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Reactor Monitoring and Safeguards using Compact Antineutrino Detectors

A Sandia and Lawrence Livermore National Laboratories Joint Project

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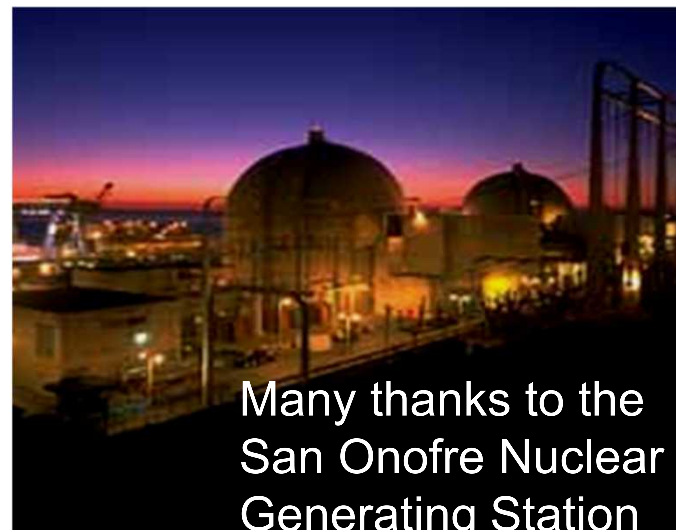

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(Office of Nonproliferation Research and Development)

Outline

- Safeguards and Non-proliferation
  - How could antineutrino measurements contribute to reactor safeguards?
- How would antineutrino safeguards work?
- Antineutrino Detection
- Deployment of a demonstration detector
- Experimental data from the detector
- Conclusions

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- **Safeguards and Non-proliferation**
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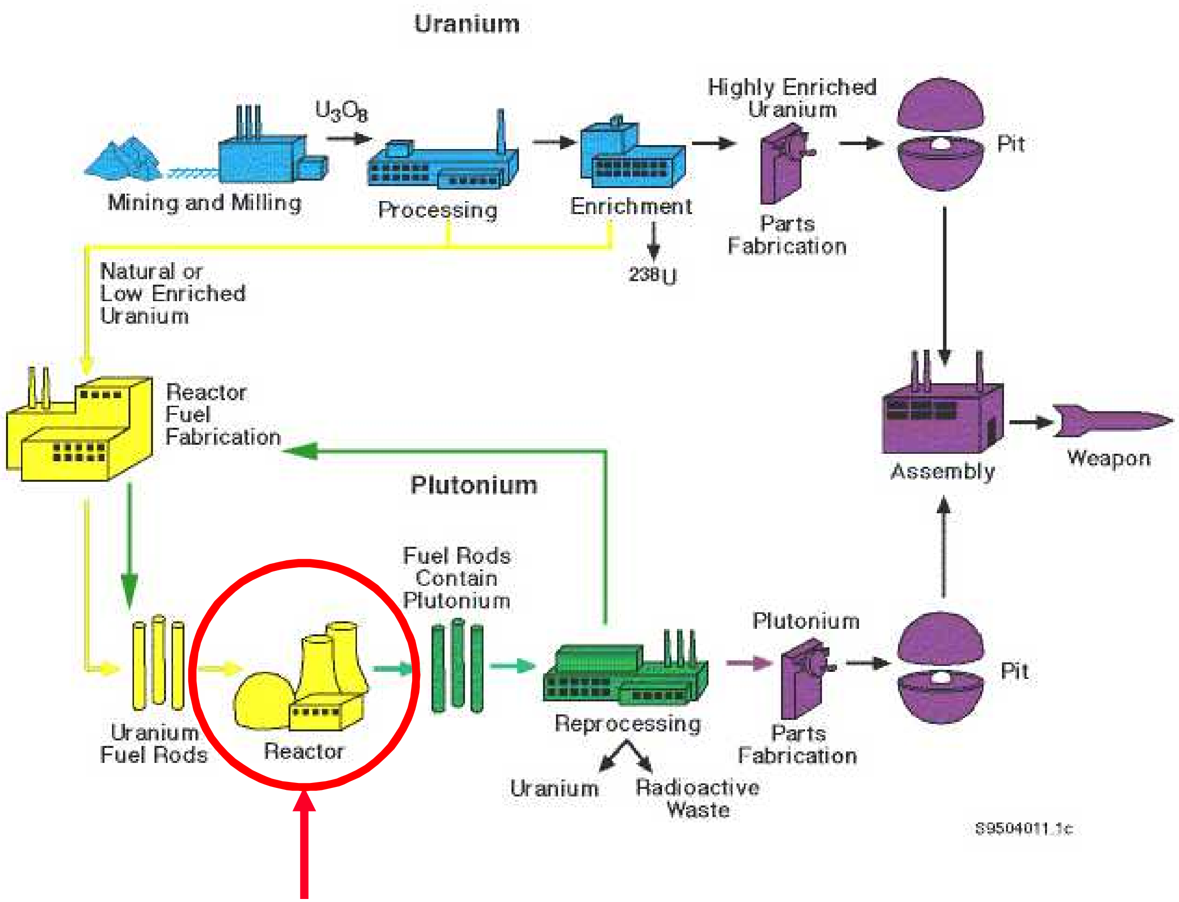
Antineutrino Detectors Address One Part Of The Fuel Cycle



Reactor monitoring with antineutrinos touches on only one element in a long fuel cycle, but important as it is here that Pu is produced

IAEA Monitoring of Fissile Material in Civil Nuclear Cycles

(1-1.5 years) | (months to years) | (months) | (forever)

Reactor (1-1.5 years):

1. Check Input and Output Declarations
2. Item Accountancy
3. Containment and Surveillance

Onsite Fuel Storage (months to years):

1 'Gross Defect' Detection
2 Item Accountancy
3. Containment and Surveillance

Reprocessing (months):

1 Check Declarations
2 Verify with **Bulk Accountancy**:

Includes automated Core Discharge Monitors and Bundle Counters for CANDU

Operators Declare Fuel Burnup and Power History

No Direct Power History Measurement is Made

No Direct Pu Inventory Measurement is Made Until Fuel is Reprocessed

Antineutrino Safeguards and Monitoring

- Direct measurements at reactors using antineutrinos could:
  - Independently detect 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

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What is an (anti)neutrino?

- **Produced in radioactive beta decay**

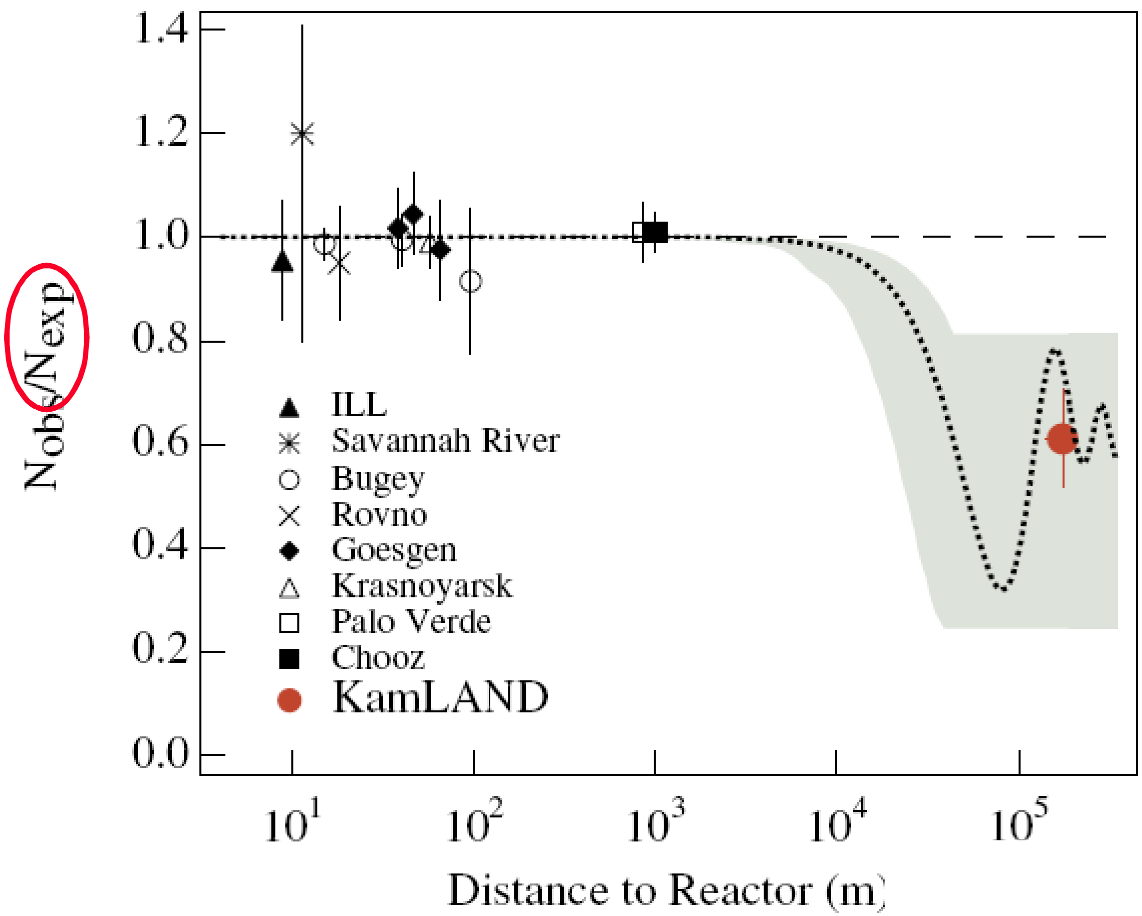
$$n \rightarrow \overline{\nu}_e + p + e^-$$

