The Safeguards Detector at SONGS

A Sandia and Lawrence Livermore National Laboratories Joint Project

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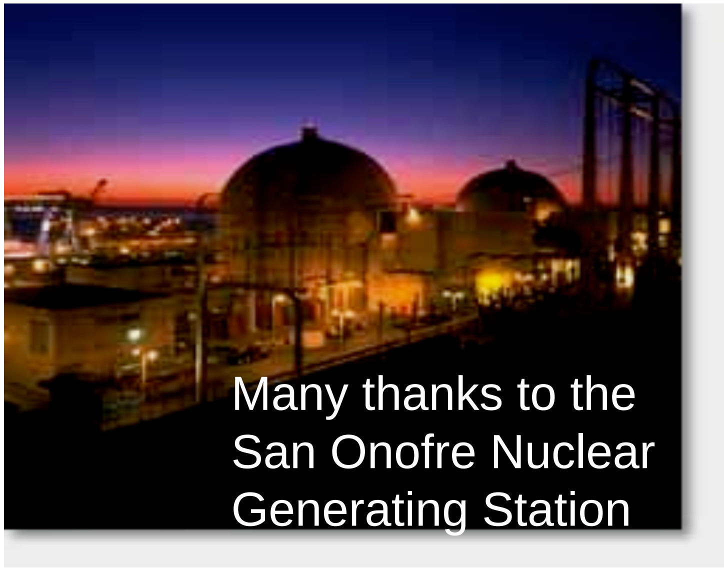

Many thanks to the San Onofre Nuclear Generating Station

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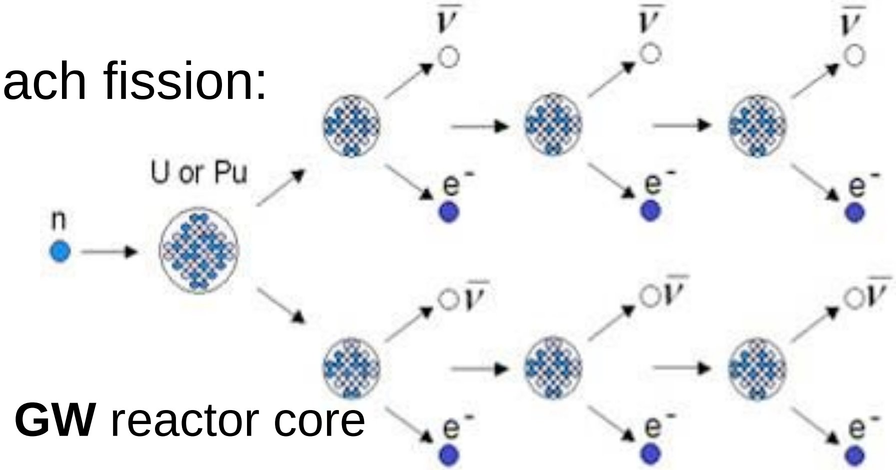
Some Salient Antineutrino/Reactor Properties

- ~ 6 Antineutrinos are produced by each fission:

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



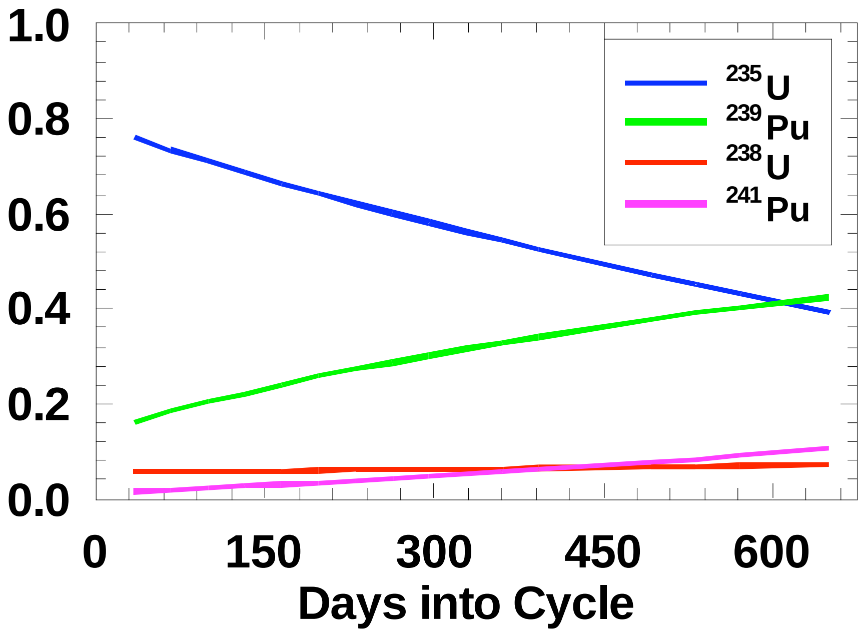
- Rates near reactors are high
  - **0.64 ton** detector, **24.5 m** from **3.46 GW** reactor core
  - 3800 events/day for a 100% efficient detector
- Rate is sensitive to the isotopic composition of the core
  - About 250 kg of Plutonium is generated during a PWR fuel cycle
  - Detailed reactor simulations show antineutrino rate change of about 5-10% through a 300-500 day PWR fuel cycle, caused by Pu ingrowth

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

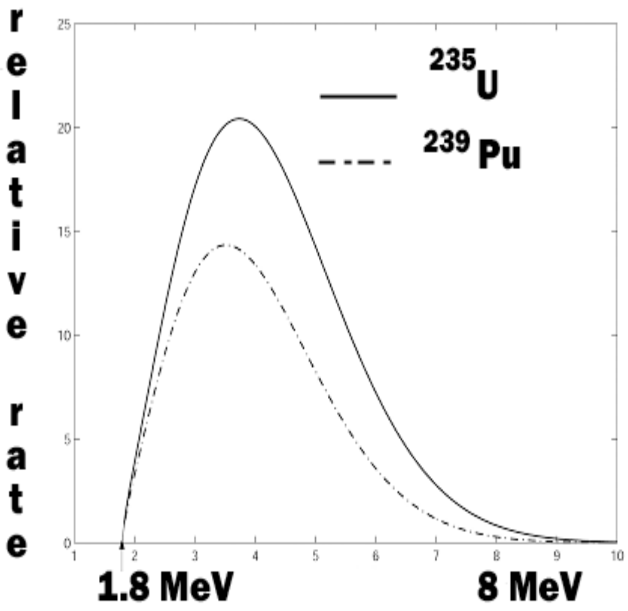
Constant
(Geometry,
Detector mass)

Fuel composition dependent
Sum over fissioning isotopes, Integral over energy dependent cross section, energy spectrum, detector efficiency

