SAND2014-17851PE

Exceptional service in the national interest

Sandia National Laboratories

Antineutrinos for nuclear reactor monitoring

Scott Kiff

Radiation and Nuclear Detection Systems

Sandia National Laboratories

September 22, 2014

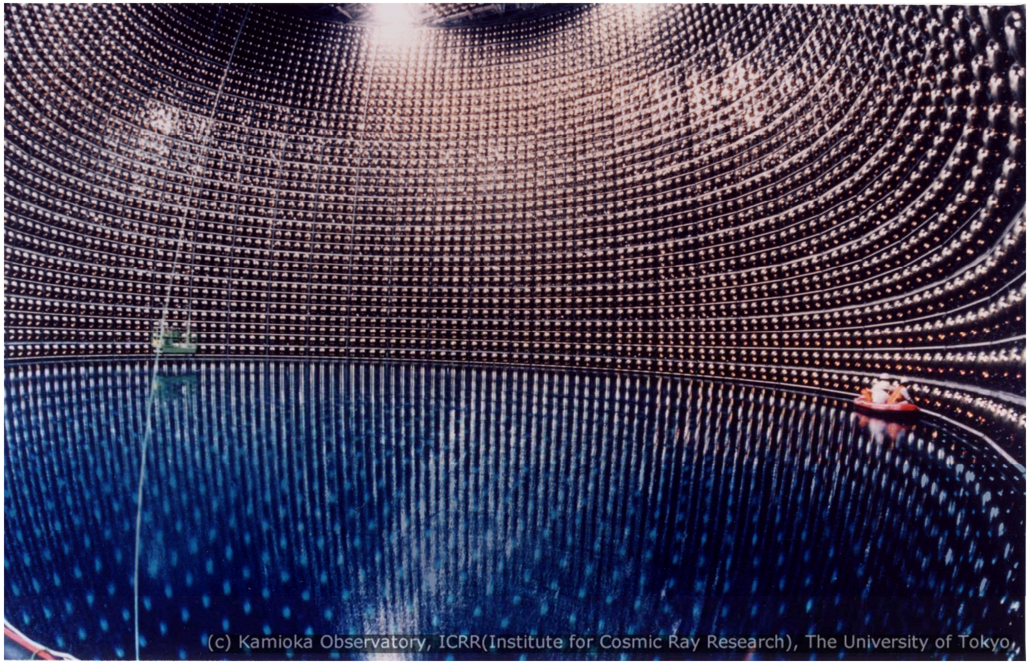
U.S. DEPARTMENT OF ENERGY

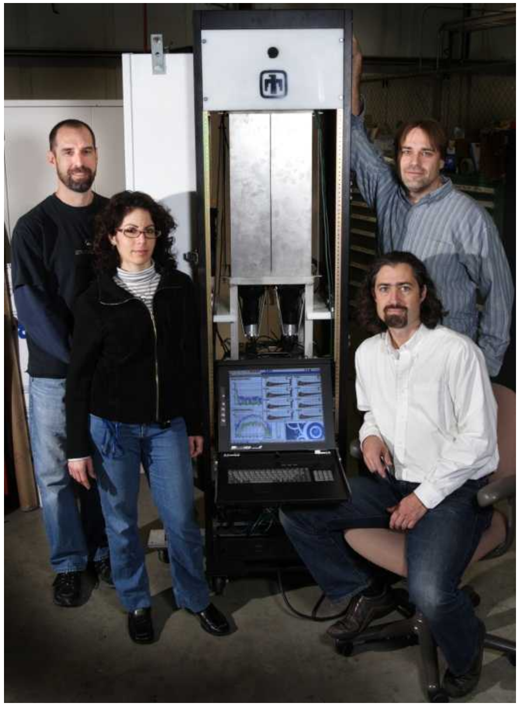
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