- **Only interact with matter by way of the weak nuclear force**
  - Therefore matter is almost invisible to neutrinos
  - To detect small numbers of neutrinos you need to create huge numbers

"All you have to do is imagine something that does practically nothing. You can use your son-in-law as a prototype"

-Richard Feynman on the difficulty of detecting neutrinos

Previous Reactor Antineutrino Experiments

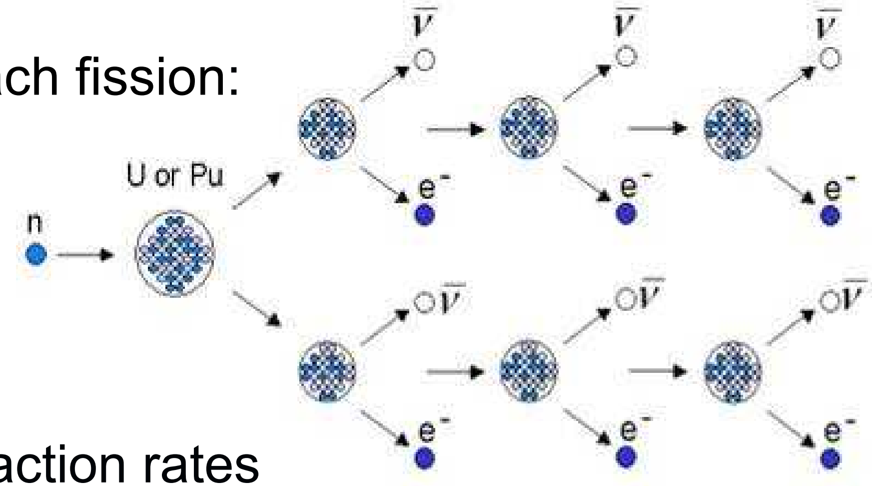


- Reactors have been used as the source for many neutrino oscillation searches
- These experiments developed
  - detection technology
  - understanding of reactors as an antineutrino source
- We seek to invert this, applying the knowledge for a practical purpose

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
  - e.g. for a PLWR, antineutrino rate change of about 10% through a 500 day PLWR 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

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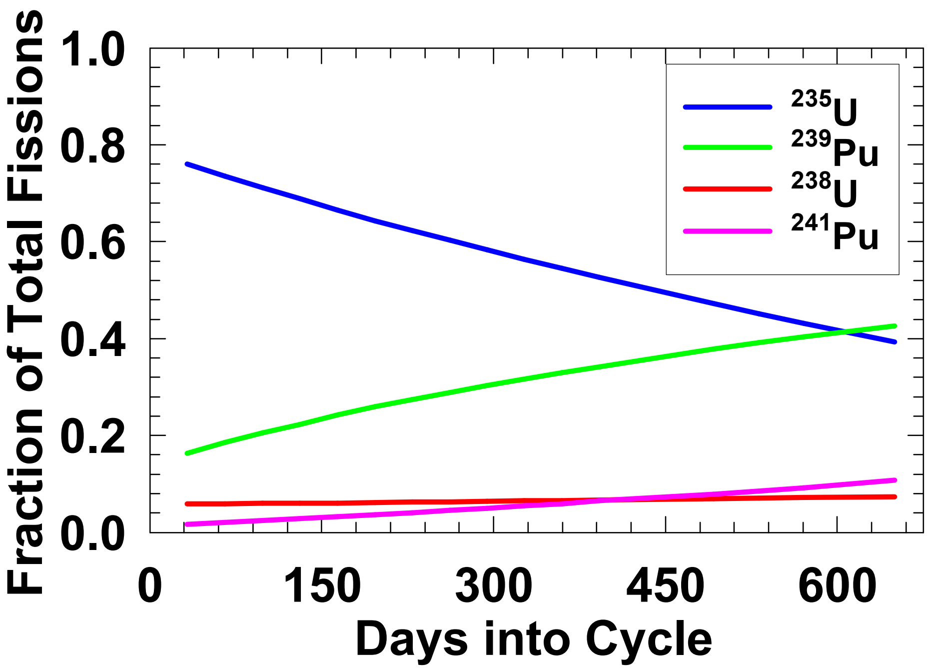
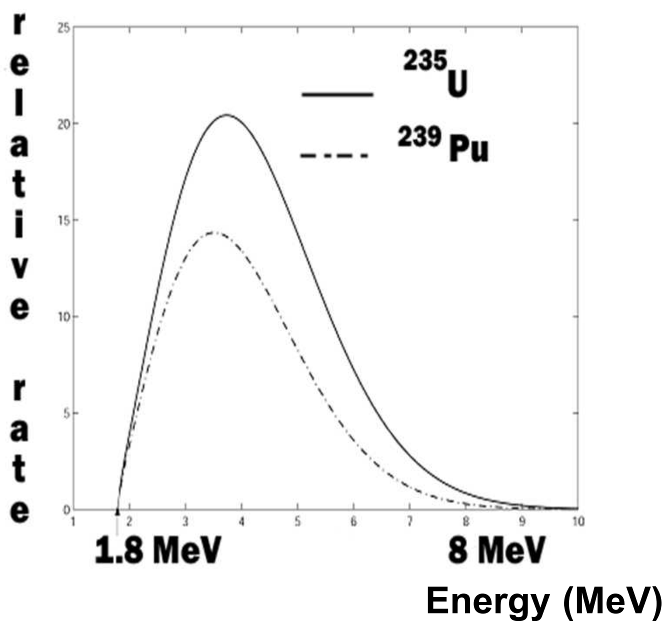
The Antineutrino Production Rate varies with Fissioning Isotope: PLWR Example

