

# Reactor Monitoring with Antineutrinos

University of California



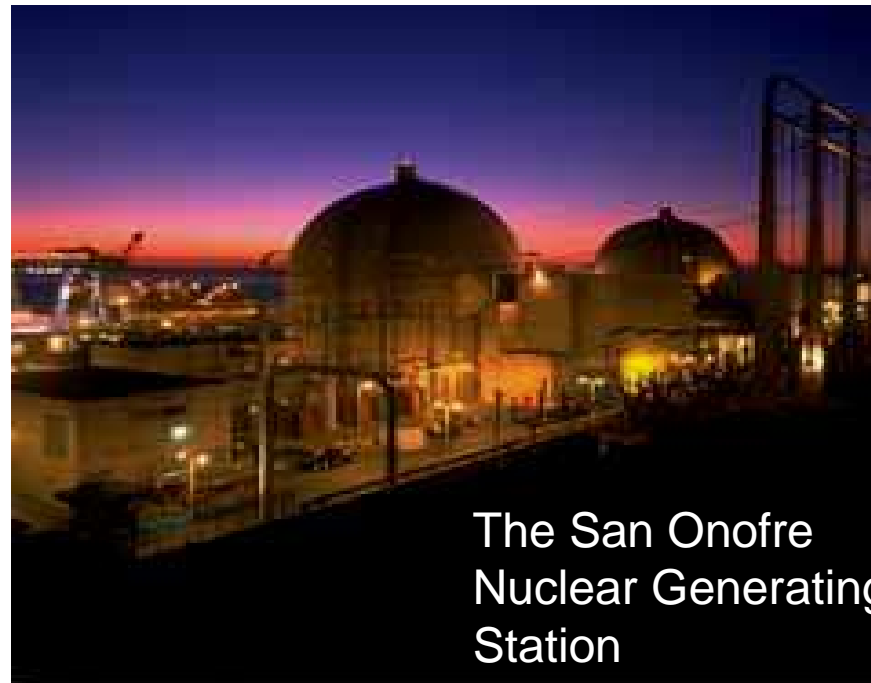
a joint collaboration between  
Lawrence Livermore and Sandia National  
Laboratories



[www.llnl.gov/neutrinos](http://www.llnl.gov/neutrinos)

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**Lawrence Livermore National Laboratory**



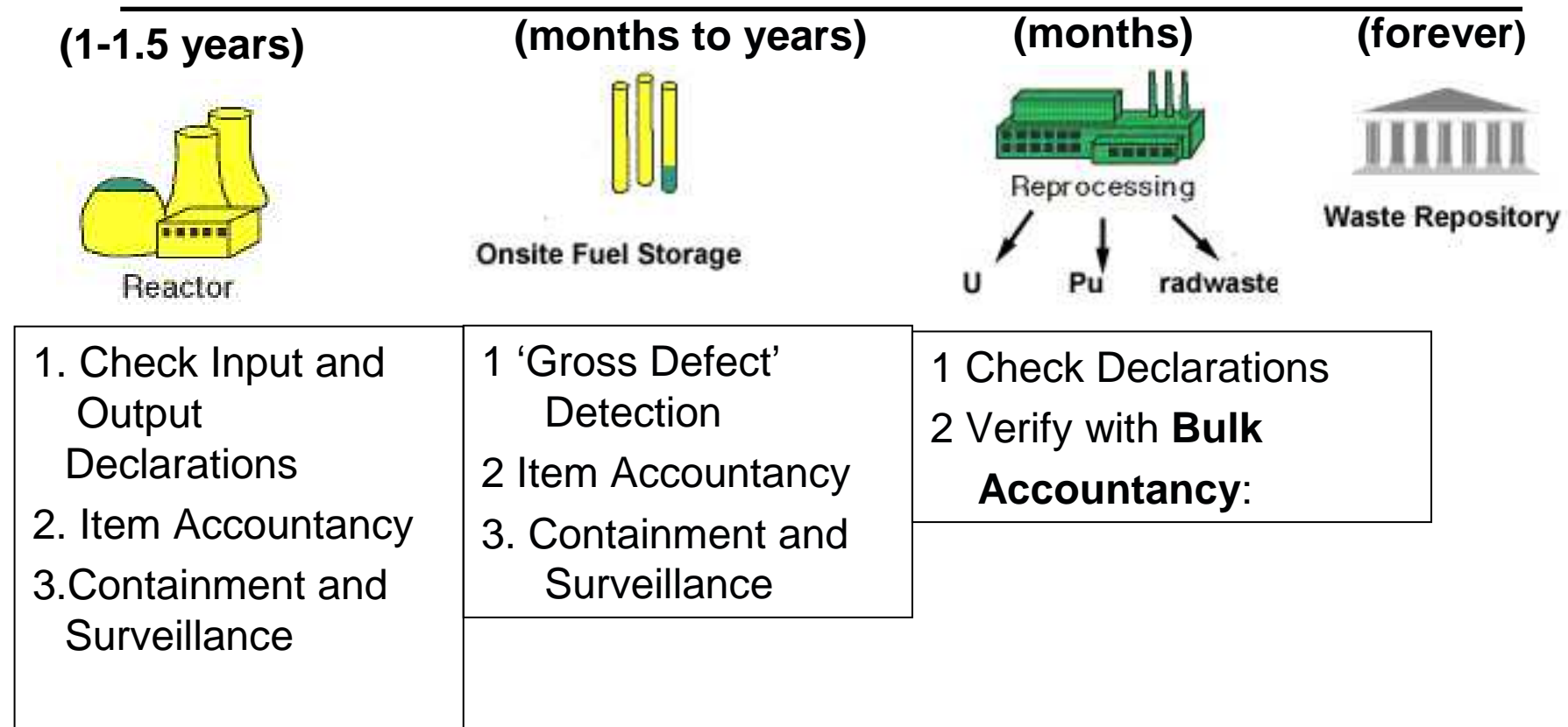
The San Onofre  
Nuclear Generating  
Station



This work was partially performed under the auspices of the US Department of Energy by the University of California, Lawrence Livermore National Laboratory, under contract No. W-7405-Eng-48.