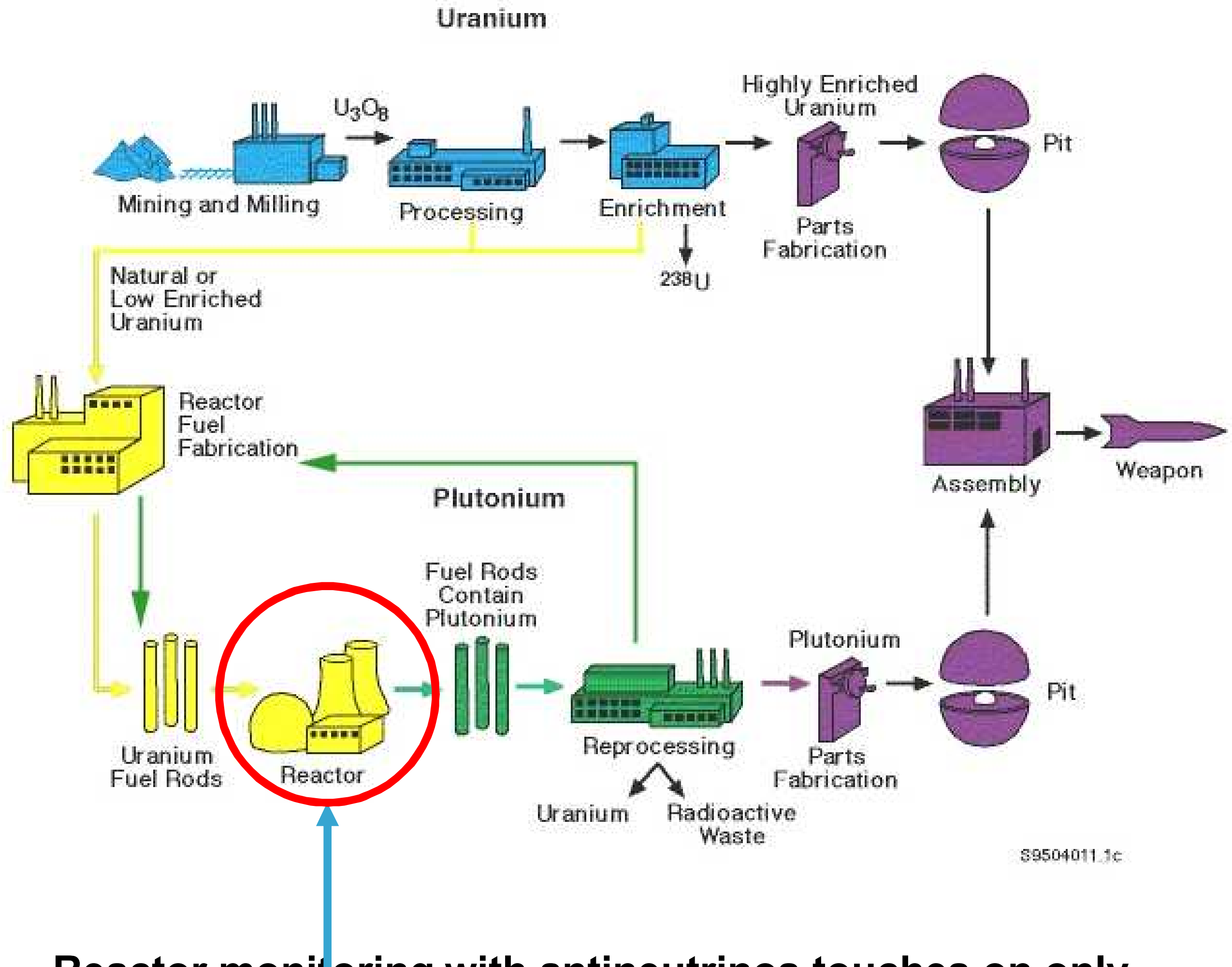
Technical talk outline

- Reactor safeguards
- First-generation instruments
- Current efforts
- Summary





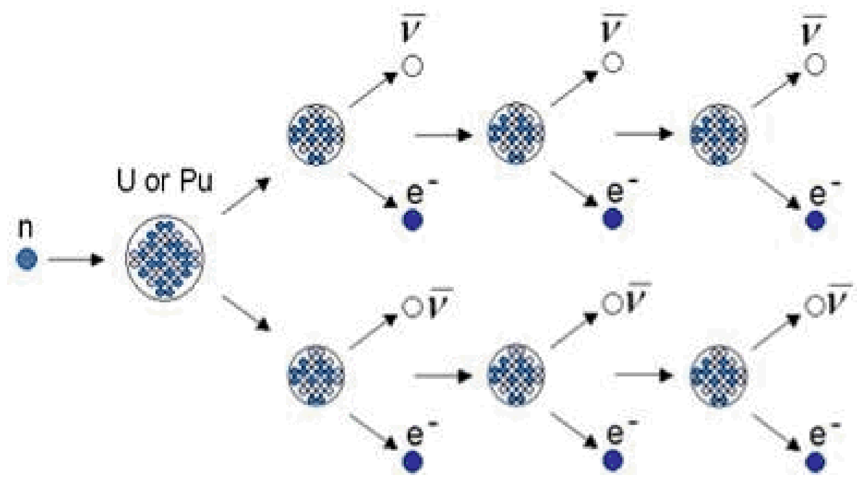
Antineutrino detectors address one part of the fuel cycle



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

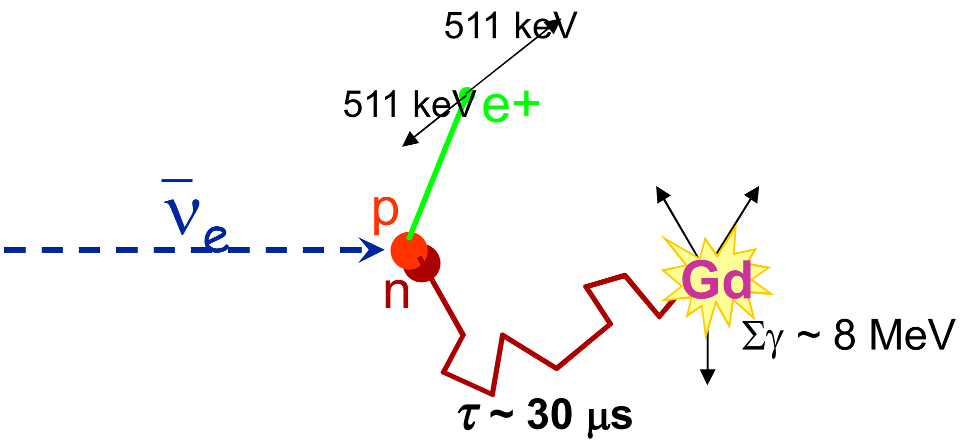
Using antineutrinos to monitor nuclear reactors

- Antineutrino production is roughly proportional to the reactor fission rate (power)
  - Some deviation due to U/Pu antineutrino emissions
  - Typical production rate for a 3000 MWt reactor: ~10^{22}/sec
- Antineutrinos cannot be shielded
  - Plant staff cannot mask operations
- Antineutrino detection rate is sensitive to the fuel composition
  - Can we estimate the fissile inventory of a reactor?