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

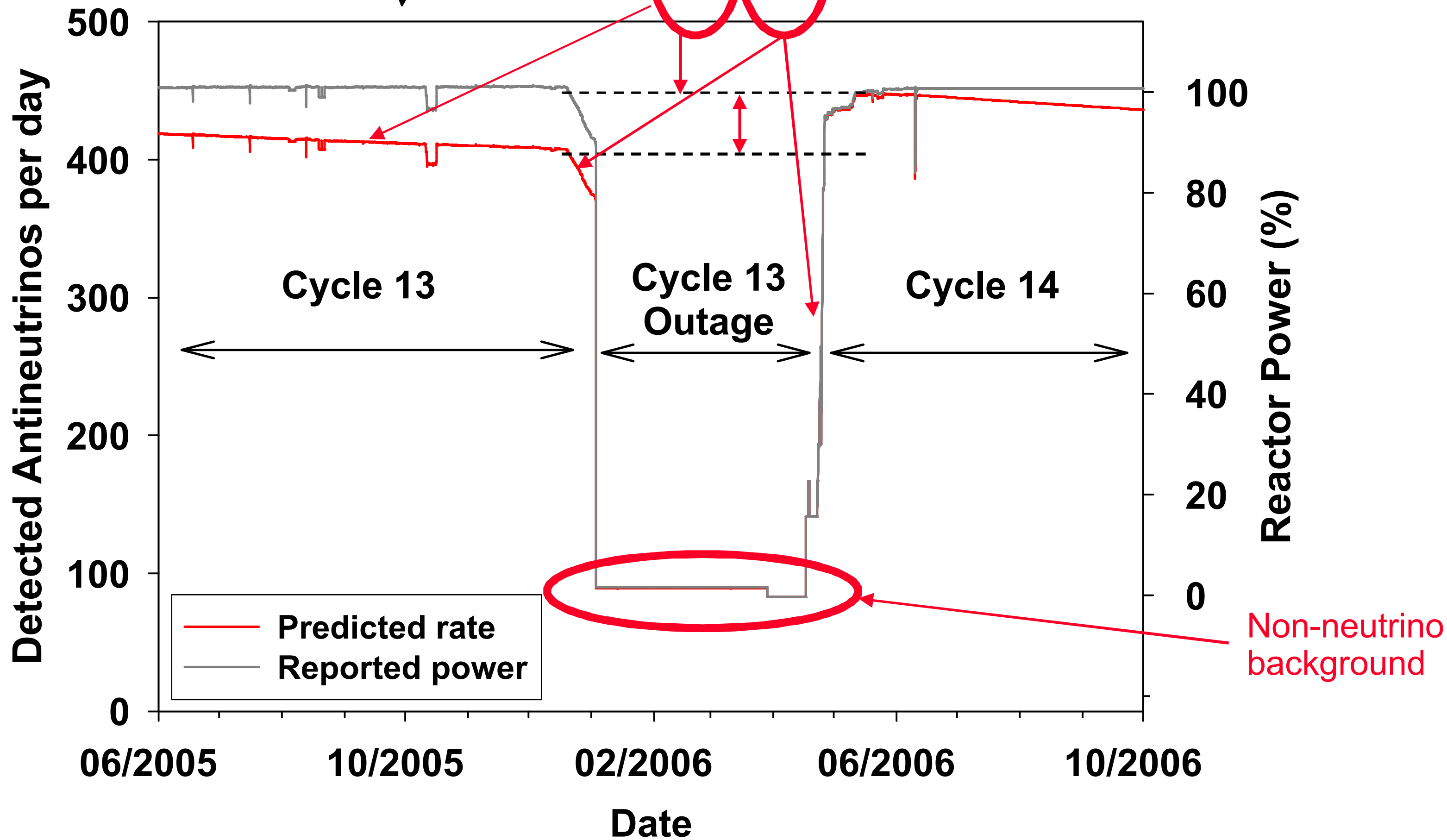


The energy spectrum and integral rate produced by each fissioning isotope is different



Prediction for a PLWR

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



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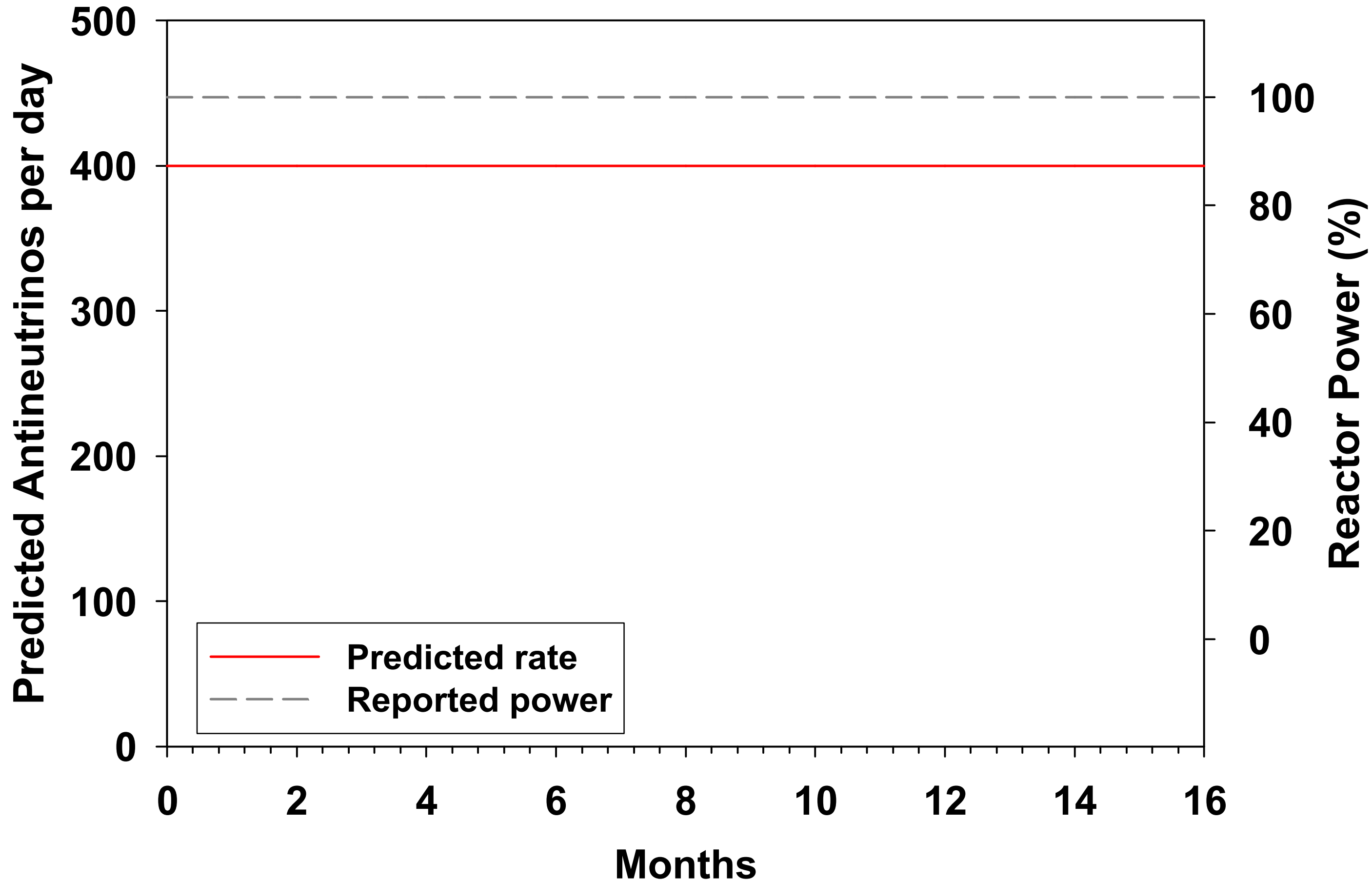
Prediction for CANDU?



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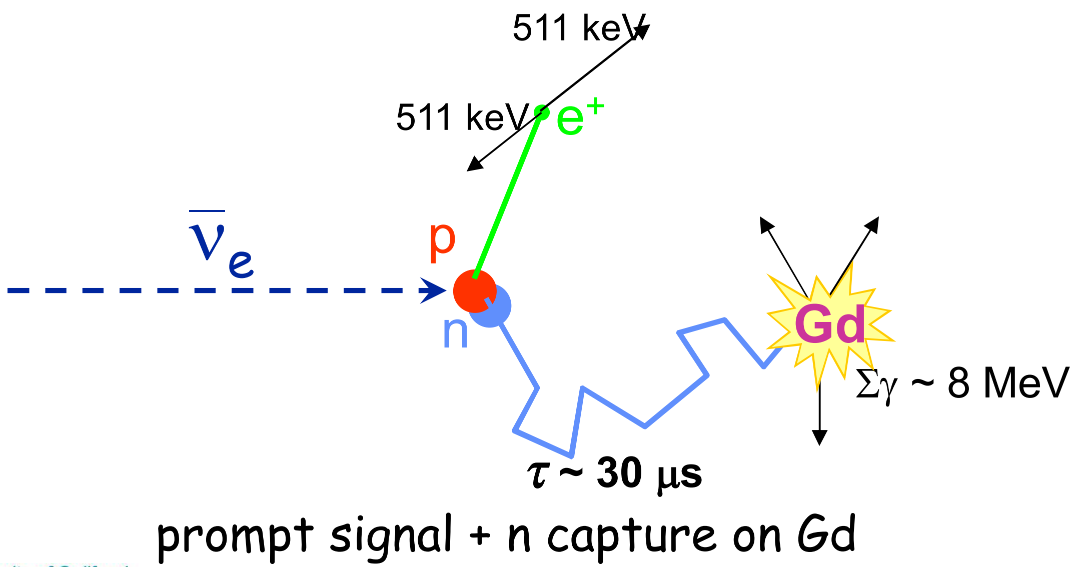
Antineutrino Detection