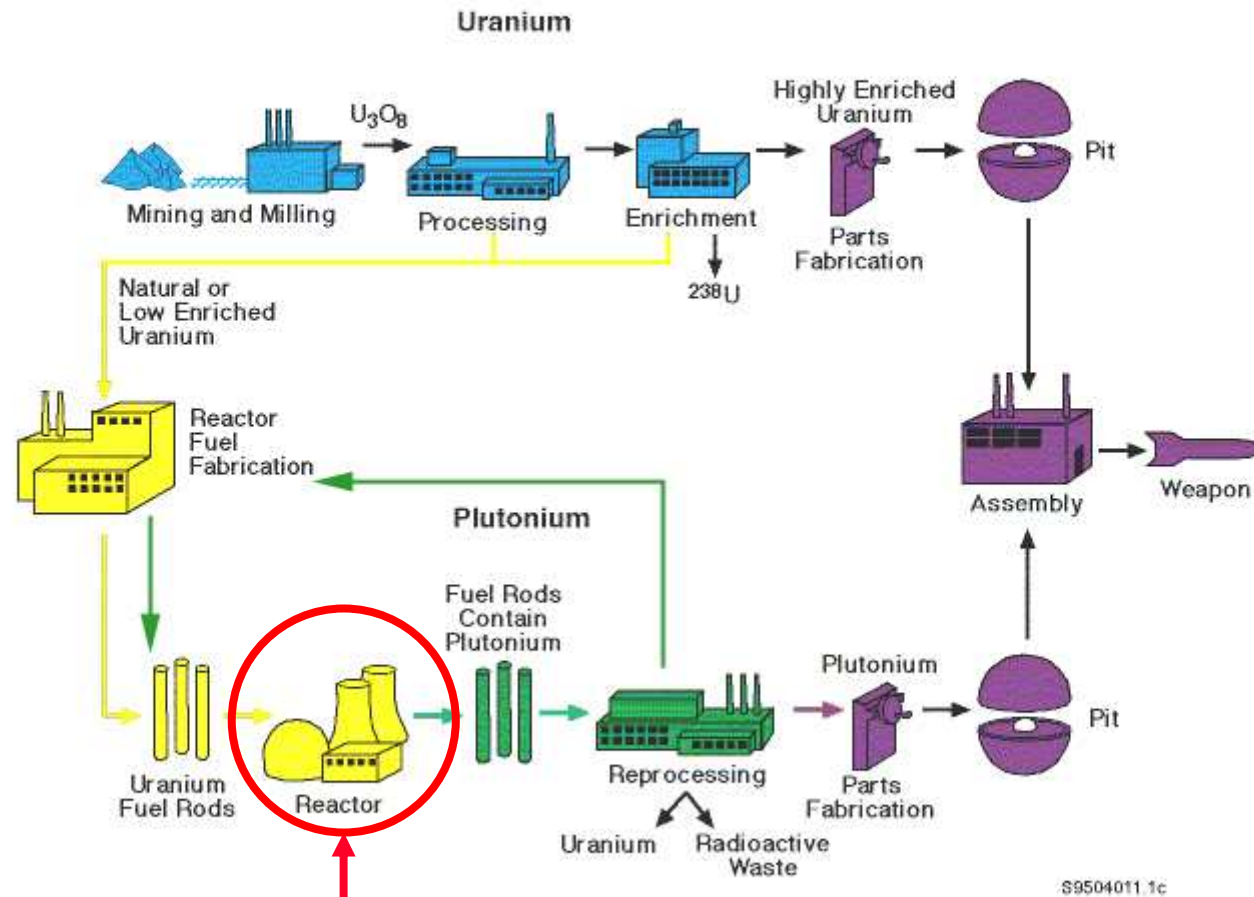
# The IAEA Monitors Fissile Material in Civil Nuclear Cycles



Operators **Declare** Fuel Burnup and Power History

**No Direct Pu Inventory Measurement** is Made Unless and Until Fuel is Reprocessed

# Antineutrino Detectors Address One Part Of The Fuel Cycle



Reactor monitoring with antineutrinos touches on only one element in a long fuel cycle

# Antineutrino Safeguards and Monitoring

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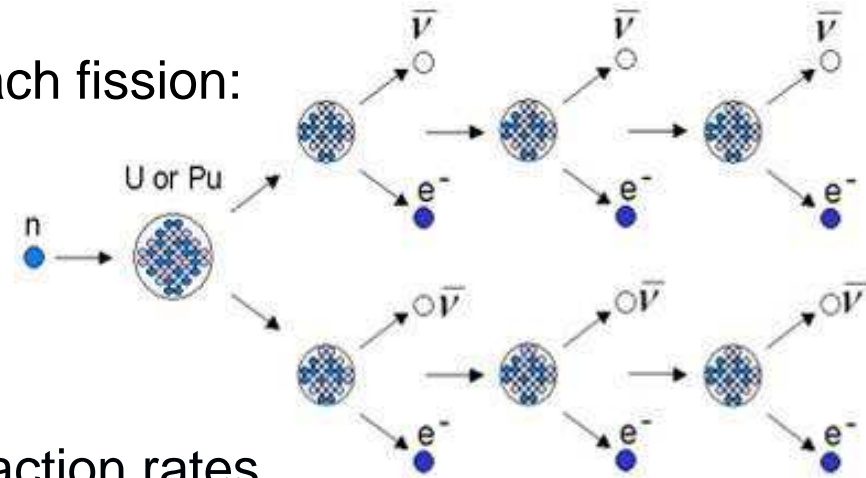
- **antineutrinos measurements at reactors could:**
  - Independently detect reactor outages in real time
  - Independently verify declarations of **power history** and **plutonium content**
  - Give early detection of **unauthorized production of plutonium**
  - Check progress of **plutonium disposition**, and ensure burnup is appropriate to core type
- **Compact antineutrino detectors could provide continuous, non intrusive, unattended measurements suitable for IAEA and other reactor safeguards regimes**



# Reactors Produce Antineutrinos in Large Quantities

- ~ 6 Antineutrinos are produced by each fission:

$$\Rightarrow N_{\bar{\nu}} \propto P_{th}$$



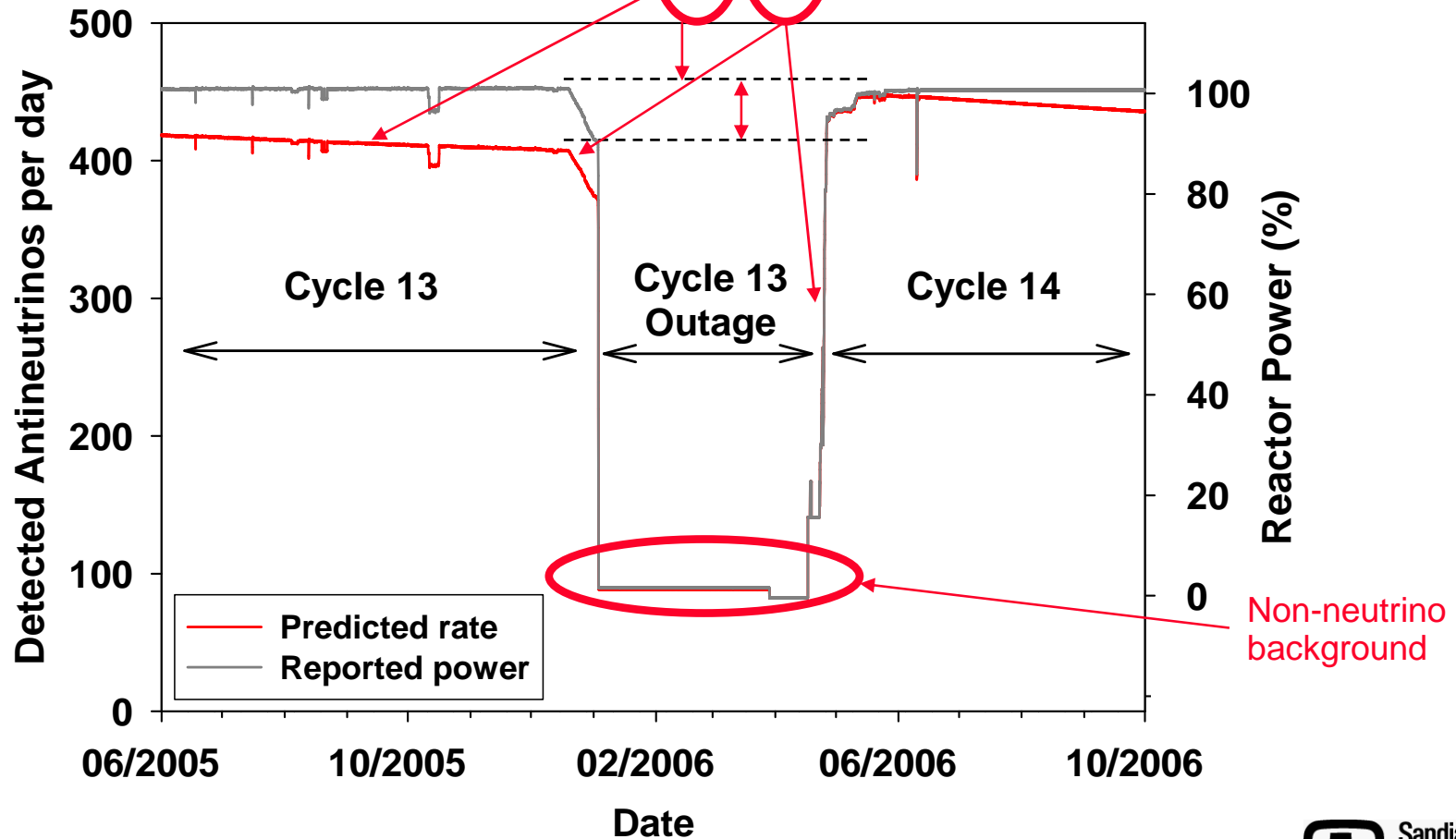
- Antineutrinos interact so weakly that they cannot be shielded, but small detectors have useful interaction rates
  - **0.64 ton** detector, **24.5 m** from **3.46 GW** reactor core
  - **3800 events/day for a 100% efficient detector**
- Rate is sensitive to the isotopic composition of the core
  - Detailed reactor simulations show antineutrino rate change of about 5-10% through a 300-500 day PWR fuel cycle, caused by Pu ingrowth