Detecting antineutrinos: the standard method

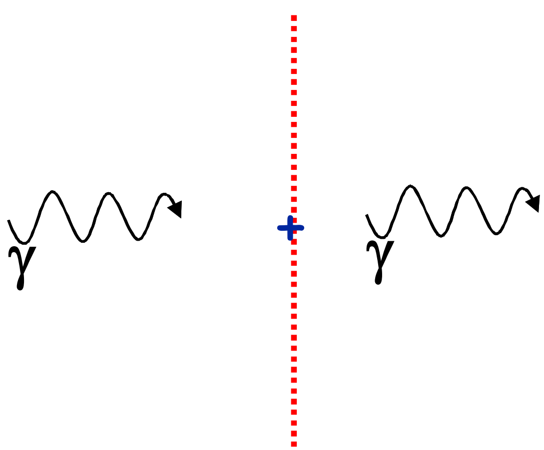
- Inverse beta decay
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
- Need a hydrogenous target
- Cross-section: ~10^{-20} b
- Energies of reaction
  - Positron: 1-8 MeV
  - Neutron energy: many keV
- Two reaction products is advantageous
  - Positron interacts immediately
  - Neutron diffuses and captures (usually 10s of μs later)
  - Detecting two events is coincidence is a unique signature that provides large reductions in backgrounds

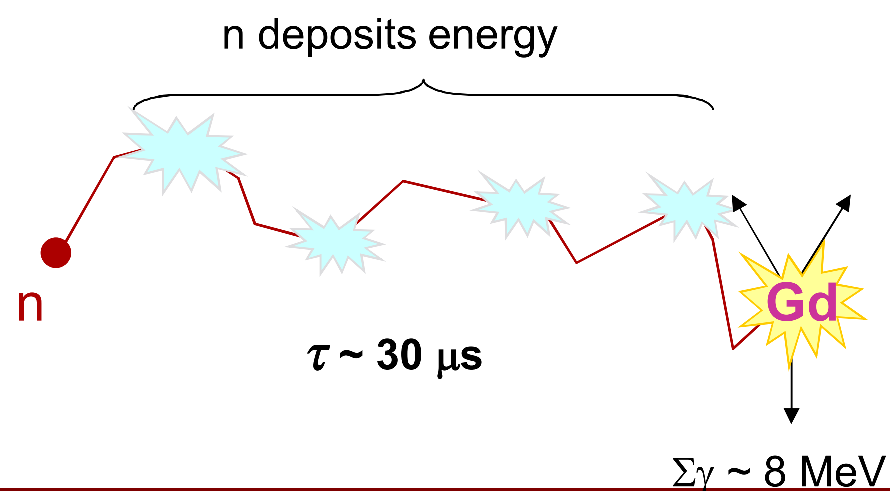


Backgrounds: important to consider during system design due to low signal-to-noise

- 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
  - Major source: 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