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

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

  - 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)

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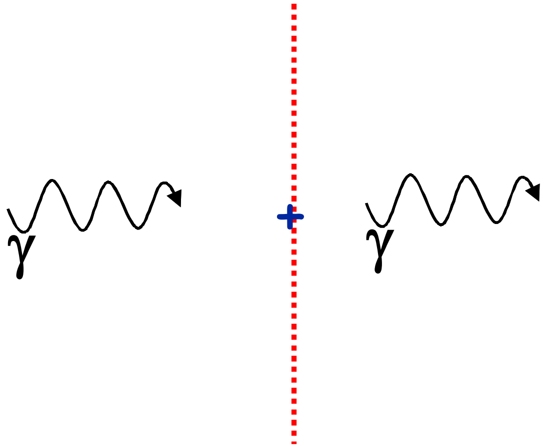
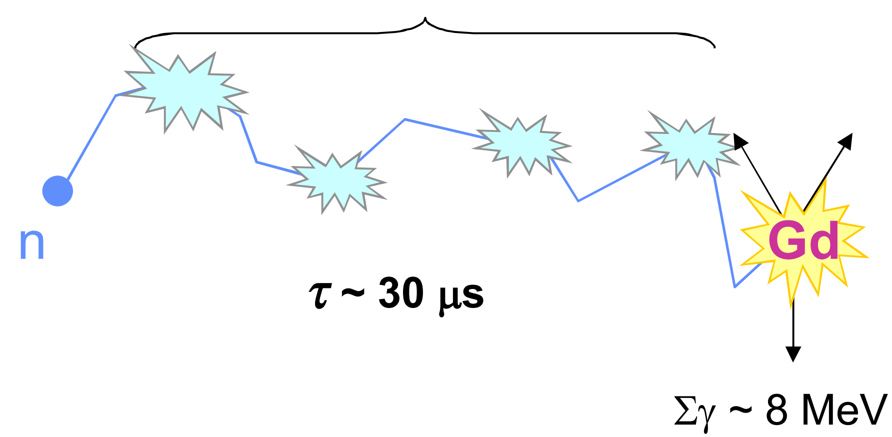
Backgrounds

- **Uncorrelated Backgrounds**
  - **Are the random coincidence of two unrelated events in the detector**
  - **Have a different time structure to antineutrino interactions**
  - **Can be reduced by:**
    - **using radiopure materials**
    - **Adding gamma and neutron shielding**
- **Correlated Backgrounds**
  - **Have the same time structure as antineutrino interactions**
  - **Cosmic ray muons produce fast neutrons, which scatter off protons and can then be captured on Gd**
  - **Can be reduced by:**
    - **going underground**
    - **Tagging muons near the detector**
    - **Adding neutron shielding**





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Deployment Goals/Design Principles

- Previous experiments have demonstrated the physics behind this monitoring concept.

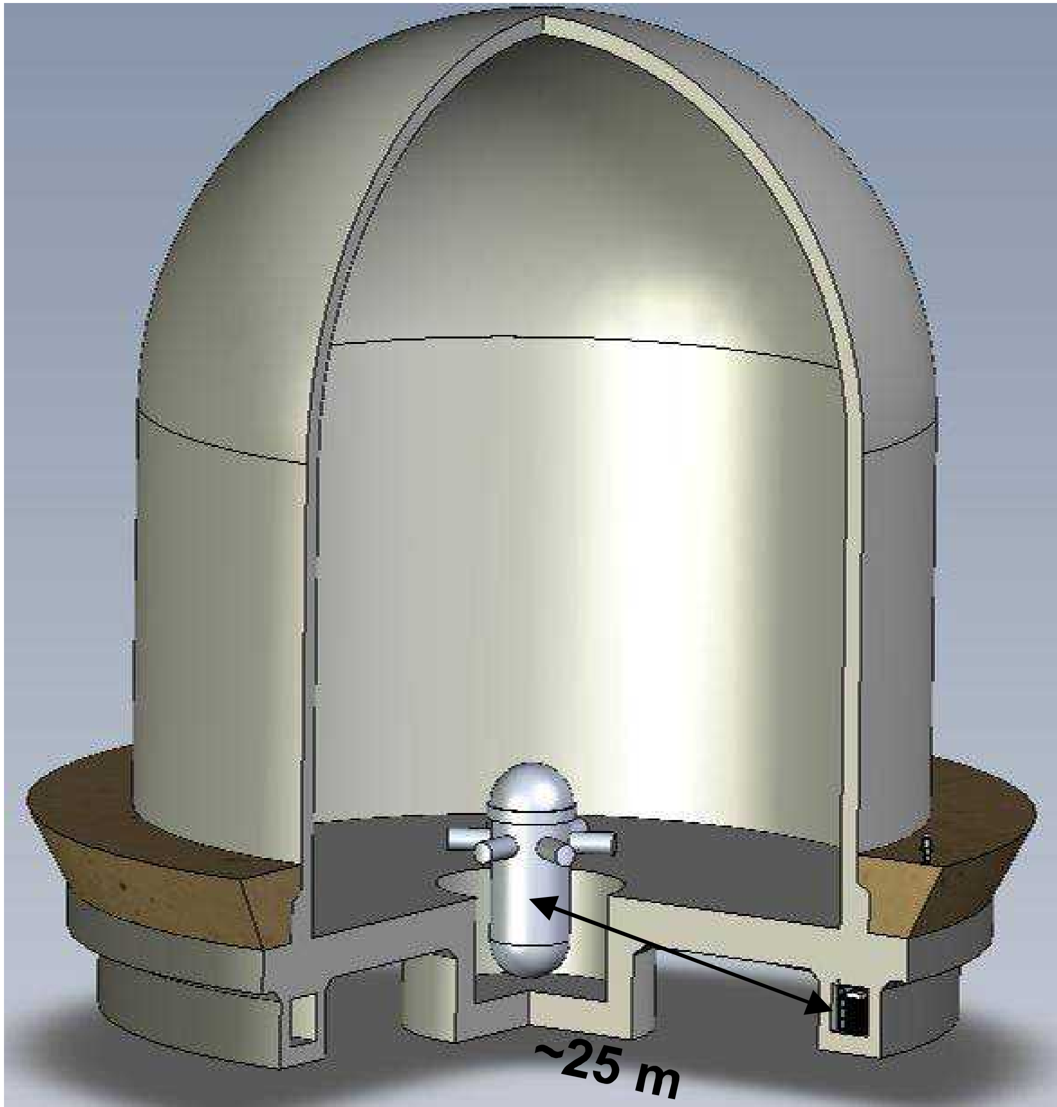
- Our goal has been to demonstrate that such monitoring is possible using a system that is:
  - Automated
  - Nonintrusive
  - Simple (e.g. ~ 3 people vs. 10-100 for physics expt.)
  - Inexpensive (e.g. < 10 PMTs vs. 100-1000 for physics expt.)
  - Uses well known detection concepts/technology
  - Physically robust for reactor environment