## Predictions for our Dataset

Detector and  
reactor constants

$$N_{\bar{\nu}} = \gamma(1+k)P_{th}$$



## Deployment Goals and Design Principles

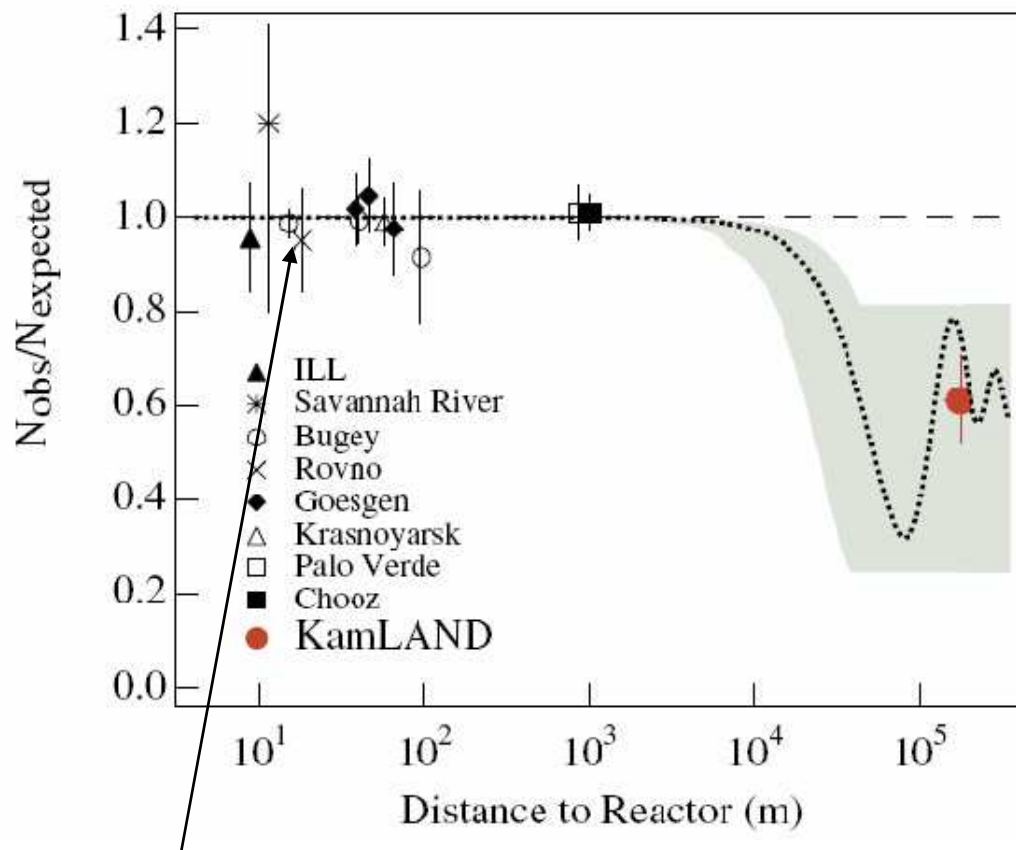
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- **Demonstrate a reactor monitoring system with the following properties:**
  - **Automated** and Unattended
  - **Non-intrusive to reactor operations**
  - **Simple** (~ 3 people vs. 10-100 for physics expt.)
  - **Inexpensive** (< 10 PMTs vs. 100-1000 for physics expt.)
  - **Well known detection concepts/technology**
  - **Physically robust**

**We have met all of these goals with our deployment at the San Onofre Nuclear Generation Station**



# Previous Reactor Antineutrino Experiments



This suite of experiments **used reactors to study 'oscillations' in the neutrino sector**

- Decades of work led to mature detection technology – esp. Liquid Scintillator
- Measurements required understanding burn-up and reactor power systematics
- **We're using antineutrinos to understand reactors**

The Kurchatov/Rovno group was first to show that reactor antineutrinos could be used for monitoring reactor power and plutonium content