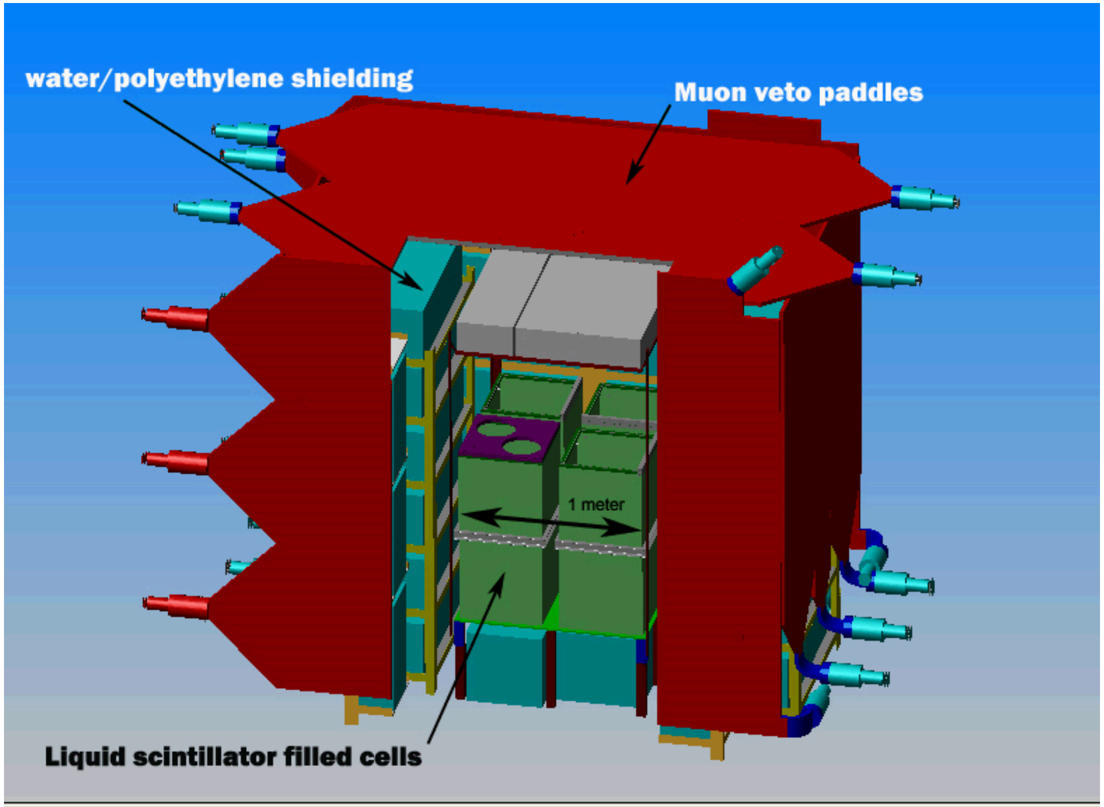


What does an ideal antineutrino detector look like?

- Automated and unattended
- Non-intrusive to reactor operations
- Simple
- Inexpensive
- Well known detection concepts/technology
  - High hydrogen density
    - Antineutrinos interact with hydrogen only
    - Need a lot of atoms due to small cross section
  - A high neutron capture efficiency & record of interaction
  - Decent timing (positron/neutron coincidence)
  - Particle (positron/neutron) identification capability
- Physically robust

The first generation detector: Sandia's SONGS1

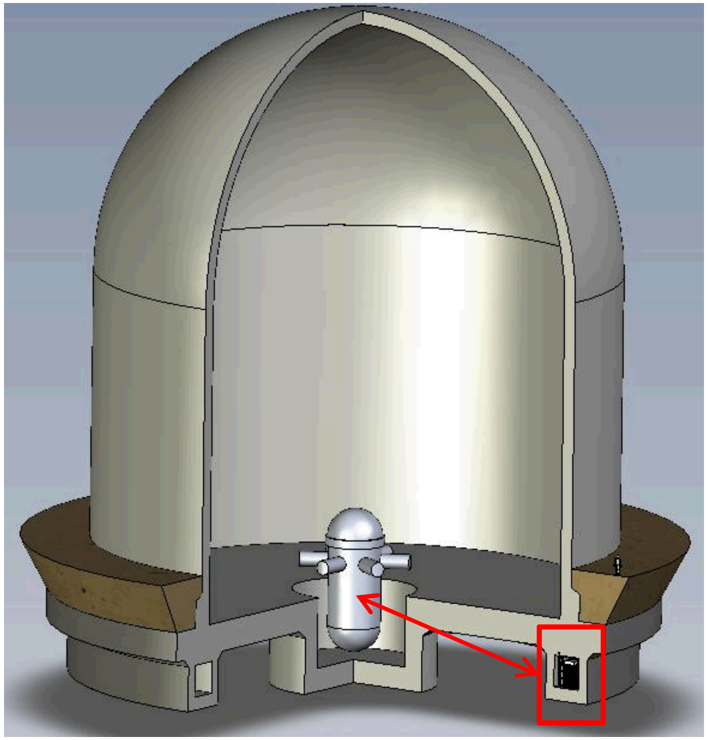
Sandia National Laboratories



- Detector system is
  - ~1 m^3 (0.64 ton)
  - 8 PMTs
  - 6-sided water shield
  - 5-sided active muon veto
- Liquid scintillator doped with Gd
- ~3500 interactions/day @ 25 m

Deploying the first detector at a nuclear power plant

- San Onofre Nuclear Generating Station (SONGS)
  - Tendon gallery
  - About 25 meters from core
  - Underground location shields from cosmic background