The Antineutrino Rate Varies with Time and Isotope



Relative Fission Rates Vary in Time



Rate of Antineutrinos/Fission Varies With Isotope

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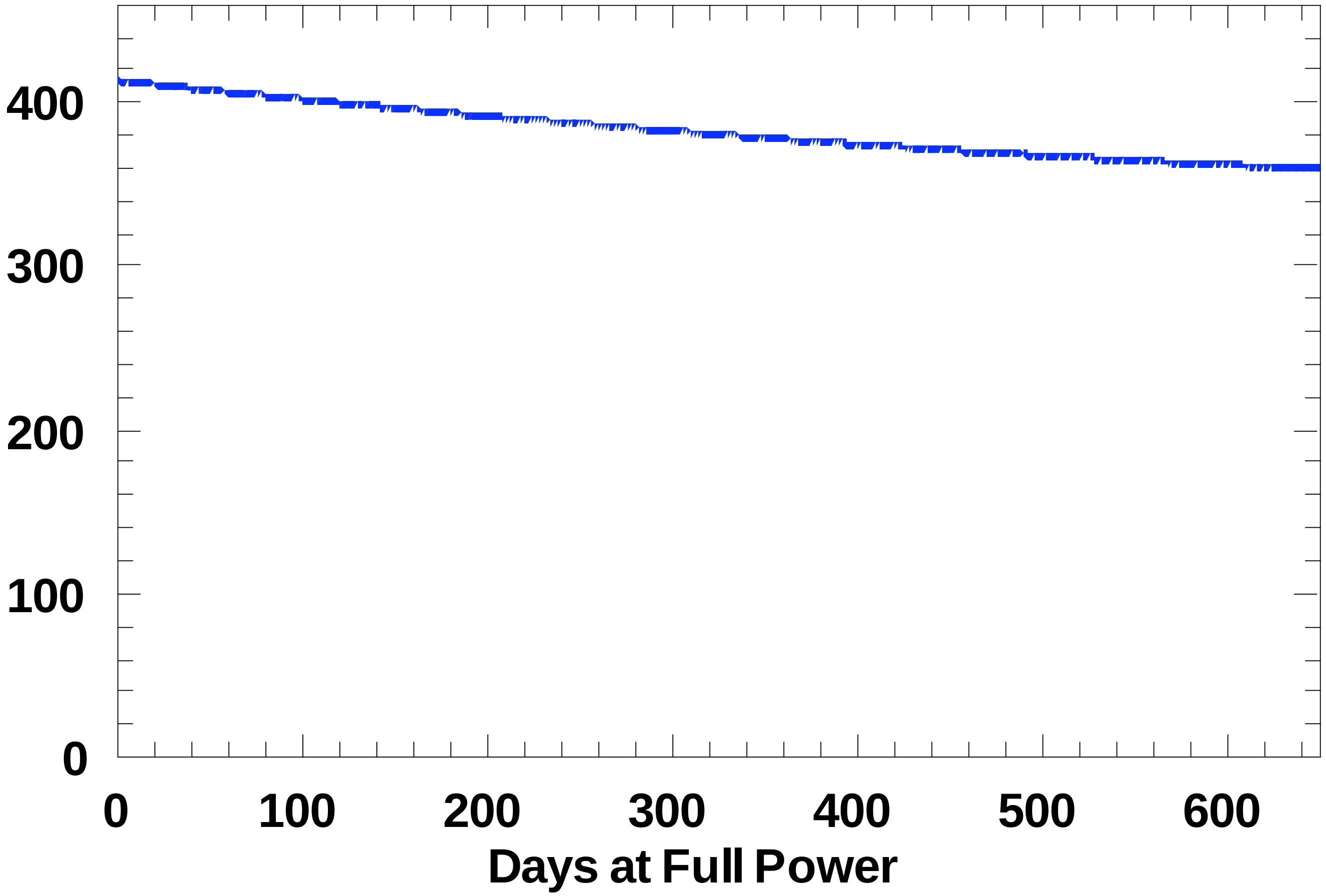
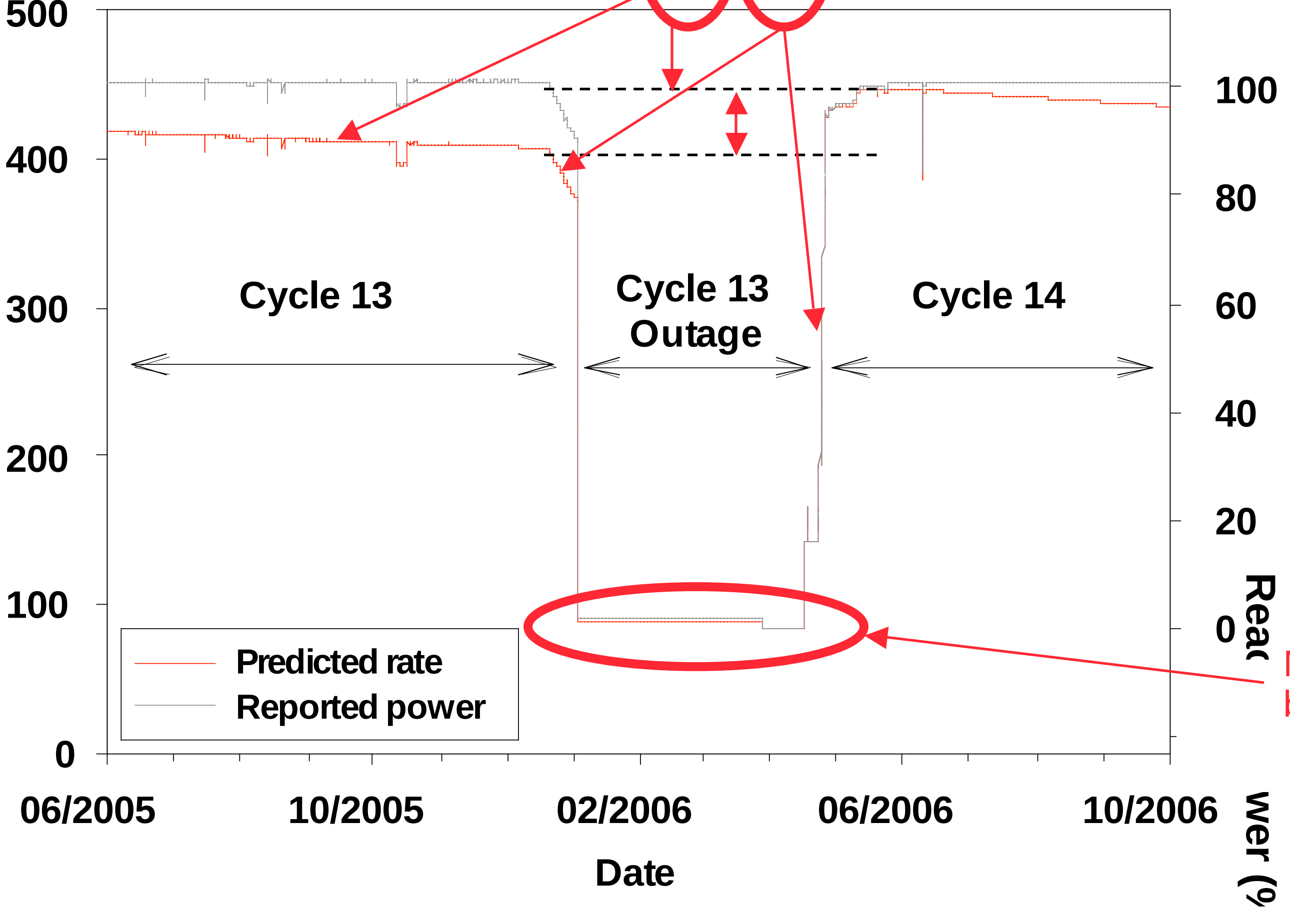
Predicted Effect of Fuel Burnup