# Prototype deployment – San Onofre Nuclear Generating Station

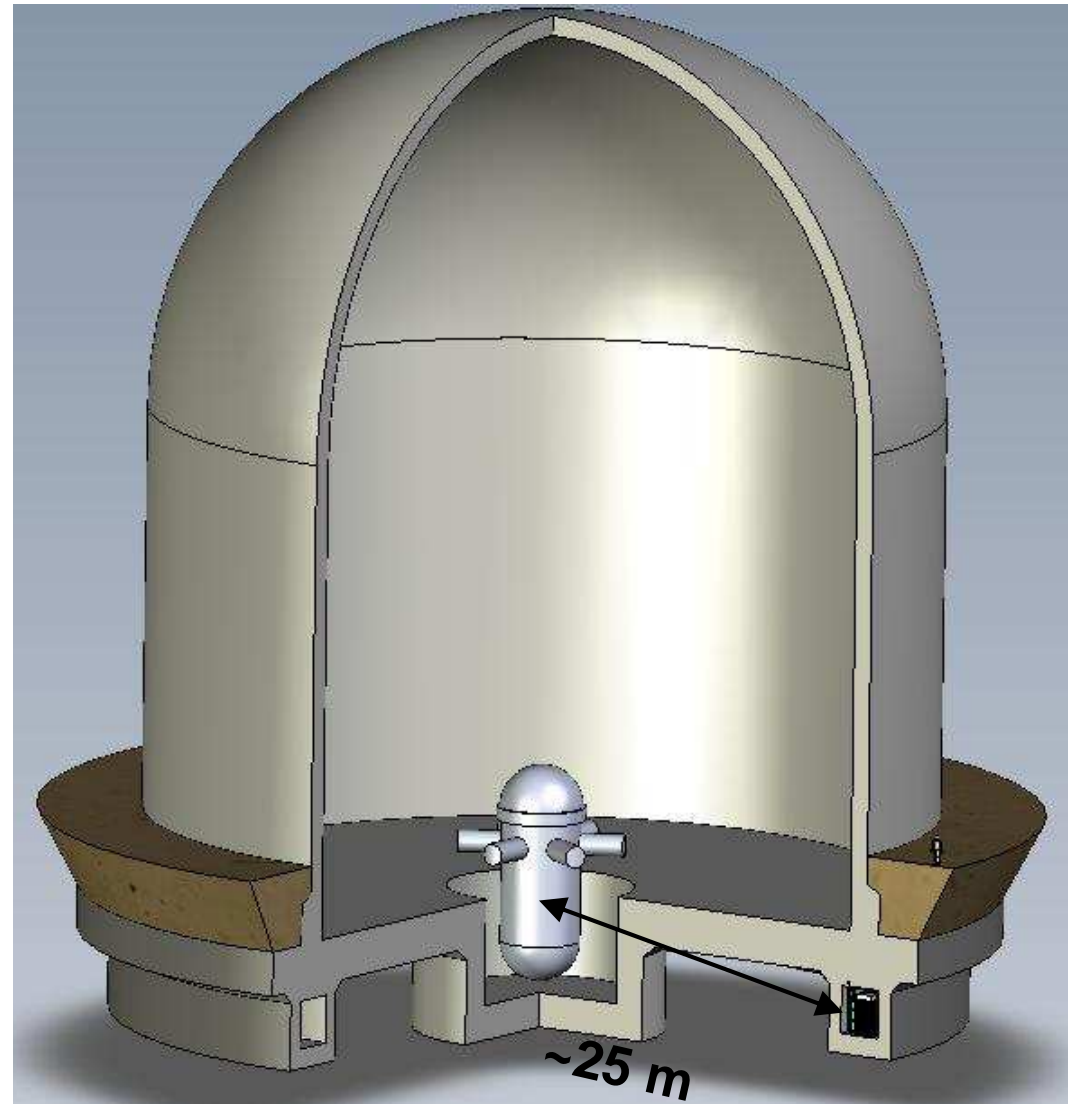
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## SONGS Unit 2 Tendon Gallery

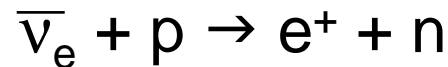
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- Tendon gallery is ideal location
  - Rarely accessed for plant operation
  - As close to reactor as you can get while being outside containment
  - ~20 m.w.e. overburden

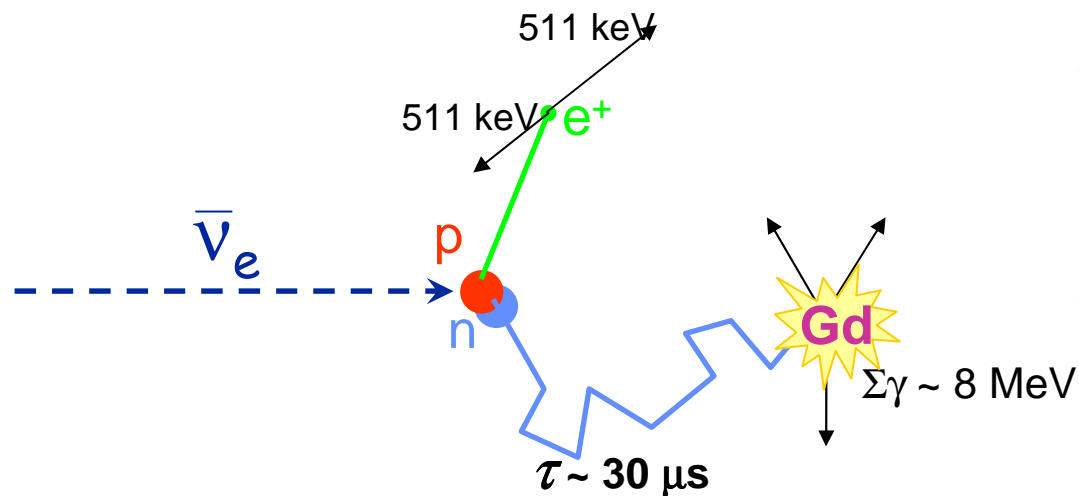


# Antineutrino Detection with Liquid Scintillator

- We use a technique developed by those who discovered antineutrinos :



- 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



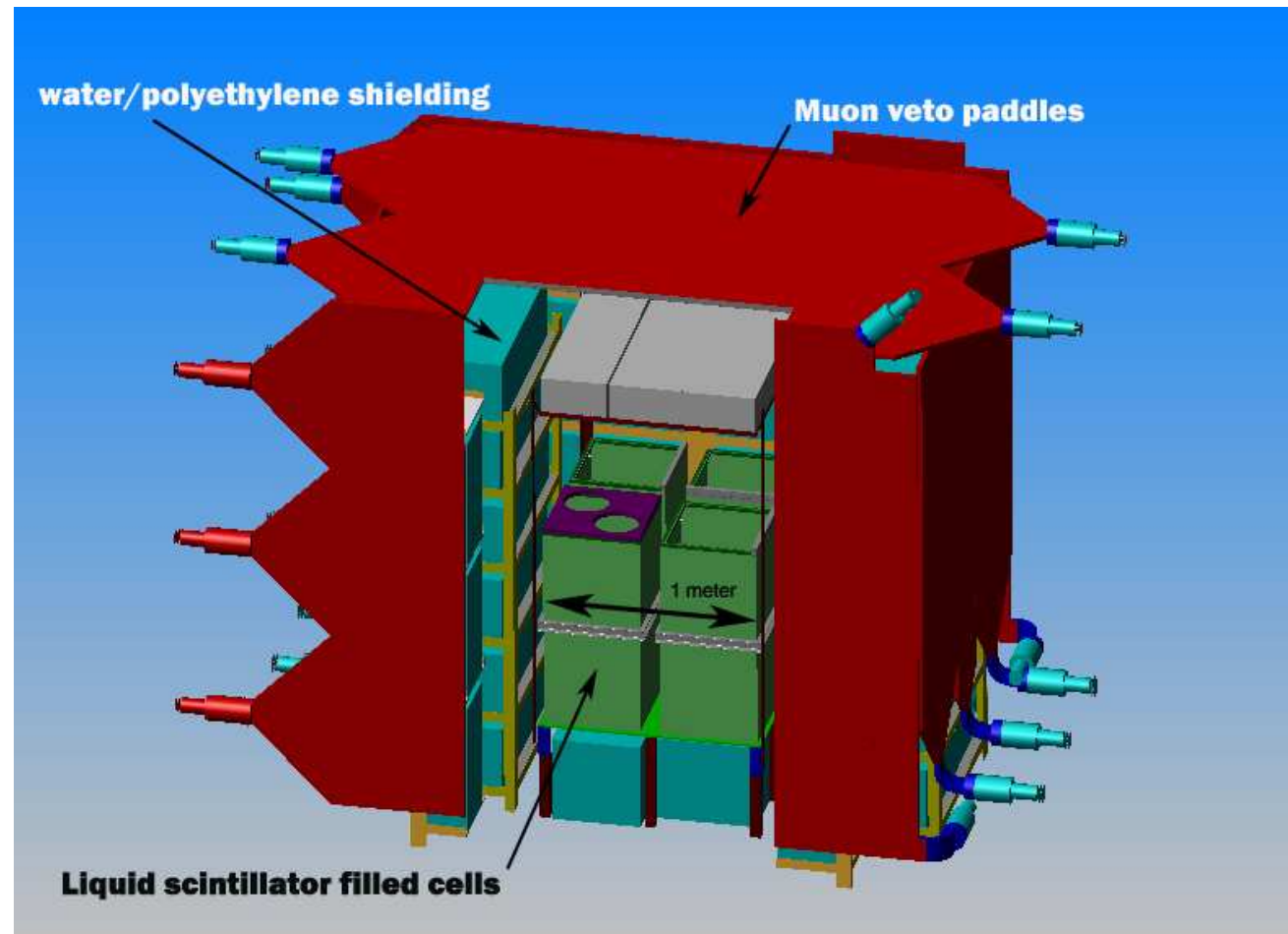
prompt signal + n capture on Gd

- **Positron**
  - Immediate
  - 1- 8 MeV (incl 511 keV  $\gamma$ s)
- **Neutron**
  - Delayed ( $\tau = 28 \mu s$ )
  - $\sim 8 \text{ MeV}$  gamma shower