First result: reactor on/off using antineutrino rate

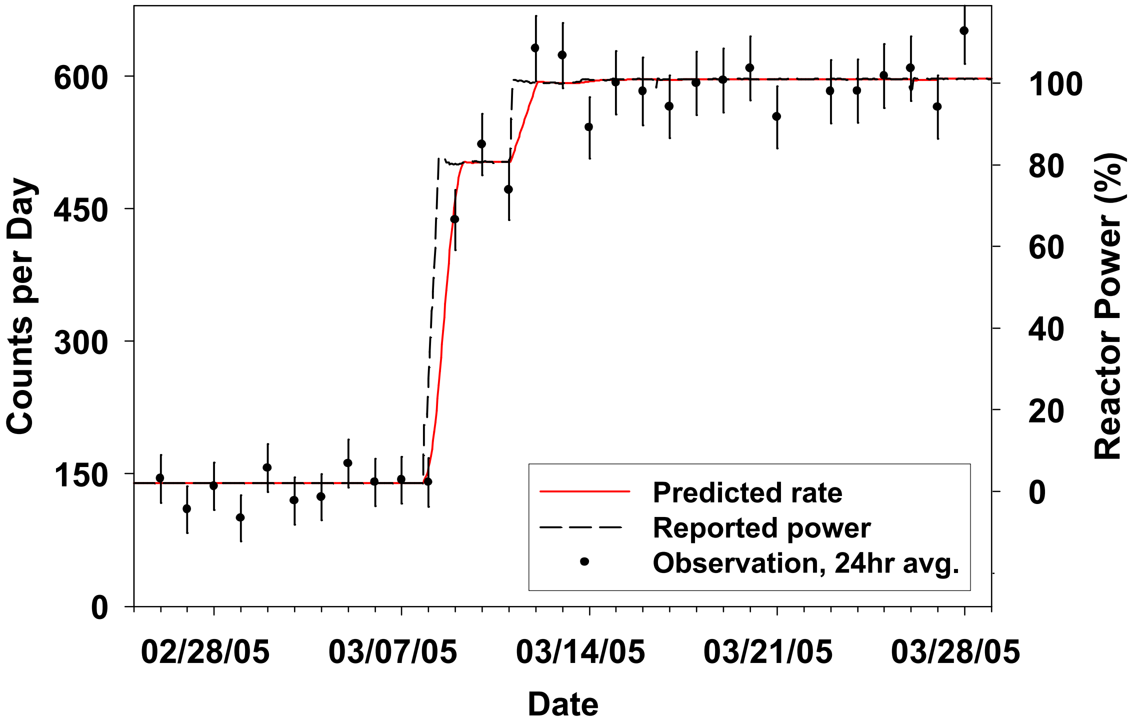
- Operate detector through transition between full power and shutdown for refueling
  - Can measure background rate and background+reactor rate

Timescale

1 – 3 Hours:
Sudden changes in operational status (on/off)

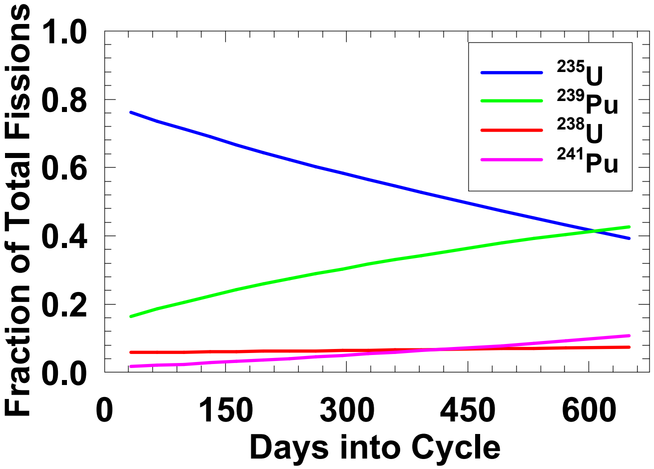
1 Day:
Large power changes

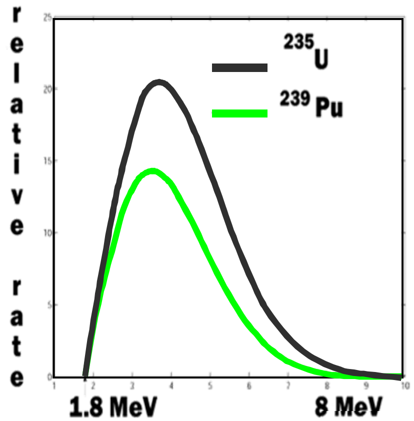
7 Days:
Relative thermal power measurement (2 – 3%)

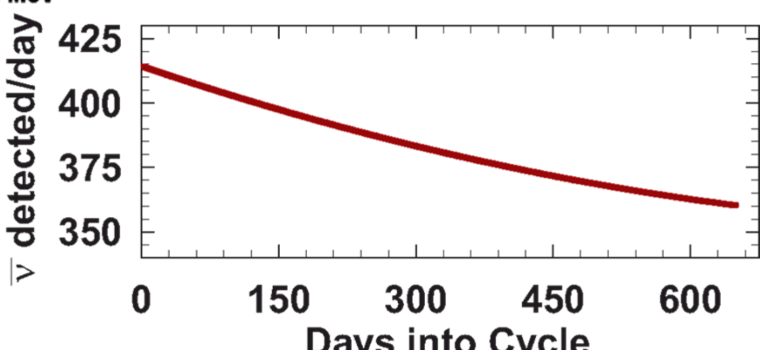


Fuel exposure (burnup) causes U/Pu inventory changes that modify antineutrino emissions

- Reactor fuel evolves during an operation cycle: ^{235}U is consumed and ^{239}Pu is produced
- The energy spectrum and integral rate produced by each fissioning isotope is different