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



Prediction for our Dataset

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



Non-neutrino background

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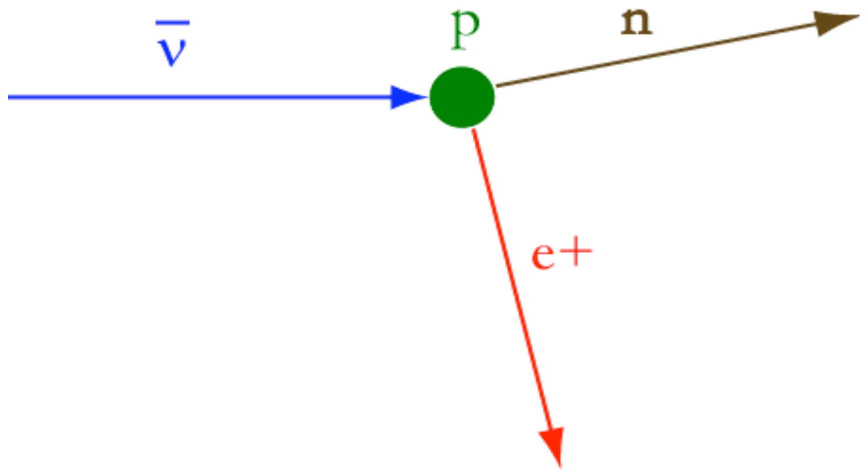
Antineutrino Detection

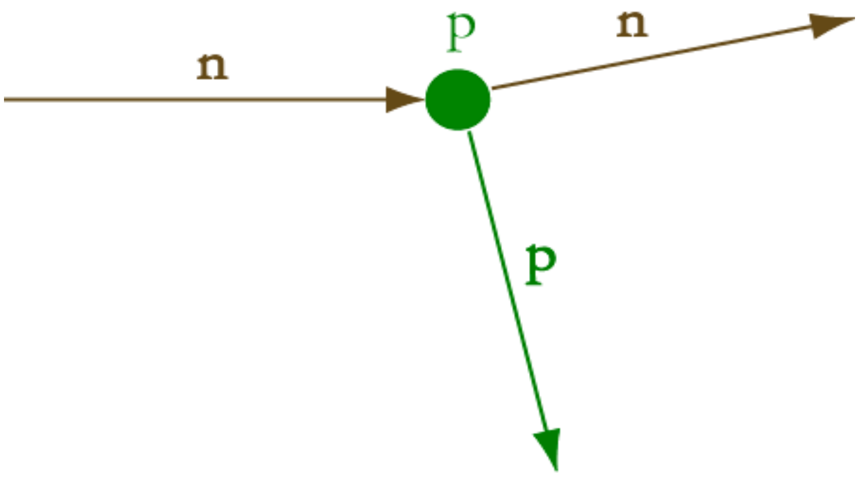
- We use “conventional” antineutrino detection technique
  - inverse beta-decay produces a pair of correlated events in the detector
- Gd loaded into the scintillator captures the resulting neutron after a relatively short time



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

Events that mimic antineutrinos (Background!)

- Antineutrinos are not the only particles that produce this signature
- Cosmic ray muons produce fast neutrons, which scatter off protons and can then be captured on Gd
- Important to tag muons entering detector and shield against fast neutrons – overburden very desirable

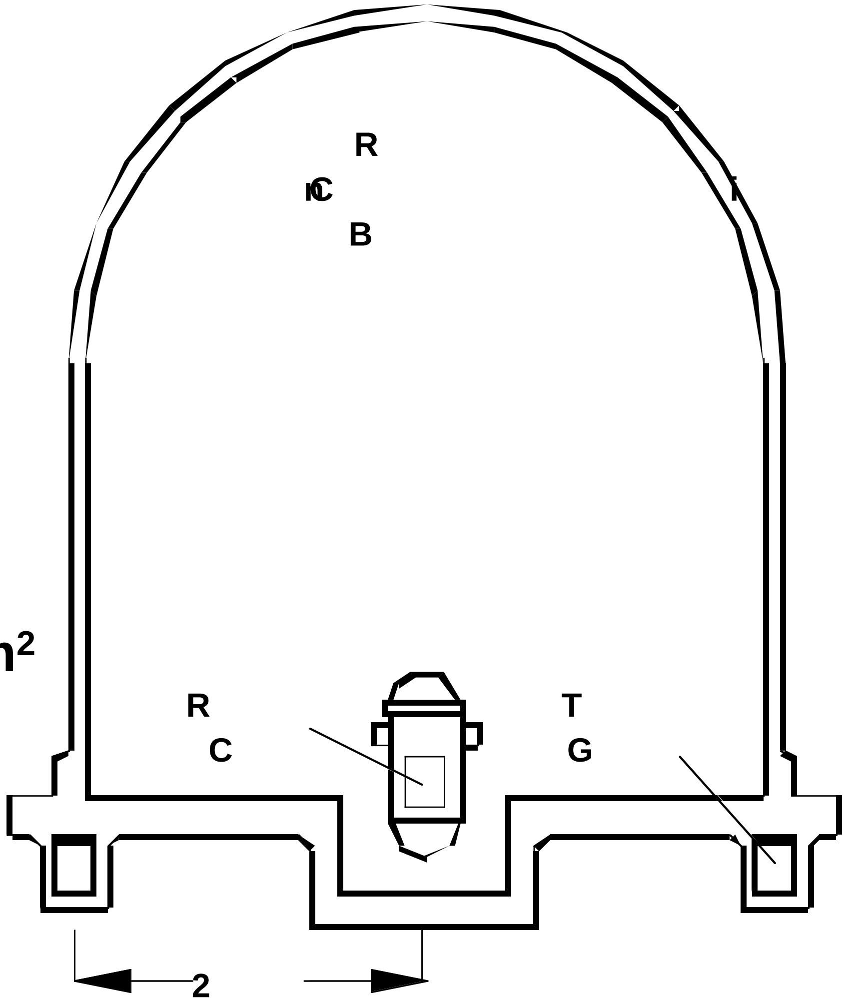


- Recoiling proton
  - Immediate
  - ~ MeV
- Neutron
  - Delayed (t = ~28 μs)
  - ~ 8 MeV gamma shower

Prototype deployment – San Onofre Nuclear Generating Station

San Onofre Nuclear Generating Station 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
- 3.4 GWt => 10^{21} ν / s
- In tendon gallery ~10^{17} ν / s per m^2
- Around 3800 interactions expected per day