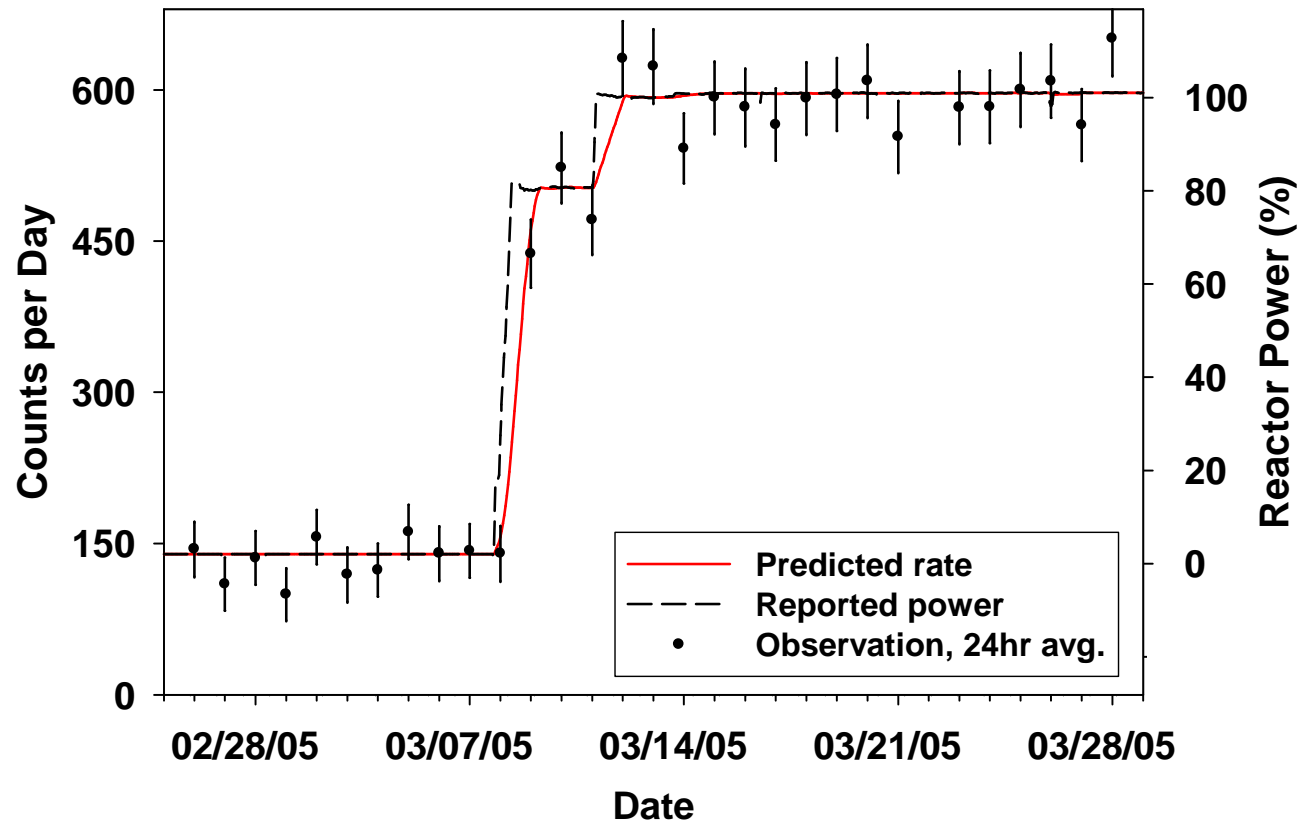


# Sandia/LLNL Antineutrino Detector

- Detector system is...
  - ~1 m<sup>3</sup> liquid scintillator
  - 8 photomultiplier tubes
  - 6-sided water shield
  - 5-sided active muon veto (16 photomultiplier tubes)



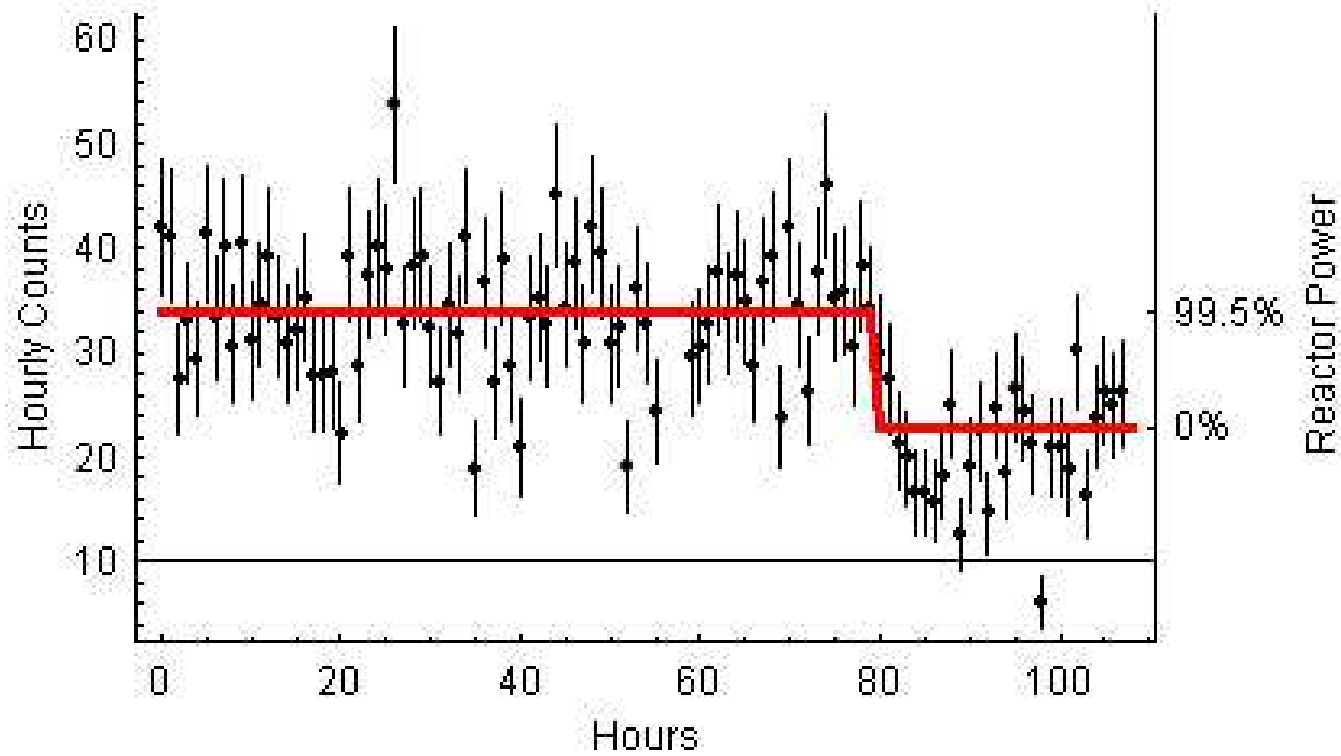
# Reactor Monitoring using only $\bar{\nu}$