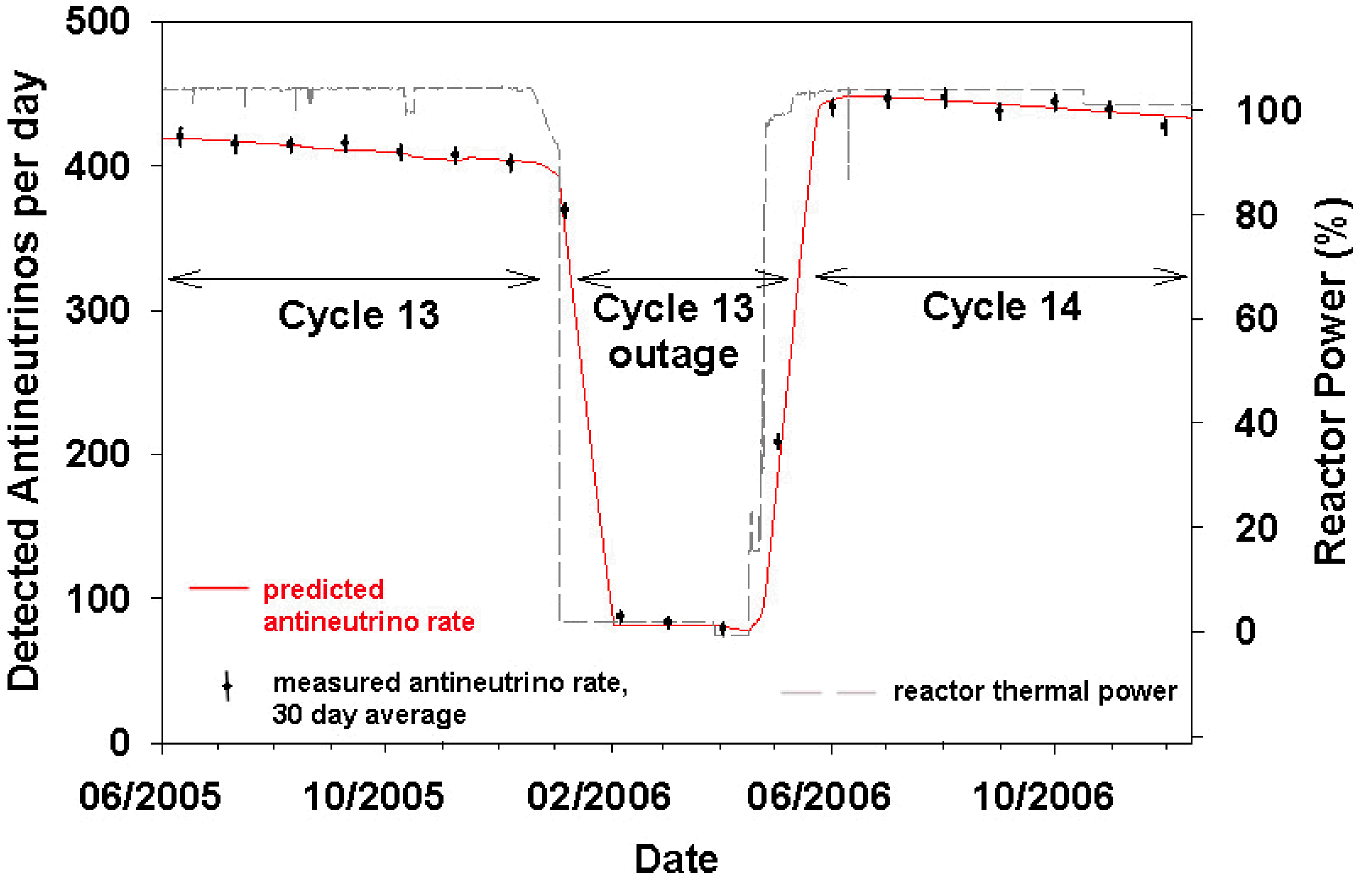






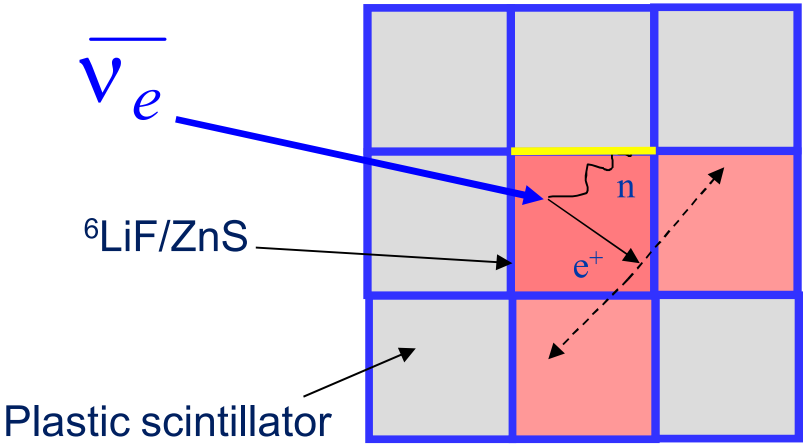
Fuel evolution measurements with SONGS1

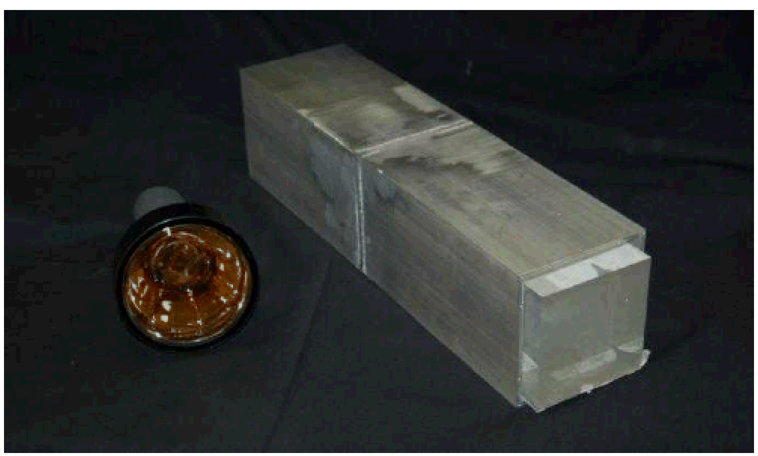
- **Refuel: replace 250 kg of ^{239}Pu with 1500 kg ^{235}U→12% change in detected antineutrino rate**