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

Prototype deployment –
San Onofre Nuclear Generating Station

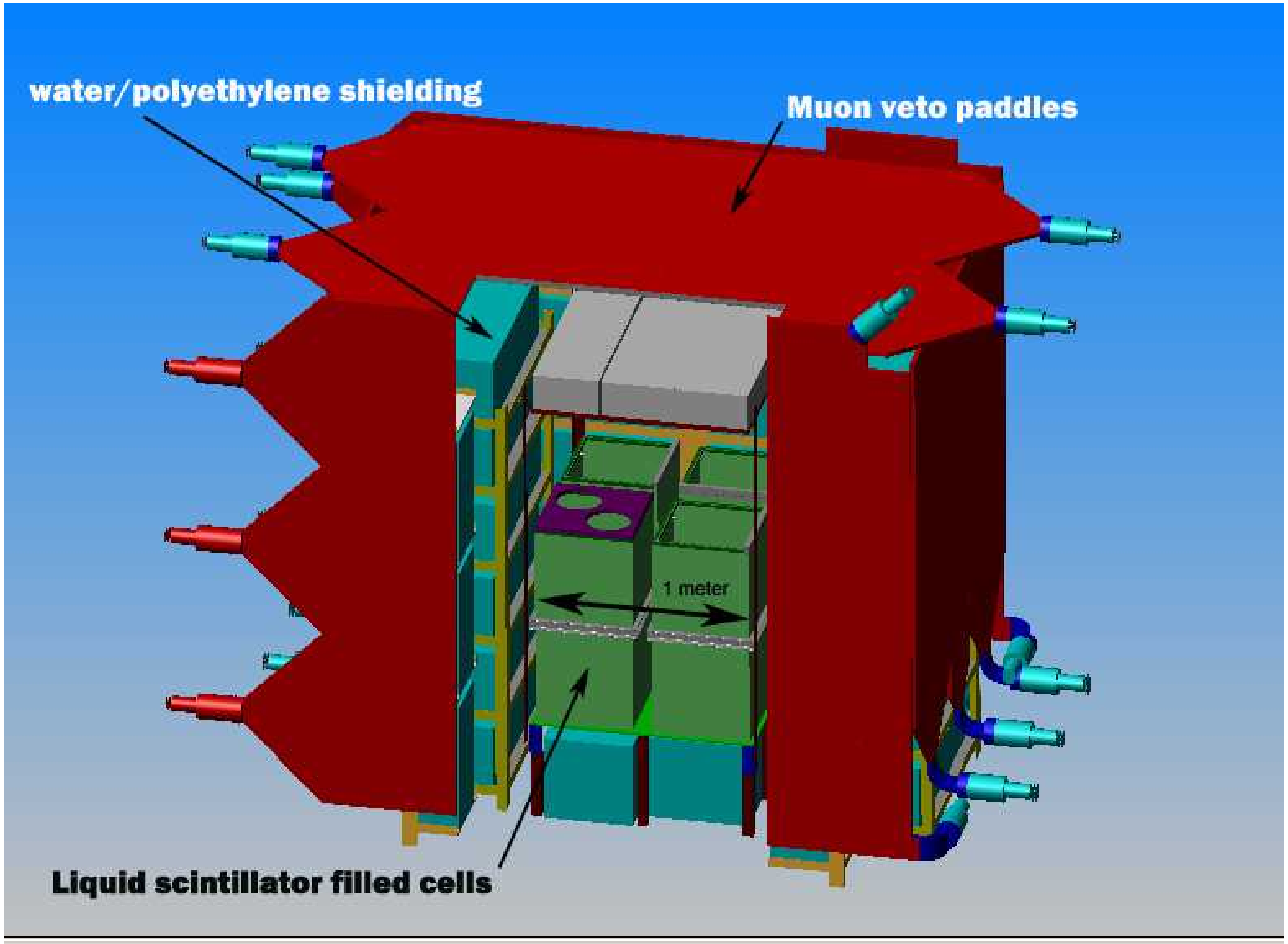
SONGS Unit 2 Tendon Gallery

- 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
- 3.4 GW_{th} => 10^{21} ν / s
- In tendon gallery ~10^{17} ν / s per m^2
- Around 3800 interactions expected per day (~ 10^{-2} / s)

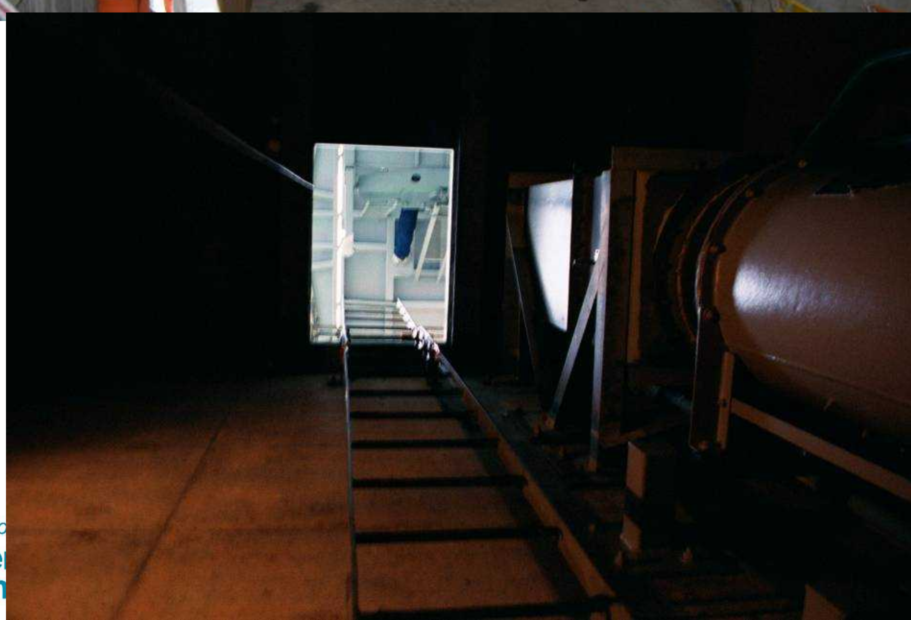


Sandia/LLNL Antineutrino Detector

- Detector system is…
  - ~1 m^3 Gd doped liquid scintillator readout by 8x 8" PMT
  - 6-sided water shield
  - 5-sided active muon veto



Installation at SONGS



Installation at SONGS

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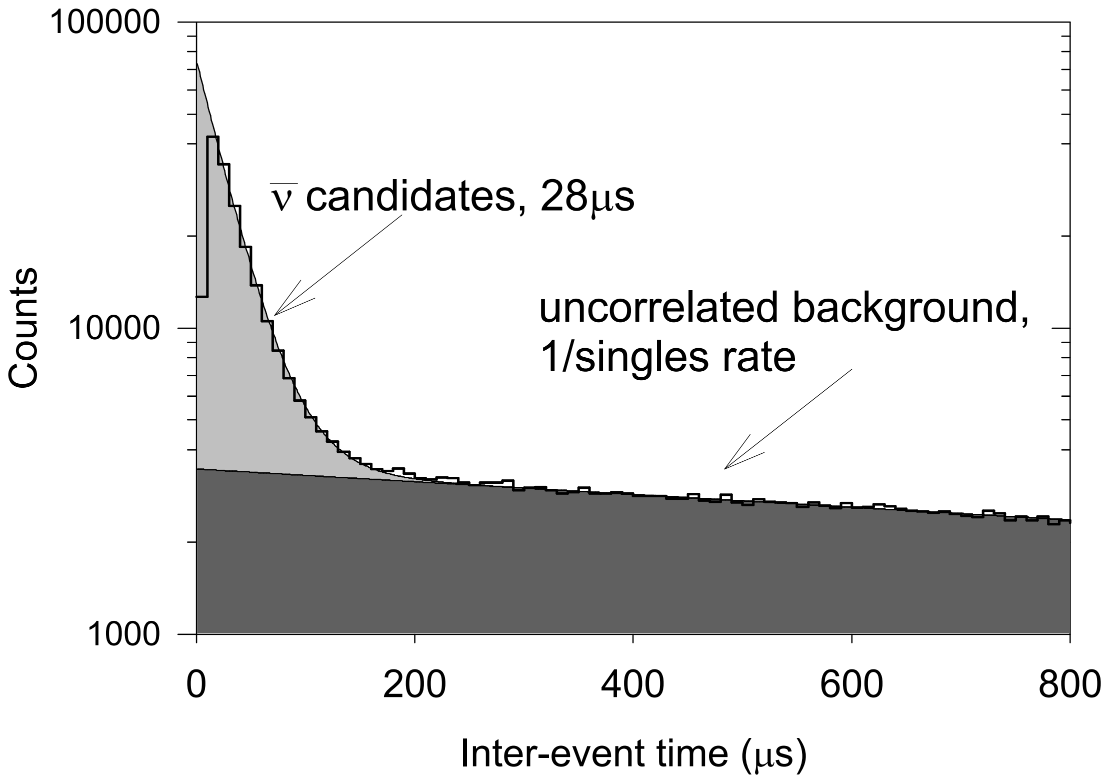
Candidate event extraction

