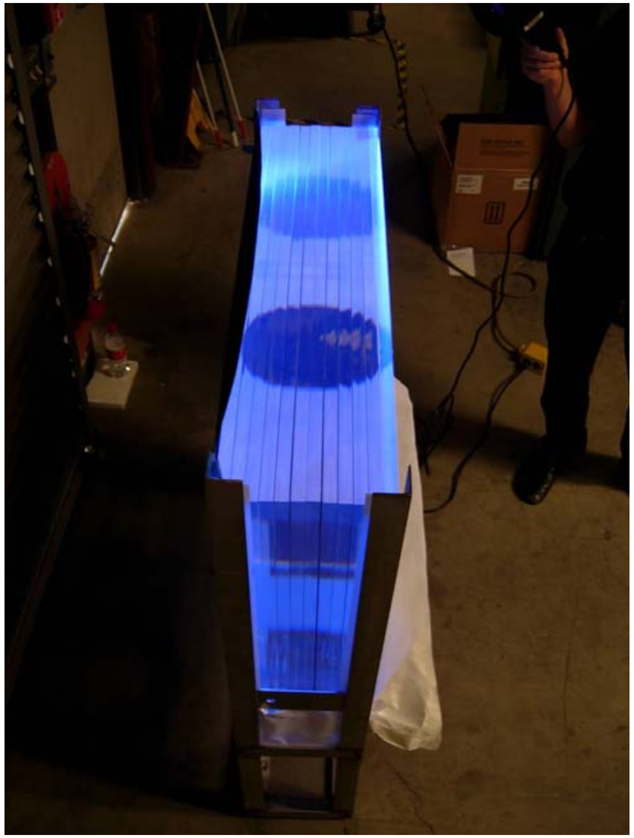
Plastic Detector

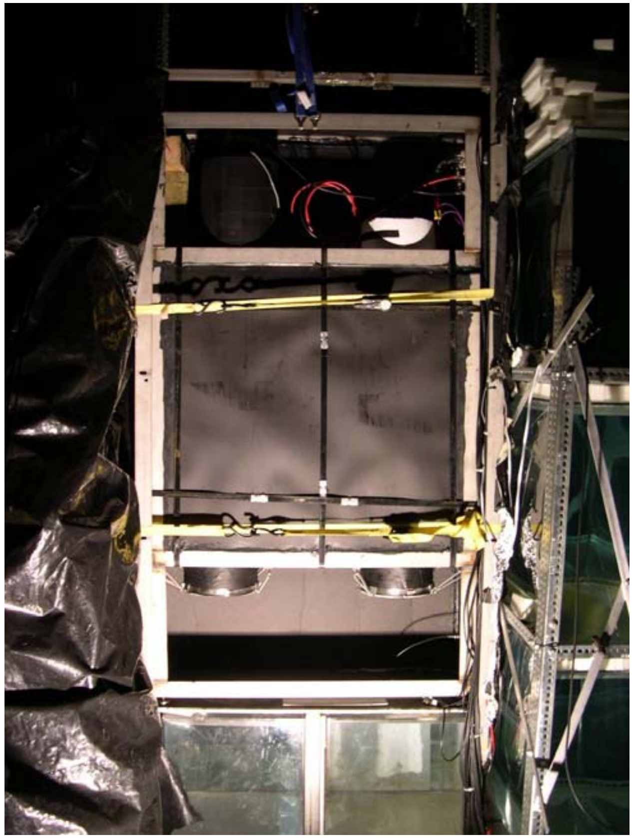
- Replace half of liquid scintillator with plastic scintillator (PS):
  - Must retain neutron capture capability, ideally on Gd
    - commercial neutron capture PS not suitable/available (e.g. Boron loaded BC-454)
  - Final design: 2 cm slabs of BC-408 PS, interleaved with mylar sheets coated in Gd loaded paint