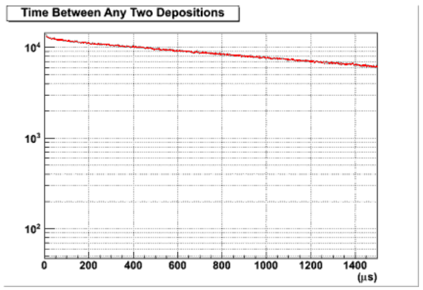


CURRENT EFFORTS

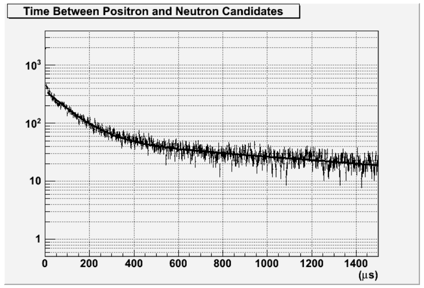
The segmented scintillator uses position and particle-discrimination cuts to manage signal-to-noise in aboveground locations



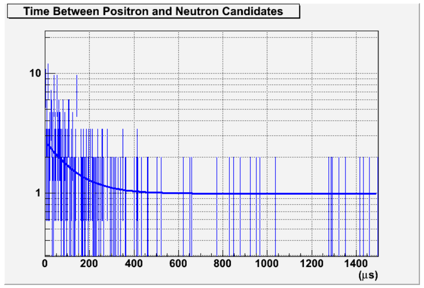




No PID
225,200 ev/day



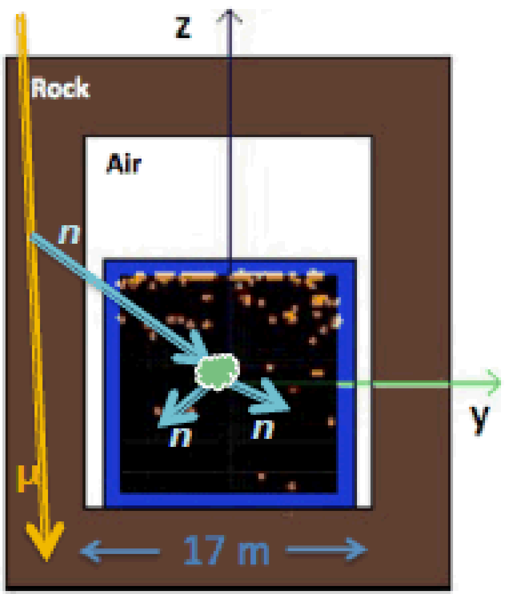
Only Neutron PID
1,830 ev/day

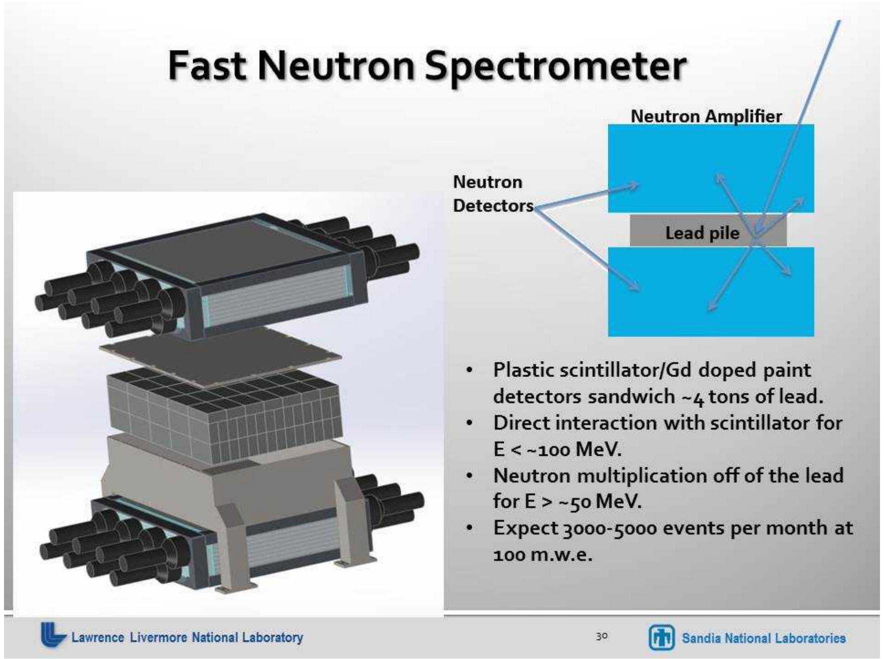


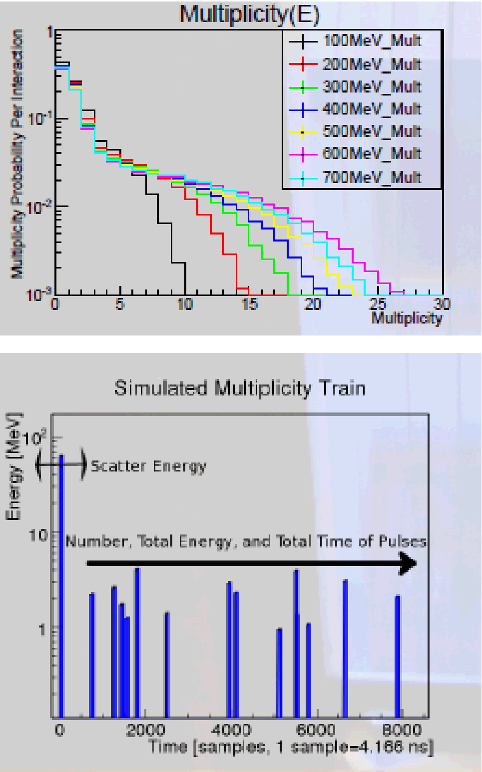