- 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



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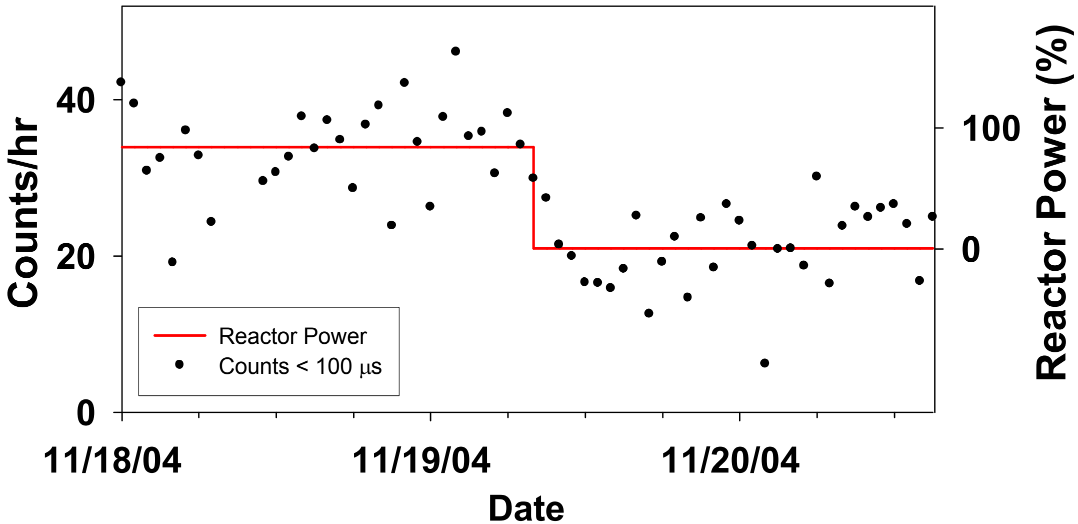
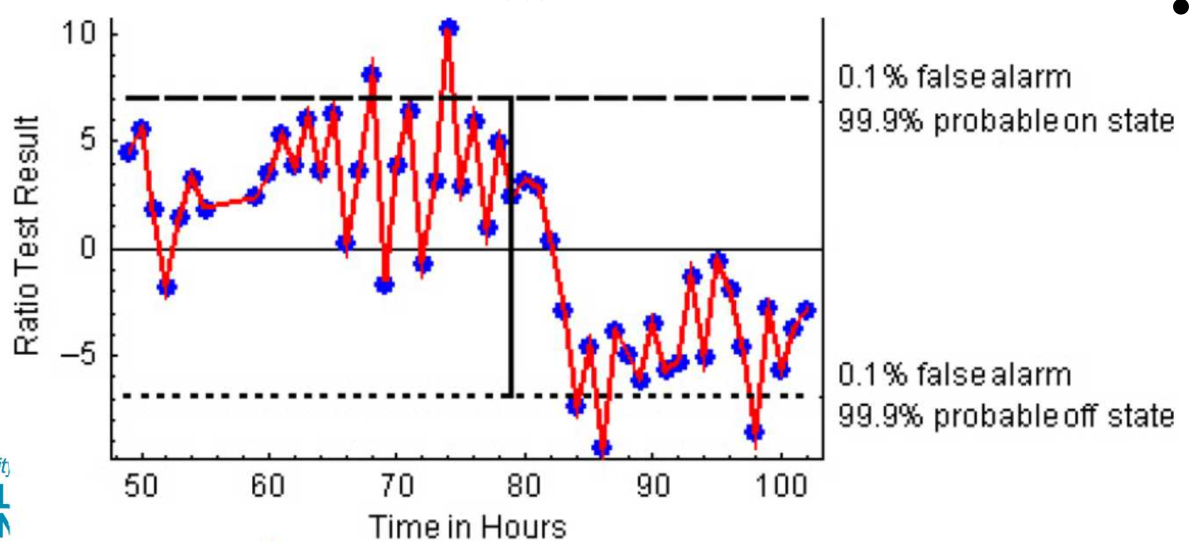
Short Term monitoring – Reactor Scram





- With a one hour integration time, sudden power changes can be seen
- In this case, a scram is “detected” via SPRT with 99.9% confidence after 5 hours

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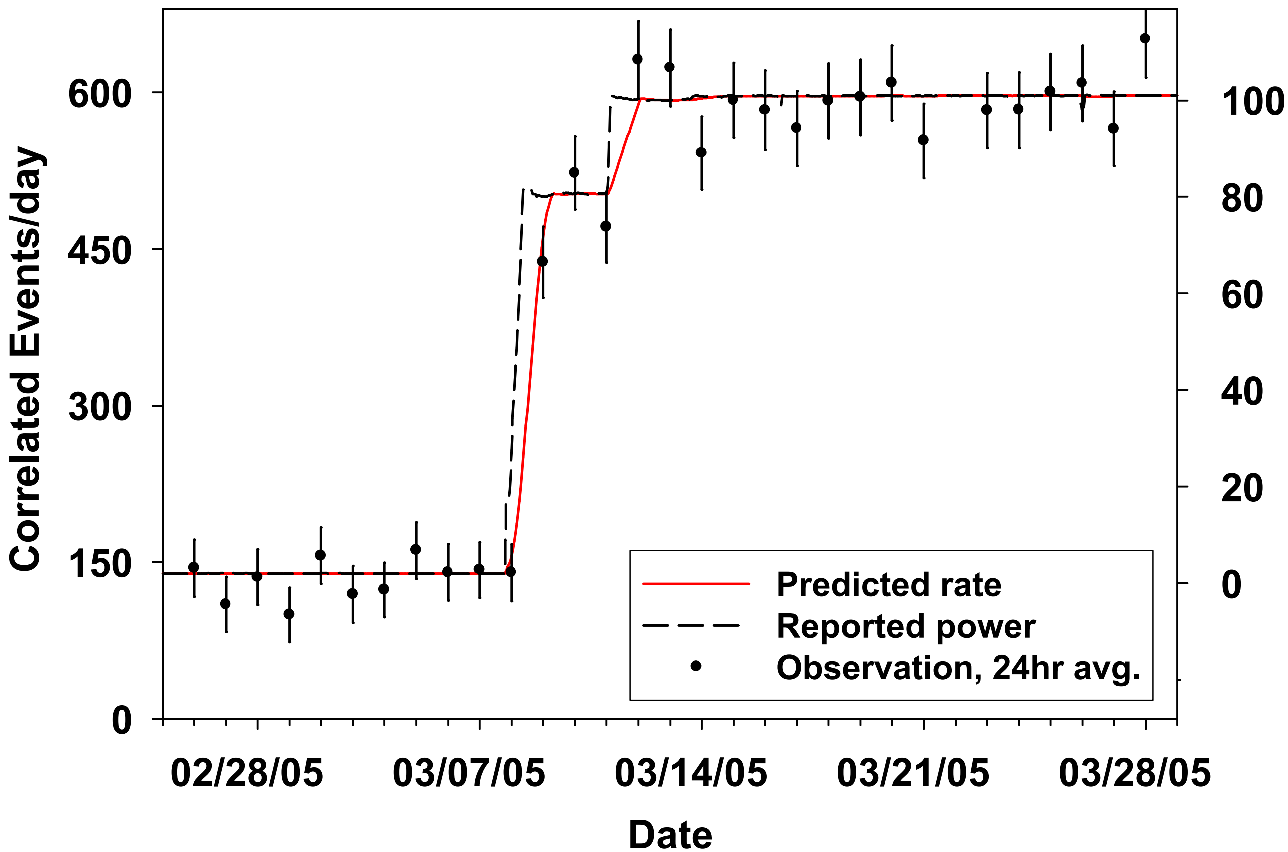
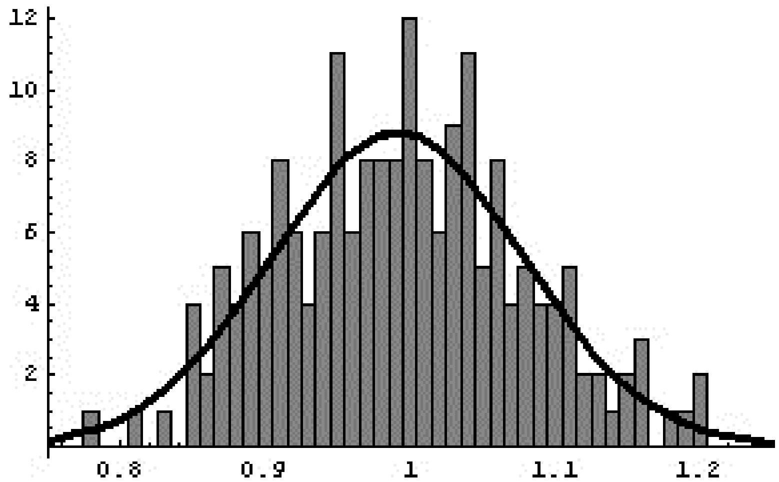
Reactor Power Monitoring using only $\bar{\nu}$