- In this example, the reactor is restarted after unscheduled maintenance
- Large power changes are readily observed **using only antineutrinos**



## How Fast Can We Detect an Outage ?

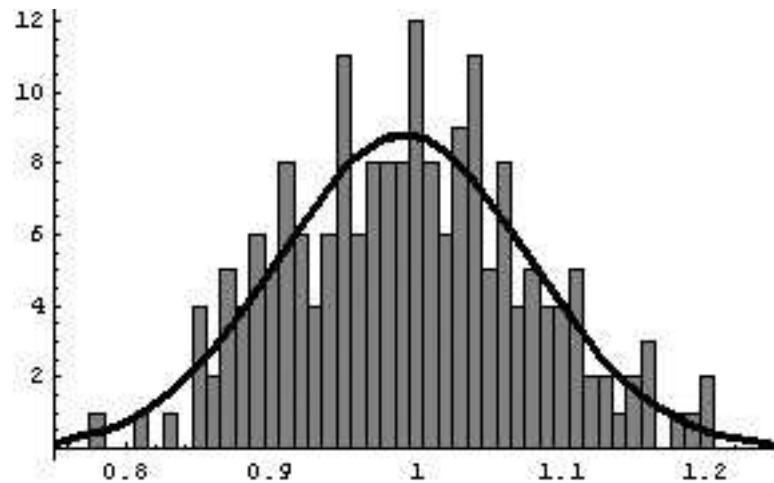


In about 4 hours – with 0.1% false positives, 0.1% missed outages

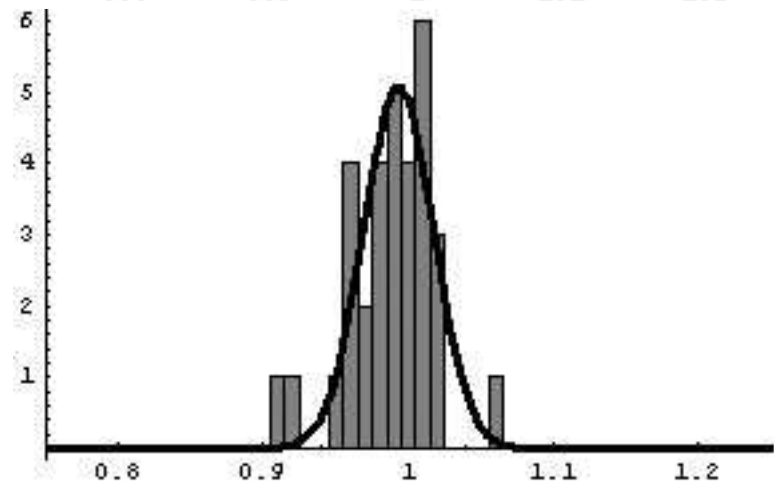


# Relative Power Monitoring Precision

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**Daily average**  
**8 % relative uncertainty**  
in thermal power estimate  
(normalized to 30 day avg.)

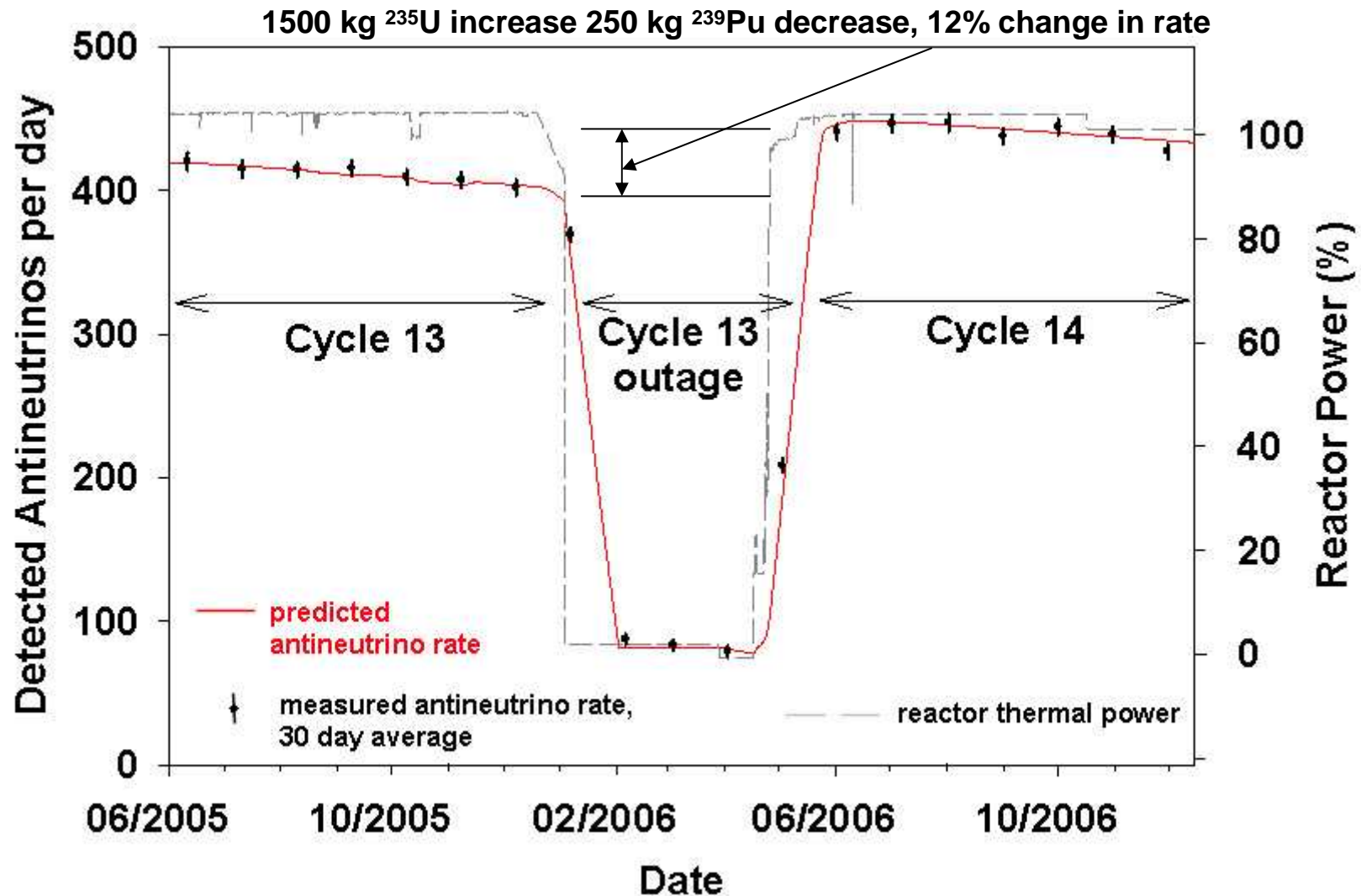


**Weekly average**  
**3% relative uncertainty**  
in thermal power estimate  
(normalized to 30 day avg.)

**Relative Power Measured using Only Antineutrinos**



# Burnup Measurement and Constraint on Plutonium Content



# What Would It Take this Method to be Used by IAEA (or someone else) ?

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- Antineutrino monitoring could provide:
  - Real-time operational status
  - A fissile inventory measurement early in the fuel cycle
  - Verification of operator power and inventory declarations
  - Reduced frequency of inspection visits
  - Reduction in reliance on surveillance and bookkeeping

But there are open questions:

- IAEA and others want a smaller footprint
  - Shielding makes up 80% of footprint in current design  
→ can we shrink the footprint (yes !)
- Can we deploy on surface?