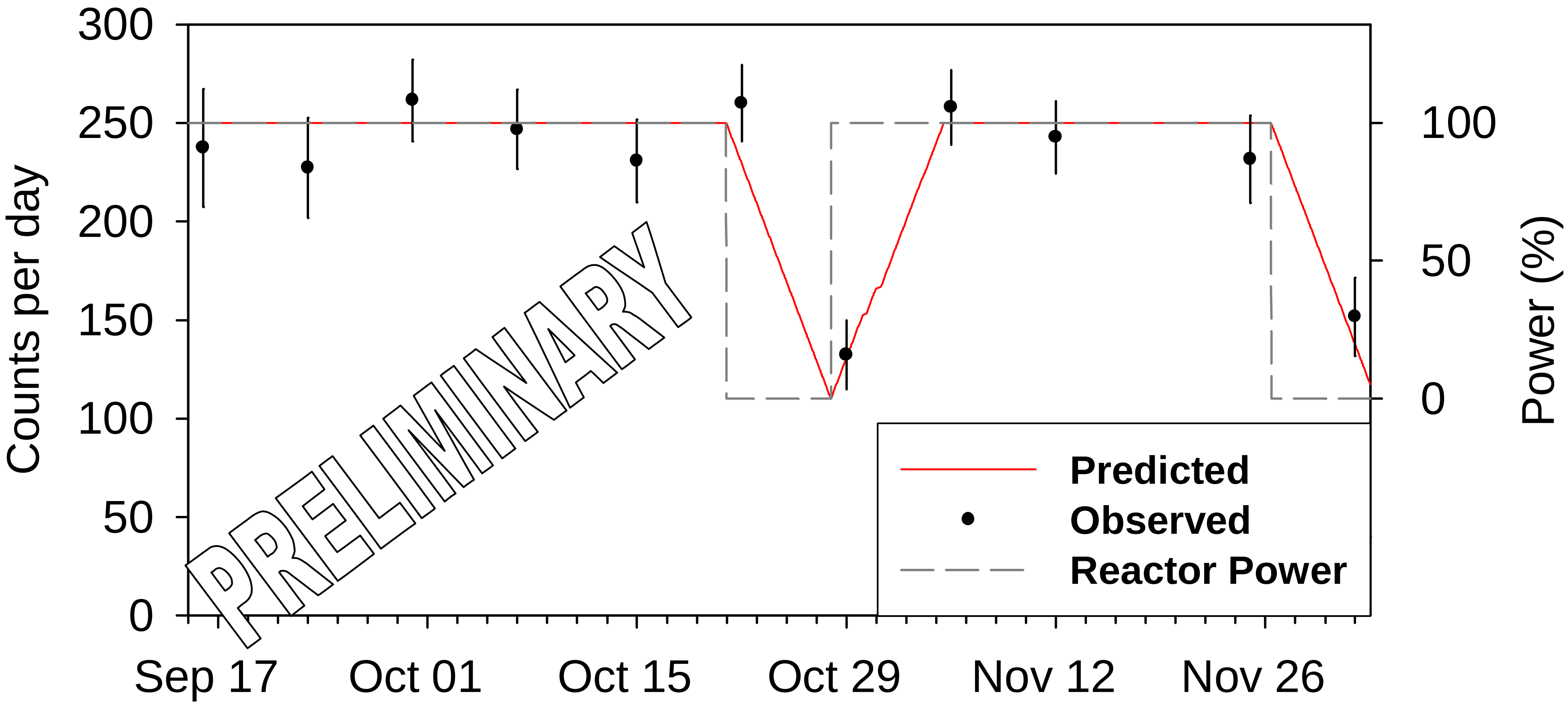


Construction of Plastic Detector





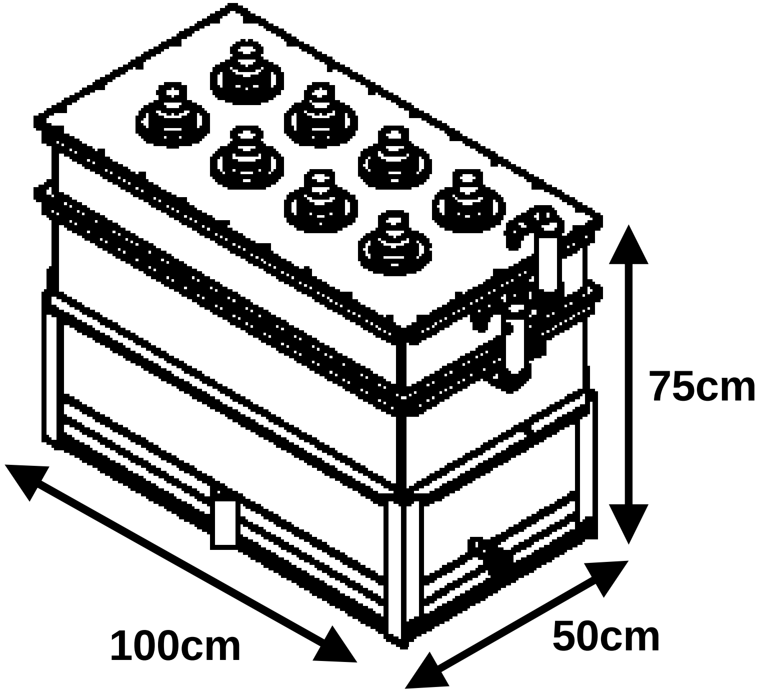
Plastic detector outage data



Plastic detector shows similar sensitivity as Liquid, when normalized to fiducial mass