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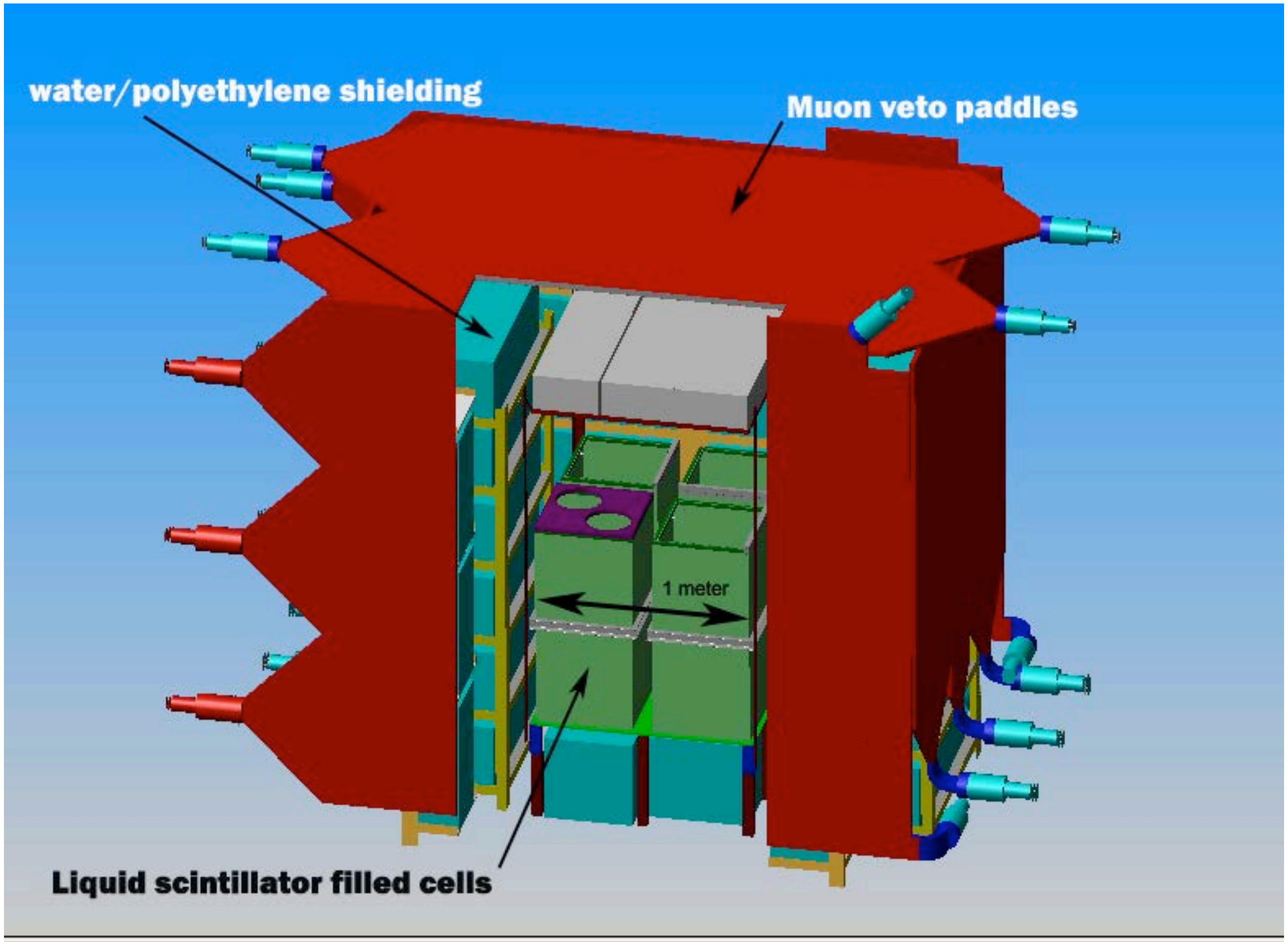
Design Principles

- **Simple, inexpensive, robust**
  - **Rapid deployment**
  - **Use well known detection concepts/technology**
    - **Antineutrino detection via inverse beta decay**
    - **Gd loaded scintillator**
    - **central target surrounded by various shielding layers**
  - **Physically robust for reactor environment (e.g. steel scintillator vessels)**
  - **Modular for manhole access**
- **Do a *relative* measurement**
  - **Use automatic calibration based on background lines to account for all time dependent variations**

Sandia/LLNL Antineutrino Detector

- Detector system is…
  - 0.64 tons of Gd doped liquid scintillator readout by 8x 8” PMT
  - 6-sided water shield
  - 5-sided active muon veto