# Conclusion

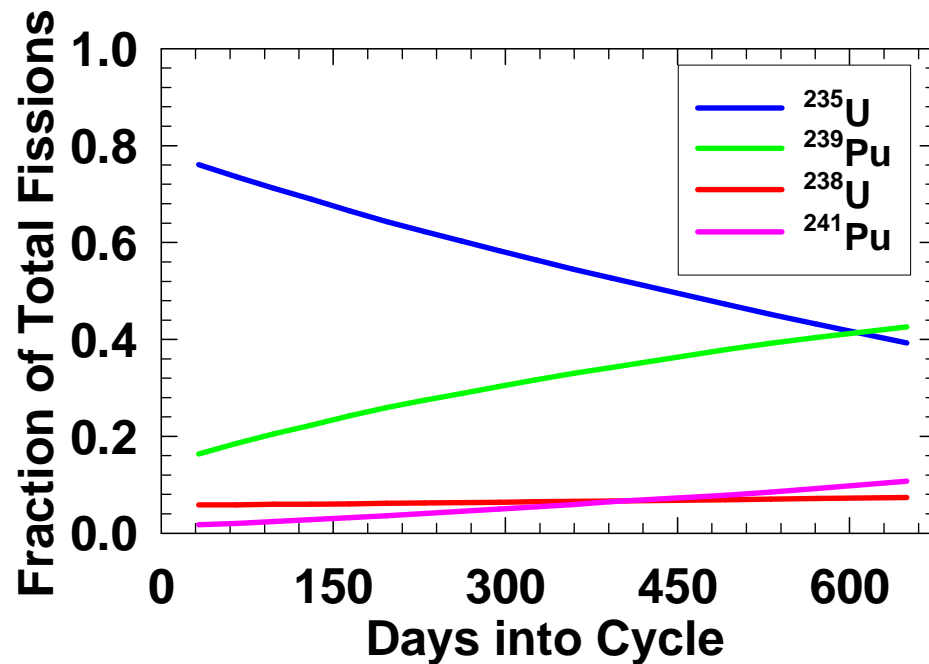
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- **Antineutrino detectors can be used to monitor nuclear reactors remotely and non-intrusively**
  - This has been firmly established by prior experiments and been demonstrated by our collaboration with a **simple and practical** device
- **The technology may fill an important niche by providing independent, unattended monitoring and quantitative measurements early in the fuel cycle**
- **Strong overlap with detector development for next generation of neutrino oscillation experiments ( $\theta_{13}$ ) gives an opportunity for improved precision on Pu content**
- **Our ongoing efforts:**
  - **Use more benign materials** (plastic or water)
  - **Shrink footprint**, improve efficiency and deployability
  - **Quantify benefits** relative to existing safeguards methods



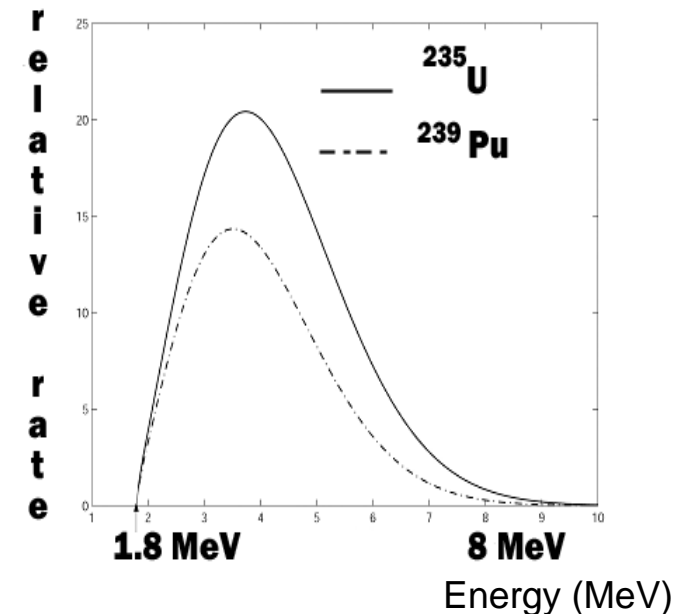
# The Antineutrino Production Rate varies Time and by Isotope

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



(A. Misner, OSU)

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



# Backup Slides

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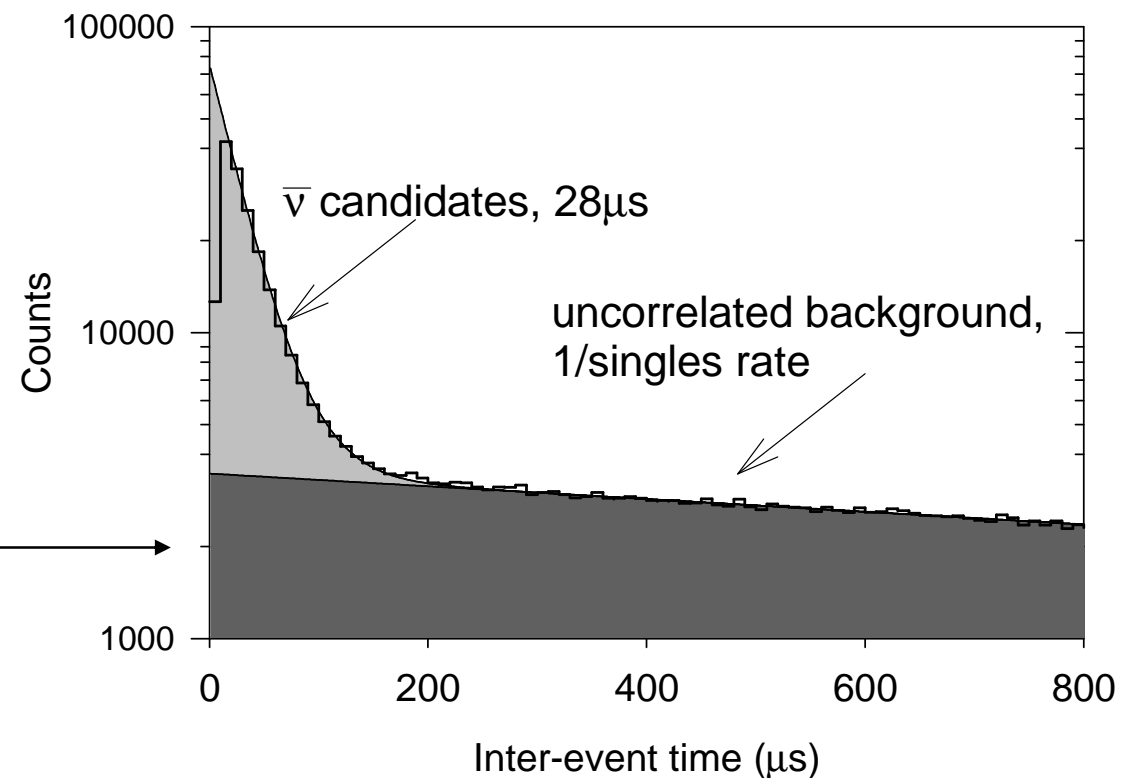
# Installation at SONGS