A Water based *Antineutrino* Detector

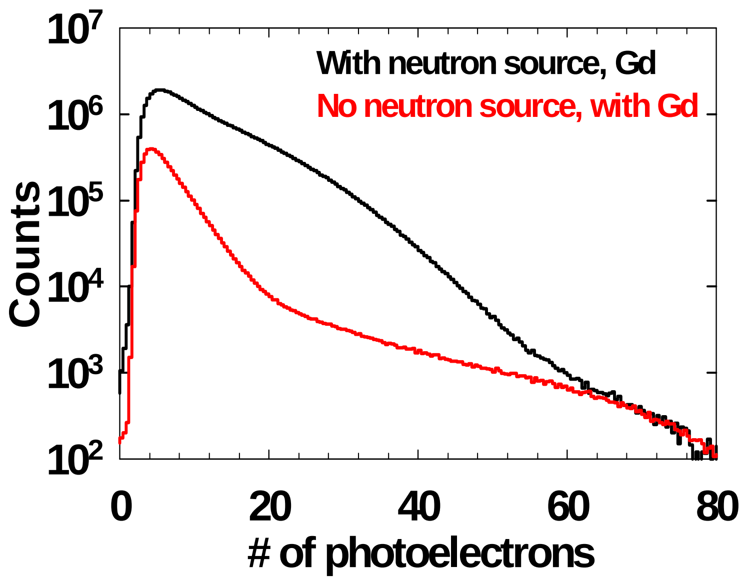
- **Water Cerenkov commonly used for neutrino detection**
- **Addition of a neutron capture agent should allow for antineutrino detection via inverse beta decay**
- **Addition of ~0.2% $GdCl_3$ has been studied at LLNL/UC Davis**
  - **known to be stable in water**
  - **Does not affect light attenuation in small detectors**