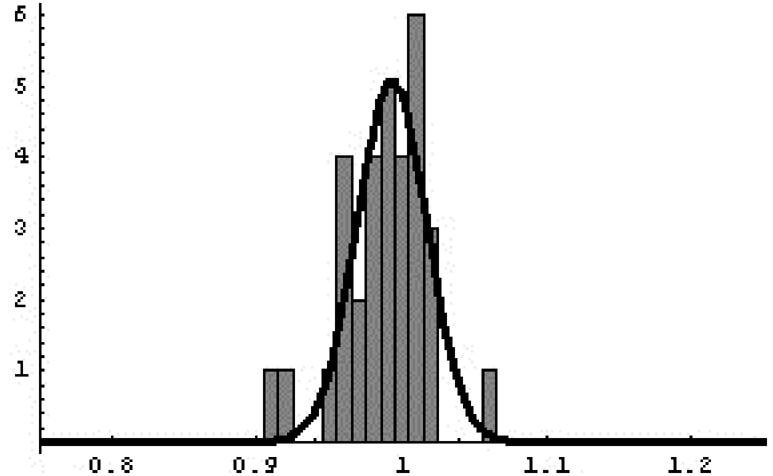


- In this example, we integrated for 24 hrs. The reactor is restarted after maintenance
- Reactor off periods allows us to measure the correlated background rate

Relative Power Monitoring Precision



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

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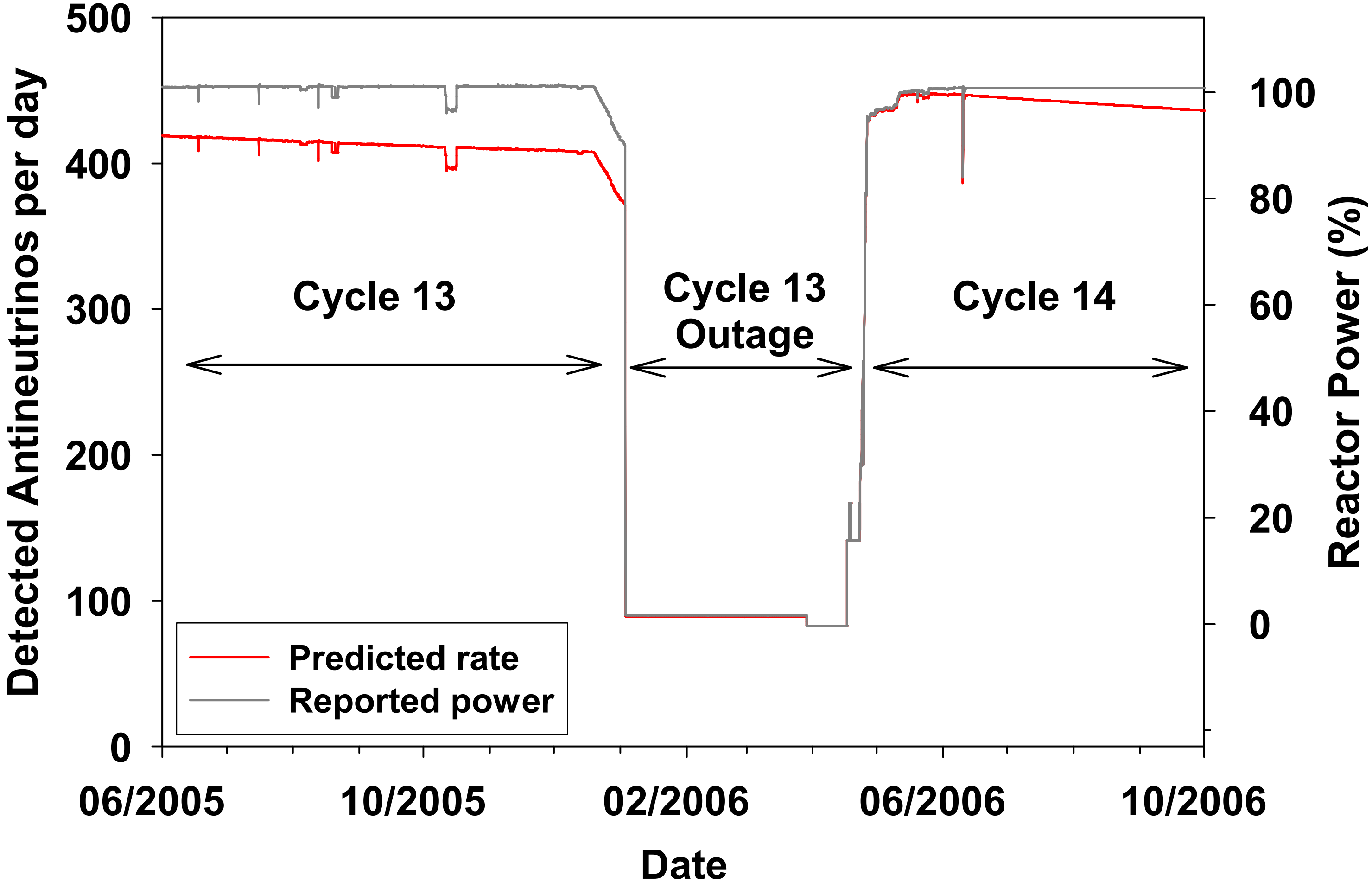
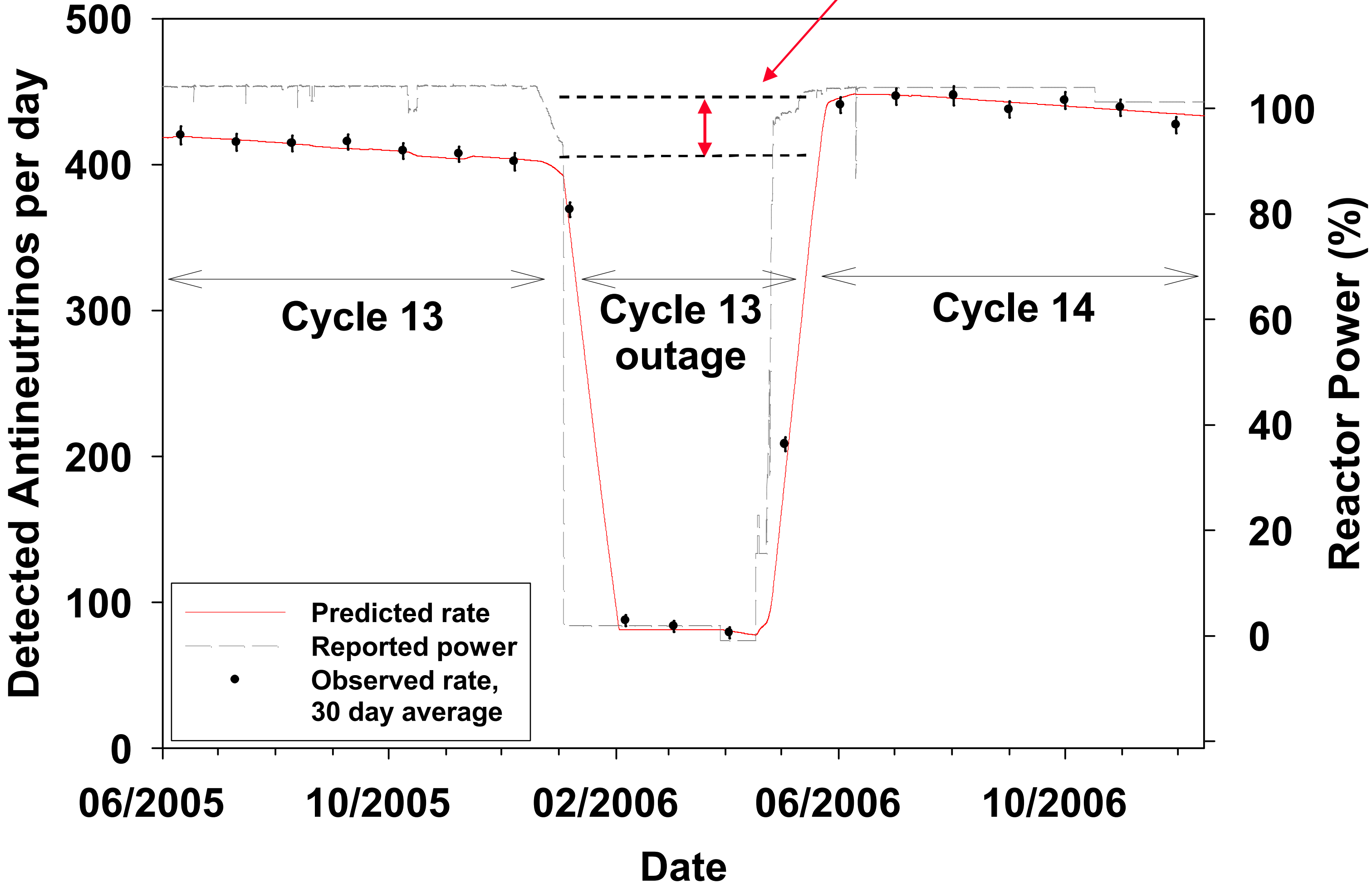
Prediction for our Dataset