## Candidate event extraction

- We record ~30 million event pairs per day, only a few hundred event pairs are caused by antineutrino interactions

- Examine time between prompt and delayed to pick out antineutrino-like events



# Double Chooz Experiment

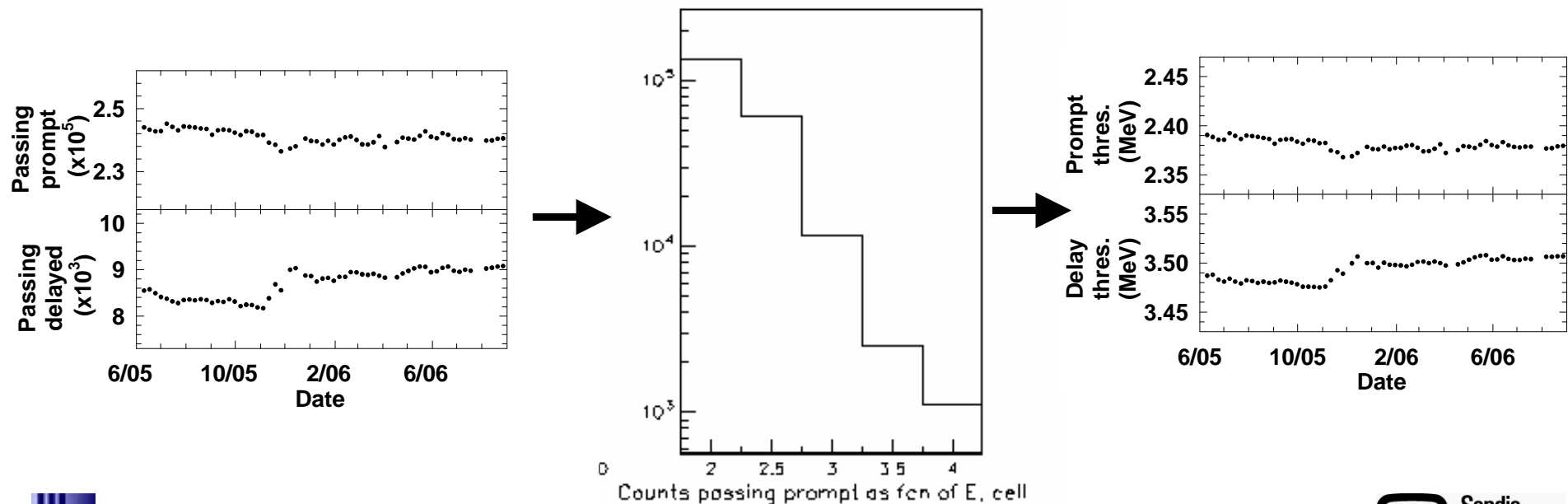


- Uses existing far cavity for a fast, inexpensive  $\theta_{13}$  search
- Two identical detectors at  $\sim 280$  m and 1 km
- Extensive detector development, e.g. less flammable liquid scintillator
- Near detector will provide an excellent (absolute) rate and spectral measurement

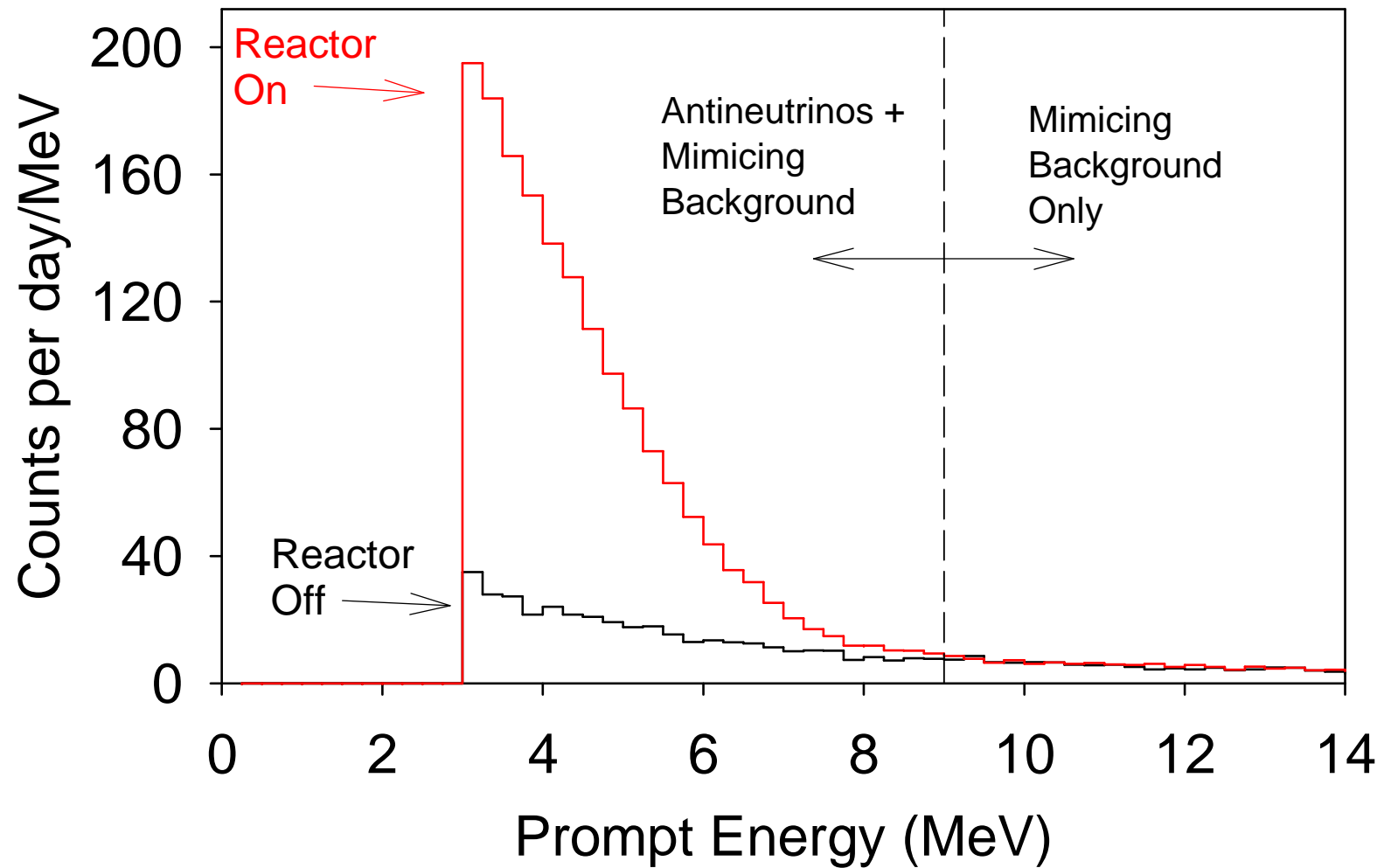


## Detector Stability

- To observe the effect of fuel burnup, we must ensure that our detector is stable over the data taking period
- We count the number of events passing the energy cuts, and from this estimate the effectiveness of energy calibration.



## Clear indication of antineutrino detection



## Calibration

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- An automatic energy calibration is performed using the 2.6 MeV line from the Th chain
  - this relatively simple procedure is sufficient