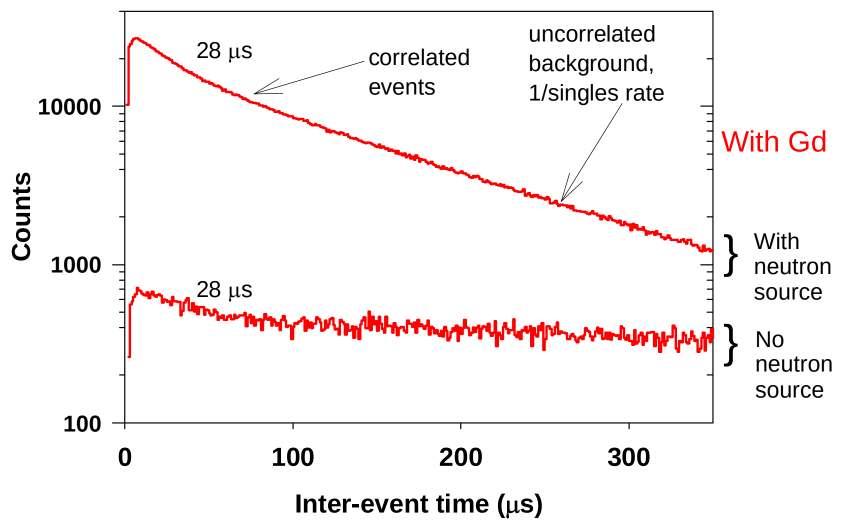


Construction of Water Detector

Initial Data

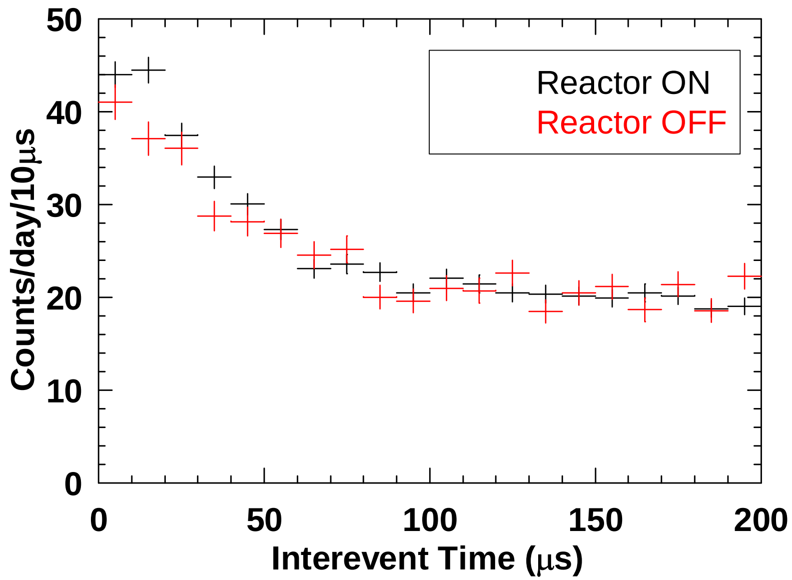
- **Aboveground At LLNL**
  - **The water detector desponds to neutrons in the expected fashion: neutron captures on Gd are observed, as well as correlated (gamma,neutron) and (neutron,neutron) ievents from an ^{252}Cf neutron source**

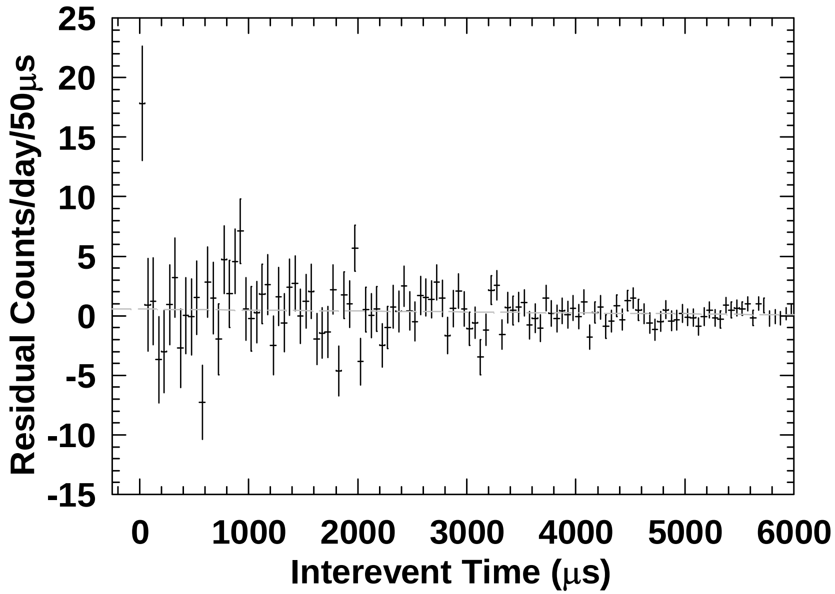




Unshielded Water Detector Results at SONGS

- The water detector was initially deployed without passive shielding
  - High correlated and uncorrelated background rates have made it difficult to clearly identify a reactor signal. Best evidence so far:

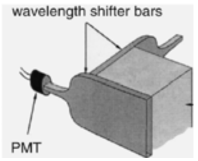




- Gd-doped water should be sensitive to reactor antineutrinos but we are yet to prove it.
- Neutron-neutron correlated backgrounds must be reduced
- Data being re-analyzed as a PhD project (Jerry Coleman at LSU)

SONGS1 Removal – August 2008
5+ years in U2TG

Timeline of LLNL/SNL Presence at SONGS



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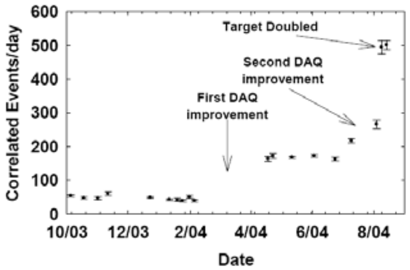

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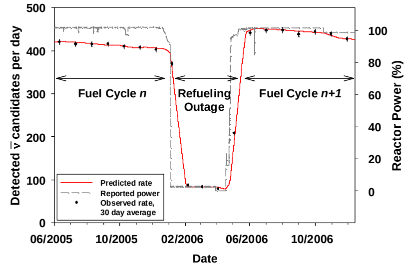

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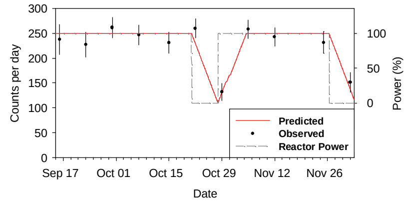