Our Dataset

- Removal of 250 kg ^{239}Pu, replacement with 1.5 tons of fresh ^{235}U fuel



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What Would It Take for the IAEA to Adopt this Method?

- **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:

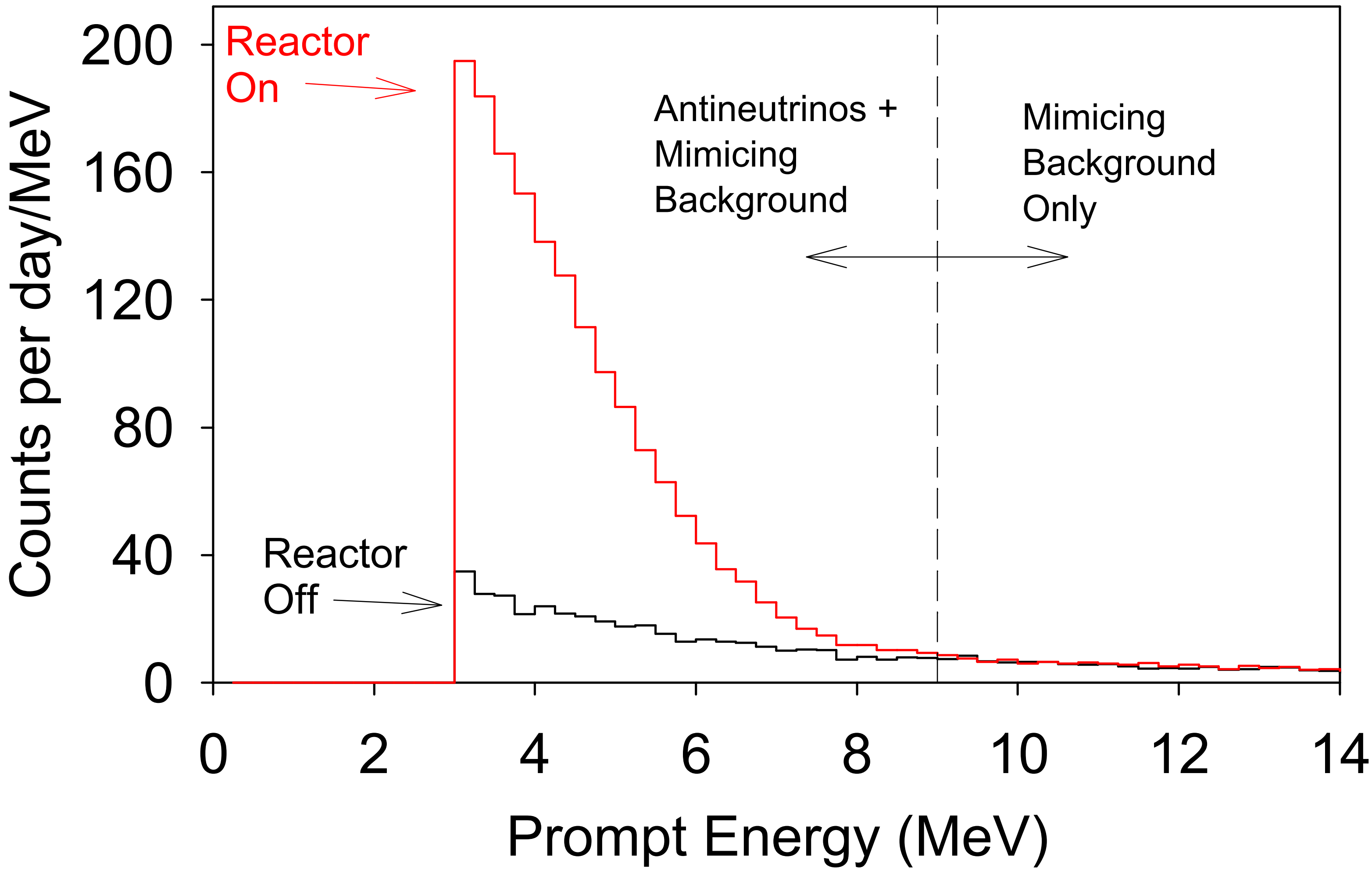
- **Footprint may be too large**
  - **Shielding makes up 80% of footprint in current design**
- **Not enough reactors with suitable deployment locations?**
  - **Possible to deploy on/near surface?**
- **IAEA may have more pressing safeguards problems**

IAEA has expressed recent interest in our results

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 simple and practical device**
- **The technology may fill an important niche by providing unattended monitoring and quantitative measurements early in the fuel cycle**
  - **But IAEA must be convinced that it really improves their regime**
- **Strong overlap with detector development for next generation of neutrino oscillation experiments (θ_{13})**
  - **gives an opportunity for improved precision on Pu content limits**
- **Ongoing effort:**
  - **Shrink footprint and improve efficiency, deployability**
  - **Quantify benefits relative to existing safeguards methods**

Clear indication of antineutrino detection



SONGS1 Efficiencies

We estimate:

- **DAQ efficiency: 58%**
  - Muon deadtime, shortest time measured between events is 10μs
- **Positron detection (2.45 MeV cut): 55%**
  - High uncorrelated background rate <2.45 MeV
- **Neutron detection : 40%**
  - Poor containment of Gd shower with only 1m^3 (0.25 m^3)
- **Fiducial Volume: 60%**

- **Total: 8%**

Figure of Merit: Detected $\bar{\nu}$/ Total Volume

400/day/20 m^3 = 20 $\bar{\nu}$ / m^3 day

SONGS ~~1~~ 2 Efficiencies

We estimate:

• DAQ efficiency:	~~58%~~	85%
• Positron detection (1.5 MeV cut?):	~~55%~~	65%
• Neutron detection :	~~40%~~	50%
• Fiducial Volume:	~~60%~~	95%
• Total:	~~8%~~	26%

Figure of Merit: High: 1300/day/4.5 m^3 = 280 $\overline{\nu}$ / m^3 day

Low: 800/day/8.0 m^3 = 100 $\overline{\nu}$ / m^3 day

400/day/20 m^3 = 20 $\overline{\nu}$ / m^3 day

Calibration

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