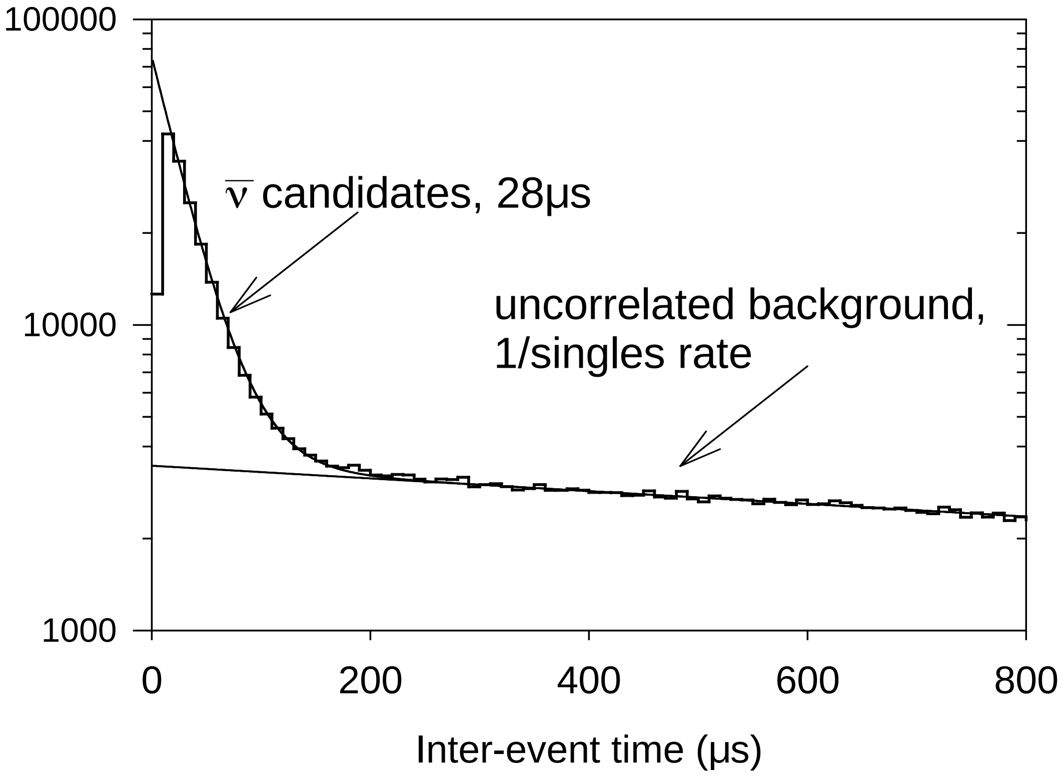


Installation at SONGS

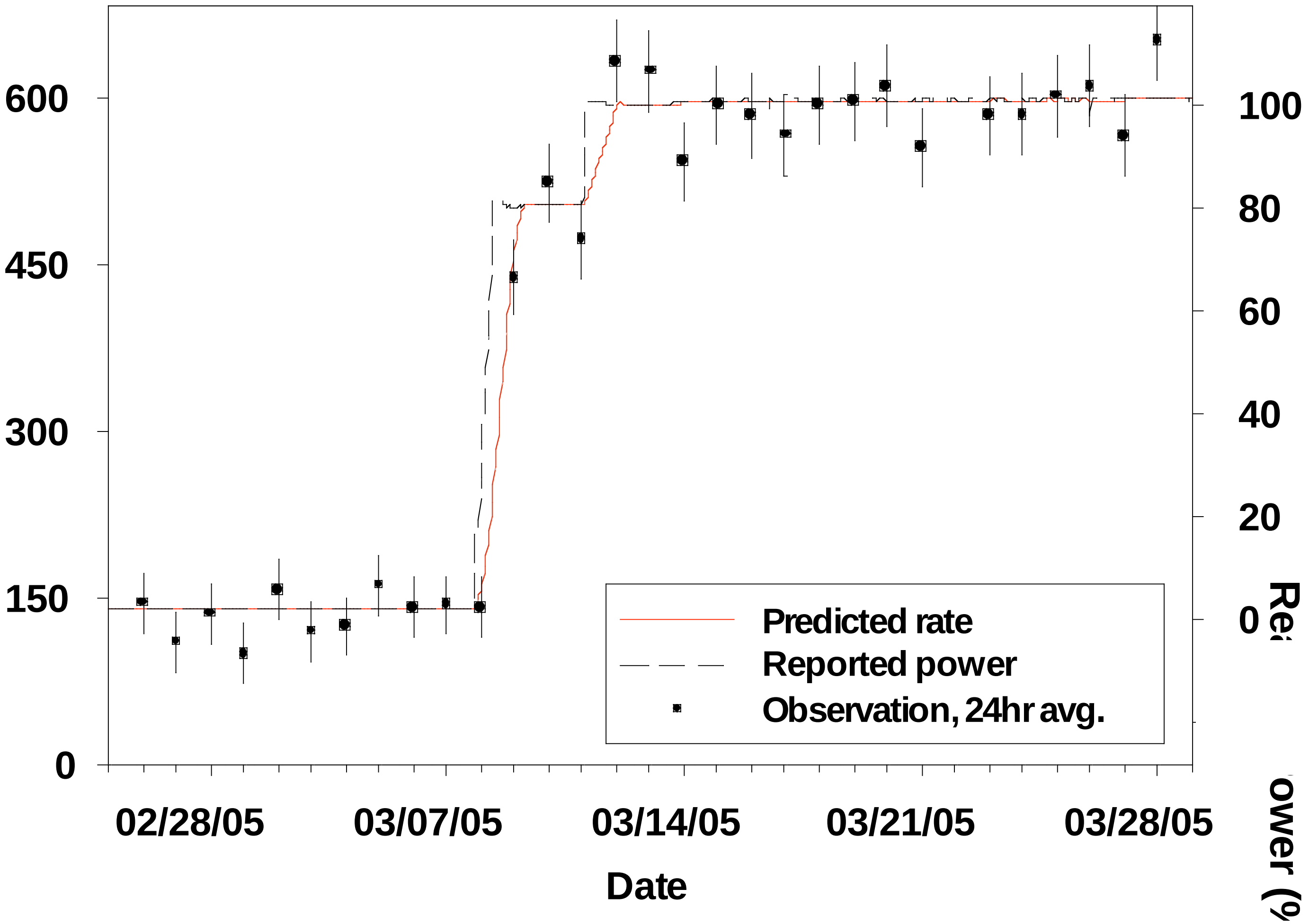
Installation at SONGS

Candidate event extraction

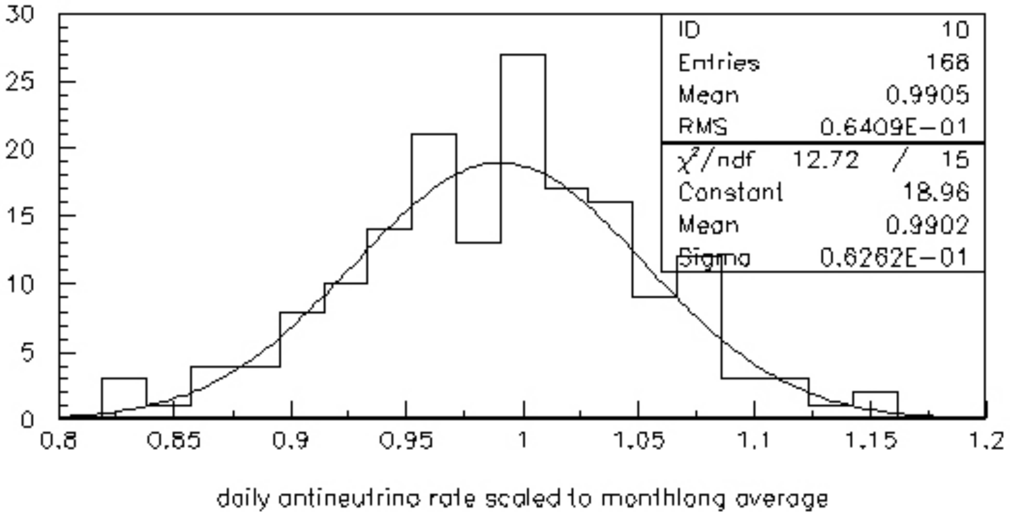
- Online calibration using 2.6 MeV background gamma
- Cuts are applied to extract correlated events:
  - energy cuts
    >2.39 MeV prompt
    >3.5 MeV delayed
  - at least 100µs after a muon in the veto detector
- Examine time between prompt and delayed to pick out neutron captures on Gd
- Event-by-event can not distinguish antineutrinos from random coincidences – perform statistical separation



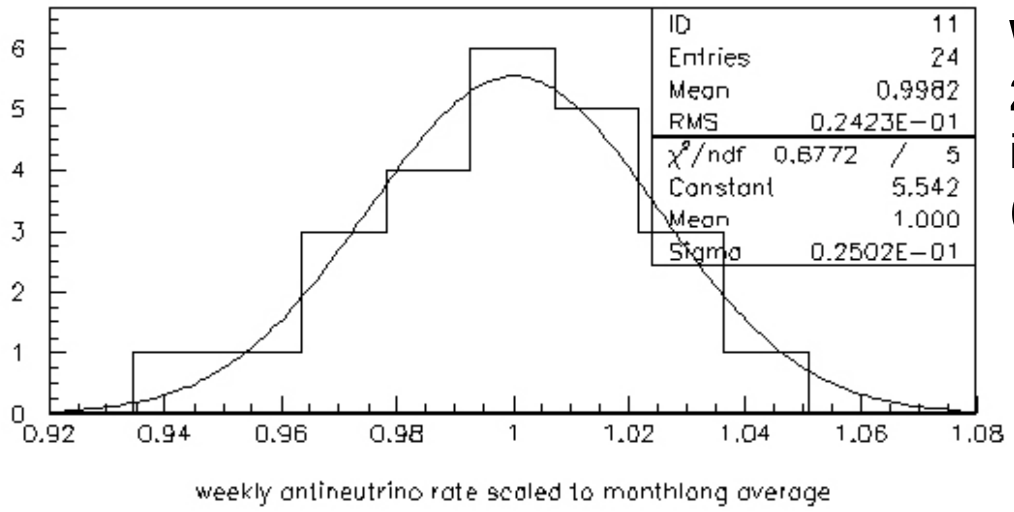
Reactor Monitoring using only $\bar{\nu}$