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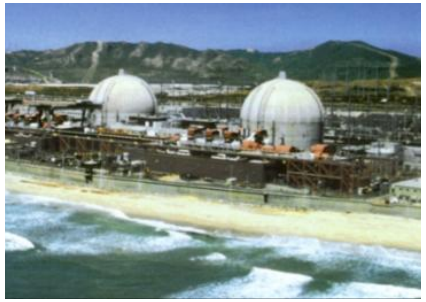

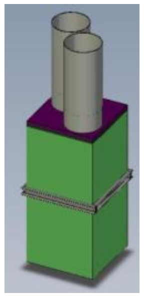

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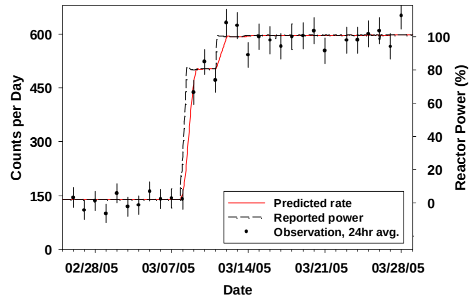

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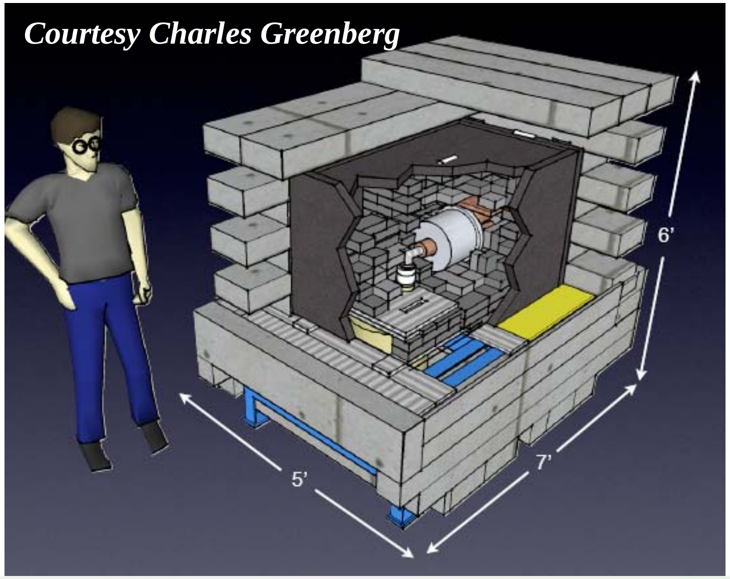
New Deployment In SONGS Unit-3