Relative power monitoring precision

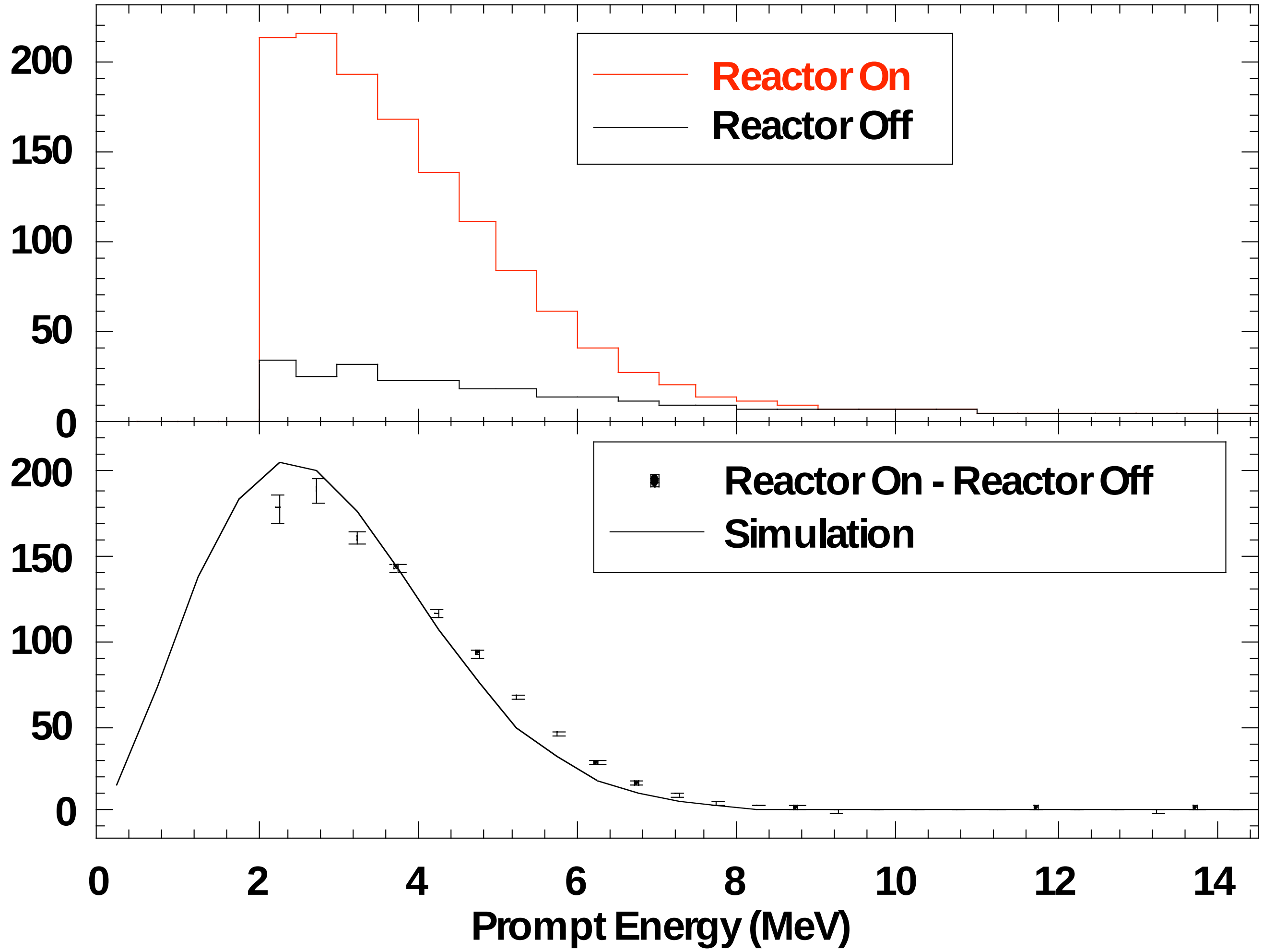


Daily average
6.2% relative uncertainty
in thermal power estimate
(normalized to 30 day avg.)



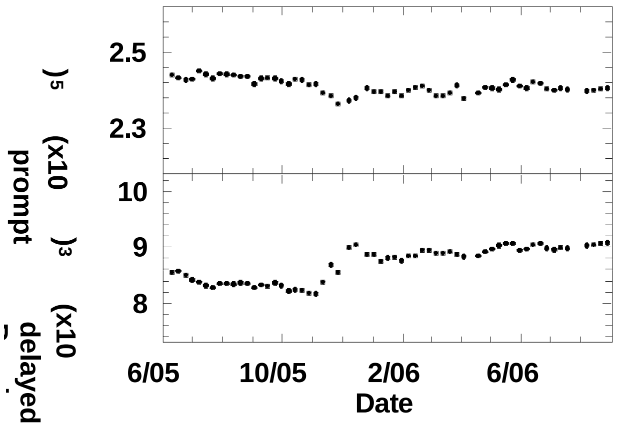
Weekly average
2.5% relative uncertainty
in thermal power estimate
(normalized to 30 day avg.)

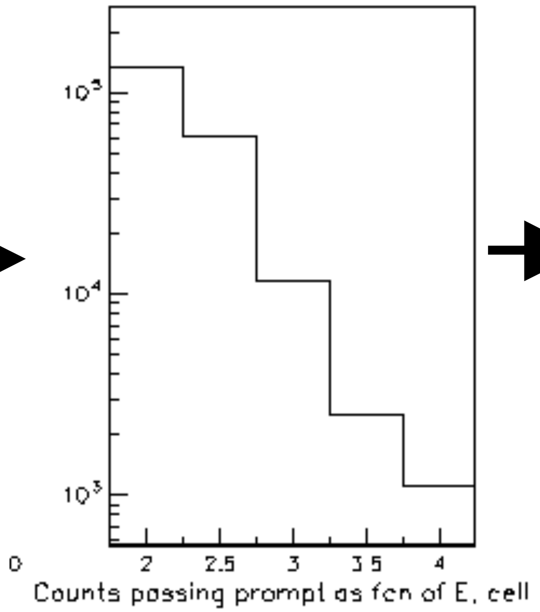
Clear indication of antineutrino detection

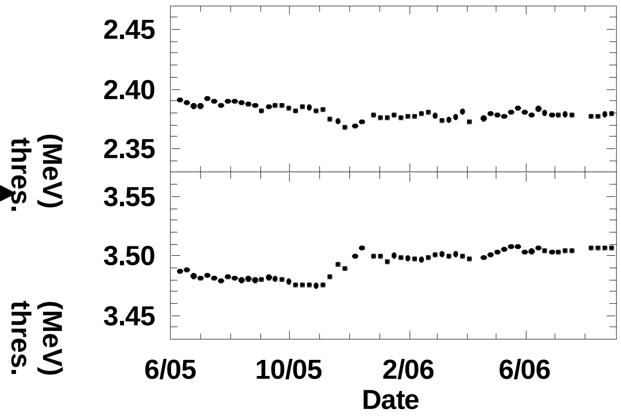


Detector Stability

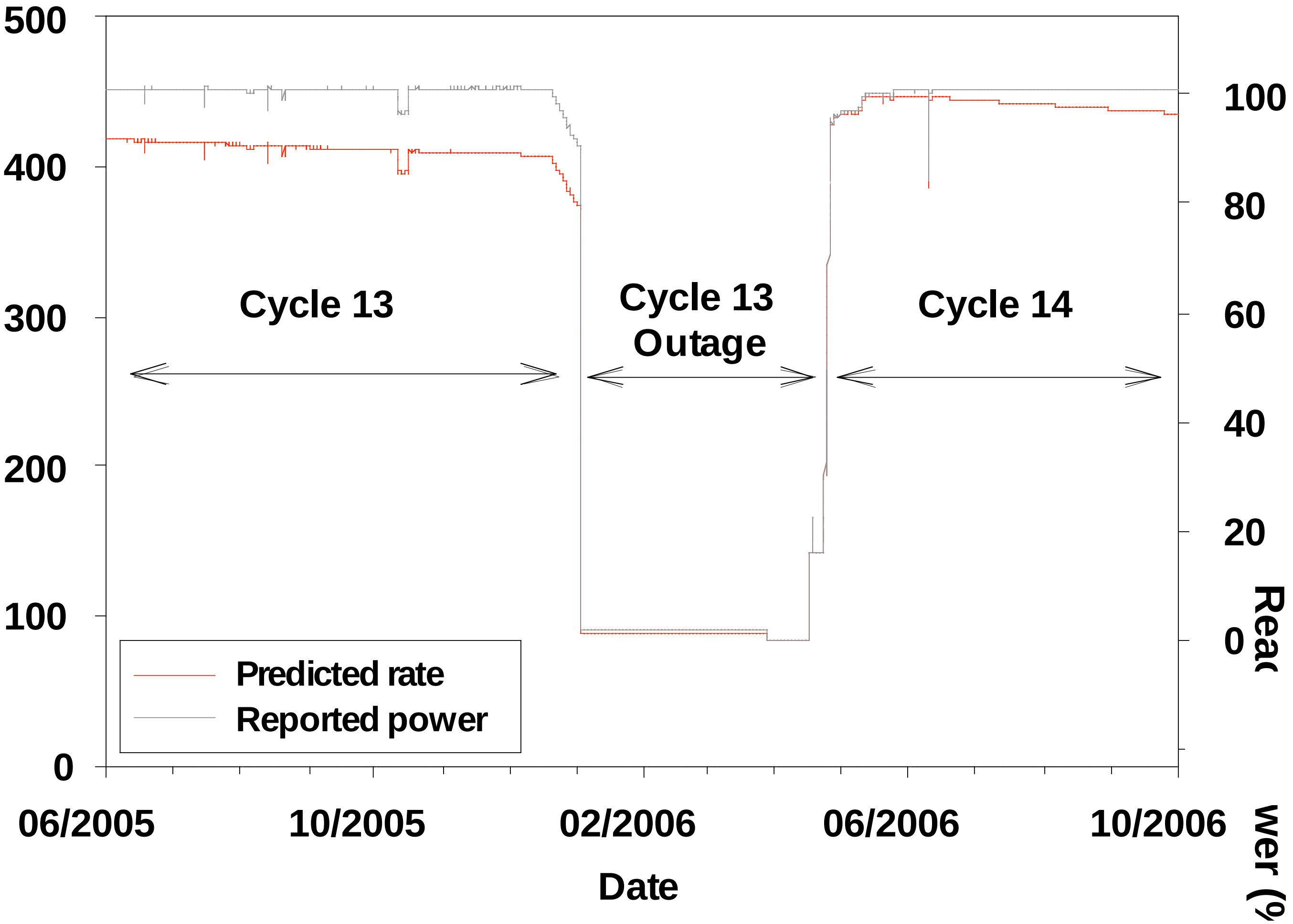
- **To observe the effect of fuel burnup, we must ensure that our detector is stable over the data taking period**
- **We count the number of events passing the energy cuts, and from this estimate the effectiveness of energy calibration.**