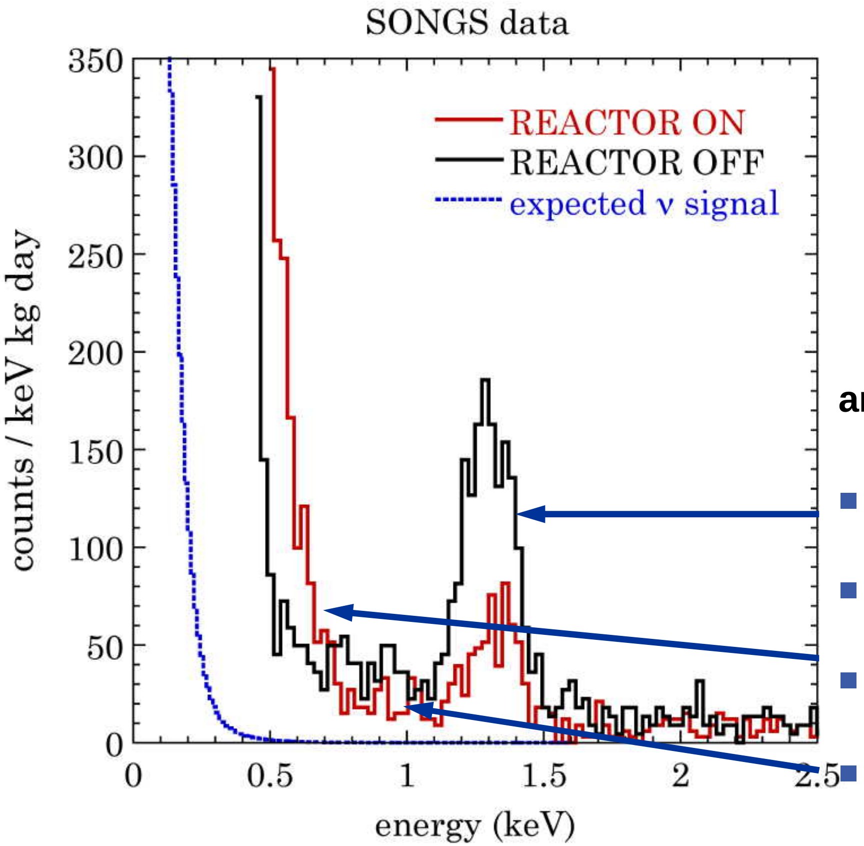
New Deployment at SONGS Unit-3 May 2008

- **Leveraged our good relationship with SONGS to initiate new deployment in the second reactor tendon gallery**
- **With University of Chicago we tested a prototype germanium detector**
  - ✓ **Non-hazardous materials**
  - ✓ **Much higher cross-section ⇒ compact size**
  - ✘ **Cryogenic system**
  - ✘ **Increased need for shielding**
  - ✘ **Physical process that has never been seen before**



Installed at SONGS

Germanium: preliminary results of SONGS deployment



First months of data show:

- **For the first time the background is of same order as the NCS signal**

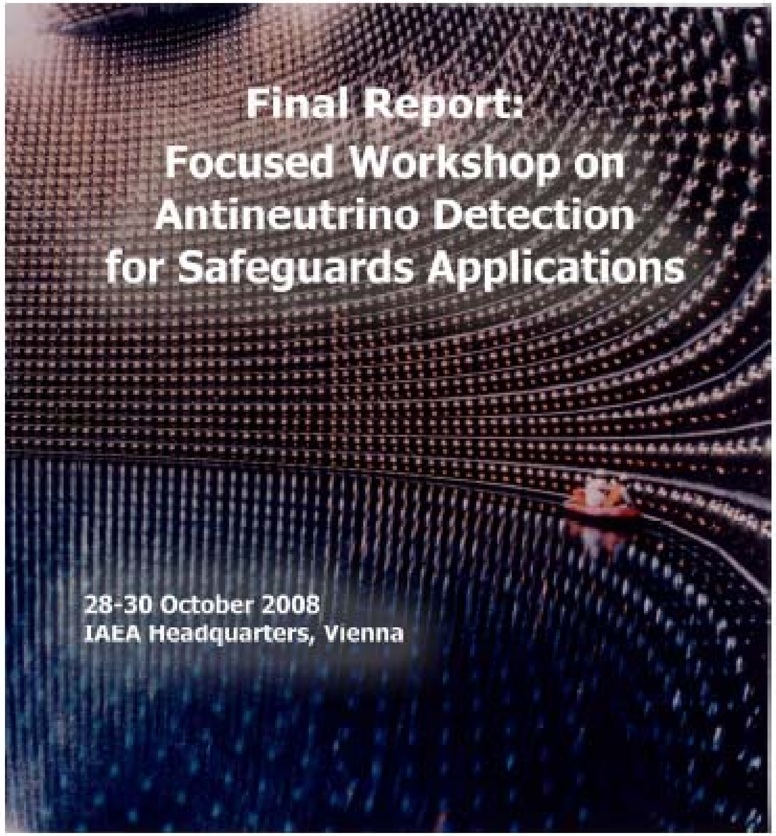
and:

- **Internal backgrounds are now within 2-3x of necessary**
- **Few weeks of reactor off data were dominated by surface activation**
- **Possible noise fluctuations have been causing poor low-energy performance**
- **No evidence of reactor induced backgrounds**

Interest Developing from Safeguards Agencies

- We are very pleased that as a result of our work, and other projects getting under way elsewhere, IAEA is considering this new tool
- Experts meeting (Vienna 2008)
  - Assessing where it might fit
  - Bulk accountancy mentioned
  - Online refueled mentioned
- Expecting an SP-1 (official IAEA request for further development and study) later this year

IAEA
International Atomic Energy Agency
Atoms for Peace



Conclusion

- Antineutrino detectors can be used to monitor nuclear reactors remotely and non-invasively
  - This has been firmly established by prior experiments and has been demonstrated by our collaboration with a more practical/simple device
- We are pursuing several directions in promising technologies that are more deployable
- Currently involved in looking towards aboveground deployments
  - Improved shielding enclosures
  - Improved water detector design
    - Should be deployed at the end of this year
  - Scintillator detectors with neutron/gamma separation
    - Novel capture agents (Li, B,…)
    - PSD for fast neutron elimination
    - Segmentation