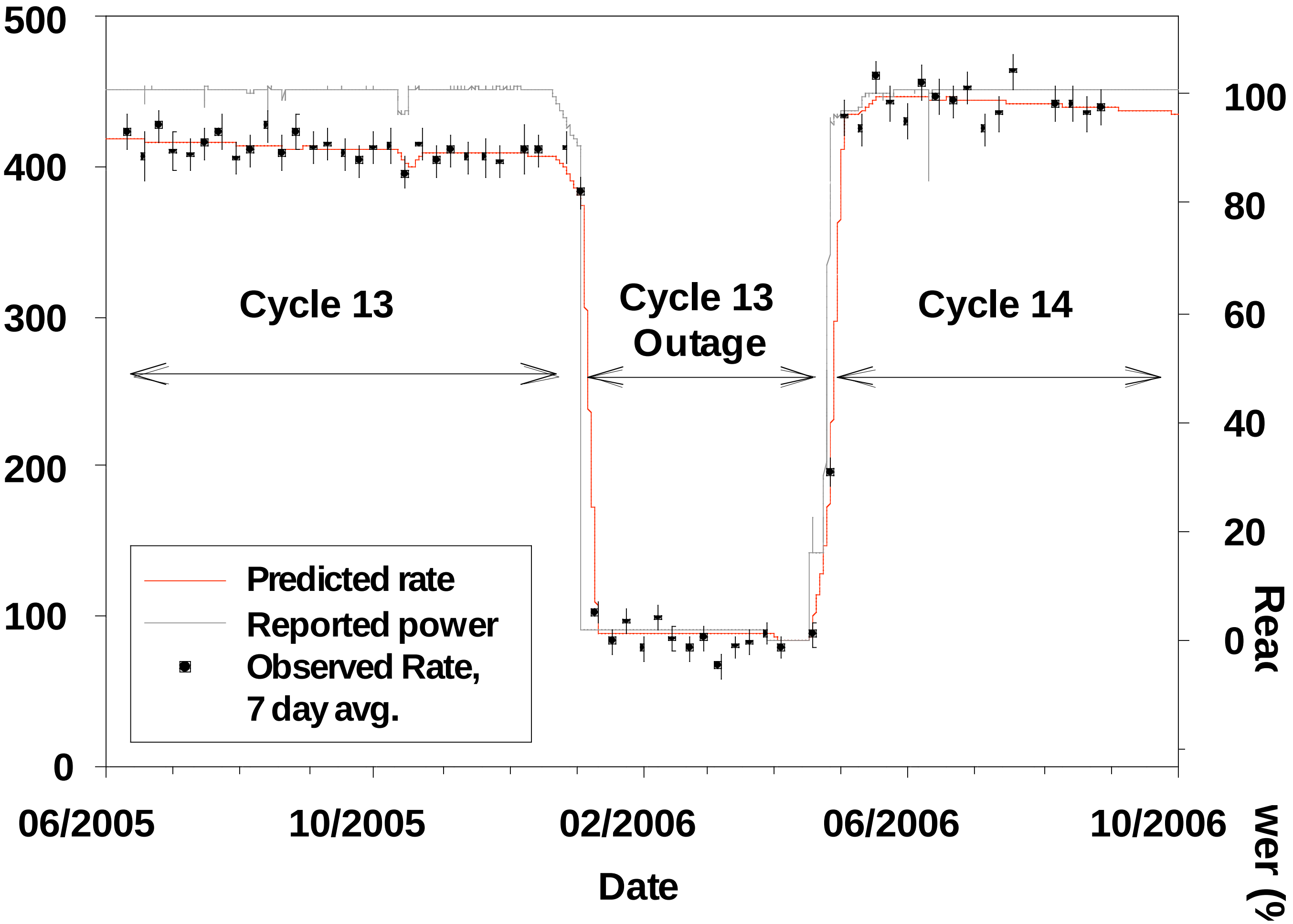




Prediction for our Dataset



Our Dataset



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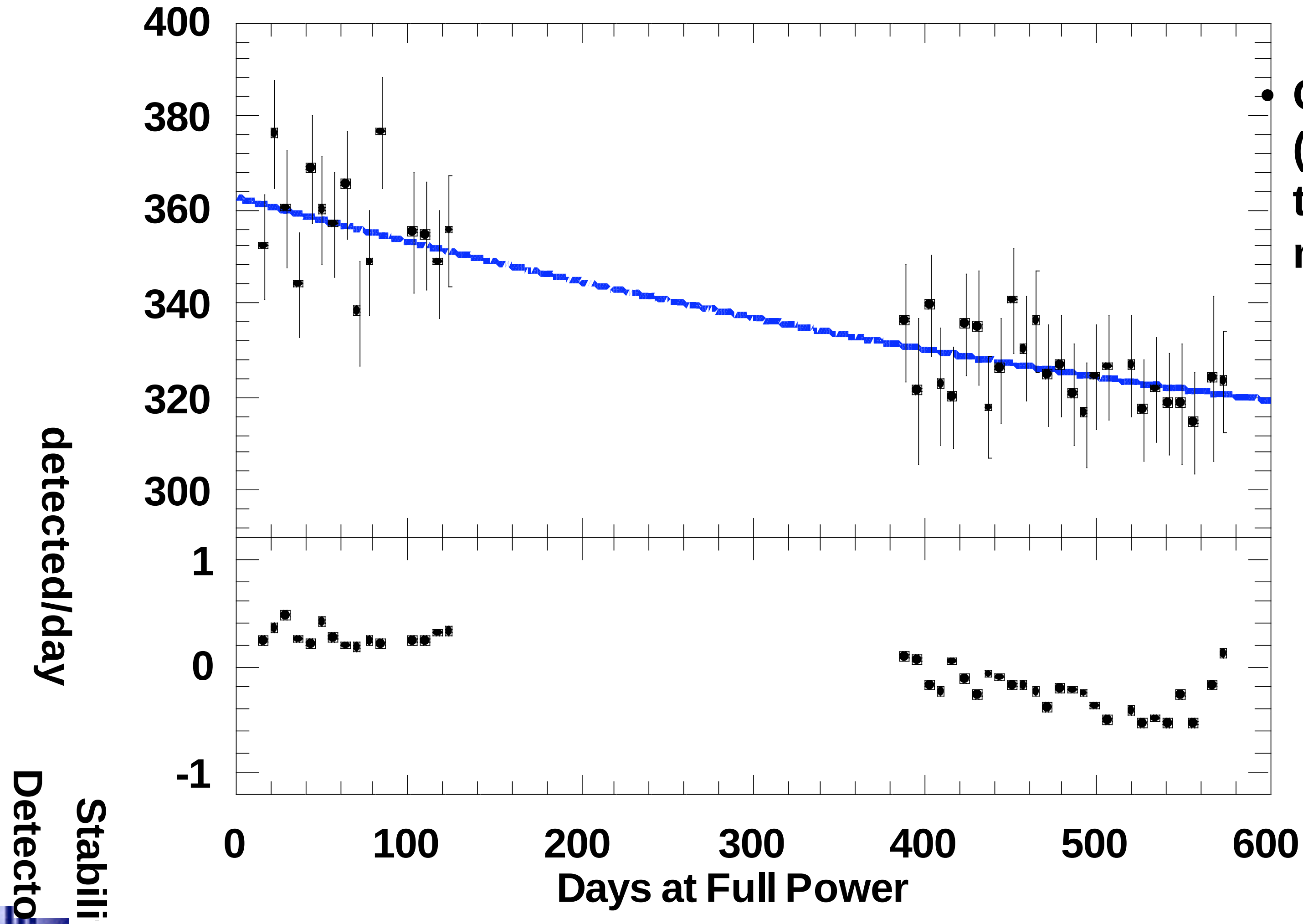
Burnup Measurement



- One parameter (normalization) fit to our burnup model

  (Consumption of
  1.5 tons of ^{235}U

  Production of
  250 kg of ^{239}Pu)

- Detector is stable to ~ 1%; burnup is ~ 10%

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Lessons Learnt

- **We need:**
  - **Better gamma shielding/cleaner material**
  - **More, and more uniform, light collection**
  - **Better calibration**
    (background lines won't be enough, no sources possible?)
  - **Smaller footprint**
- **We would like**
  - **Less flammable/aggressive scintillator**
  - **Smaller surface/volume ratio**
- **Leading to *higher efficiency in a smaller volume, with excellent stability***

Conclusions

- **Antineutrino detectors can be used to monitor nuclear reactors remotely and non-invasively**
  - **This has been firmly established by prior experiments and is being confirmed by us with a more practical/simple device**

- **Our simple device has been very successful and invaluable as a demonstration, but we can and must do better**

- **We will begin a new detector development program this year, beginning by studying the use of steel shielding with shallow overburden**

- **It is important in our discussions to identify the *necessary* features to make nonproliferation detectors successful, but not too complex or expensive**

Efficiencies

We estimate:

- **DAQ efficiency: 58%**
  - Muon deadtime, shortest time measured between events is 10µs
- **Positron detection (3 MeV cut): 55%**
  - High uncorrelated background rate <3 MeV
- **Neutron detection : 40%**
  - Poor containment of Gd shower with only $1m^3$
- **Fiducial Volume: <u>83%</u>**

- **Total: 11%**

At present, our measurement is <u>relative</u>