Max PID info
23 ev/day

Far-field antineutrino detection is accomplished using large water-based detectors

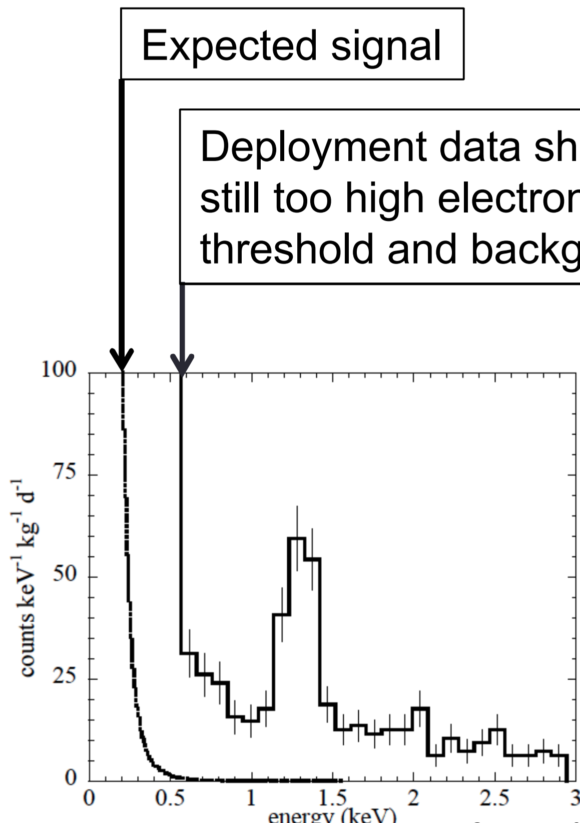
WATCHMAN: WATer CHerenkov Monitoring of Anti-Neutrinos
MARS: Multiplicity And Recoil Spectrometer
A collaboration led by LLNL



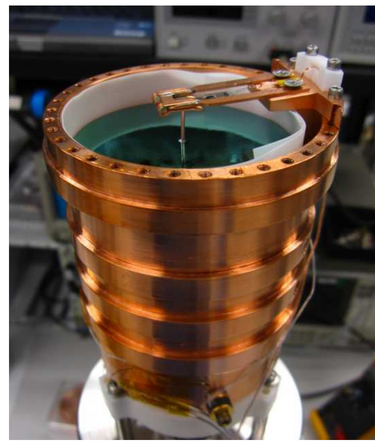


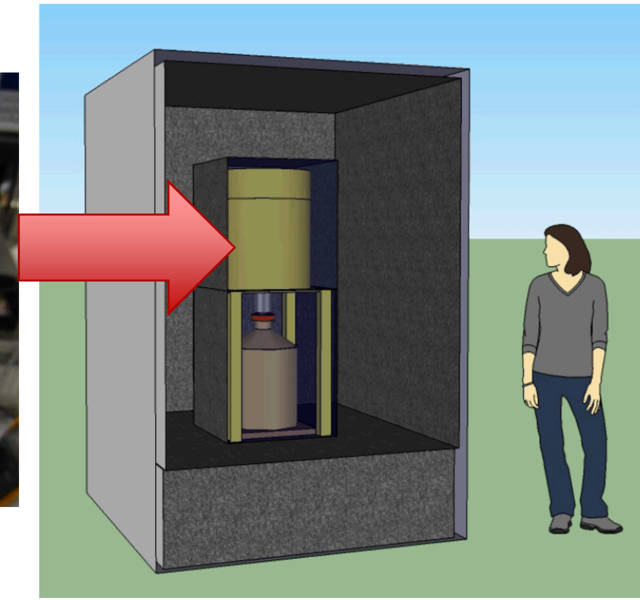


ULGeN: detecting antineutrinos using coherent scattering (with LBNL)



Courtesy of P. Barbeau





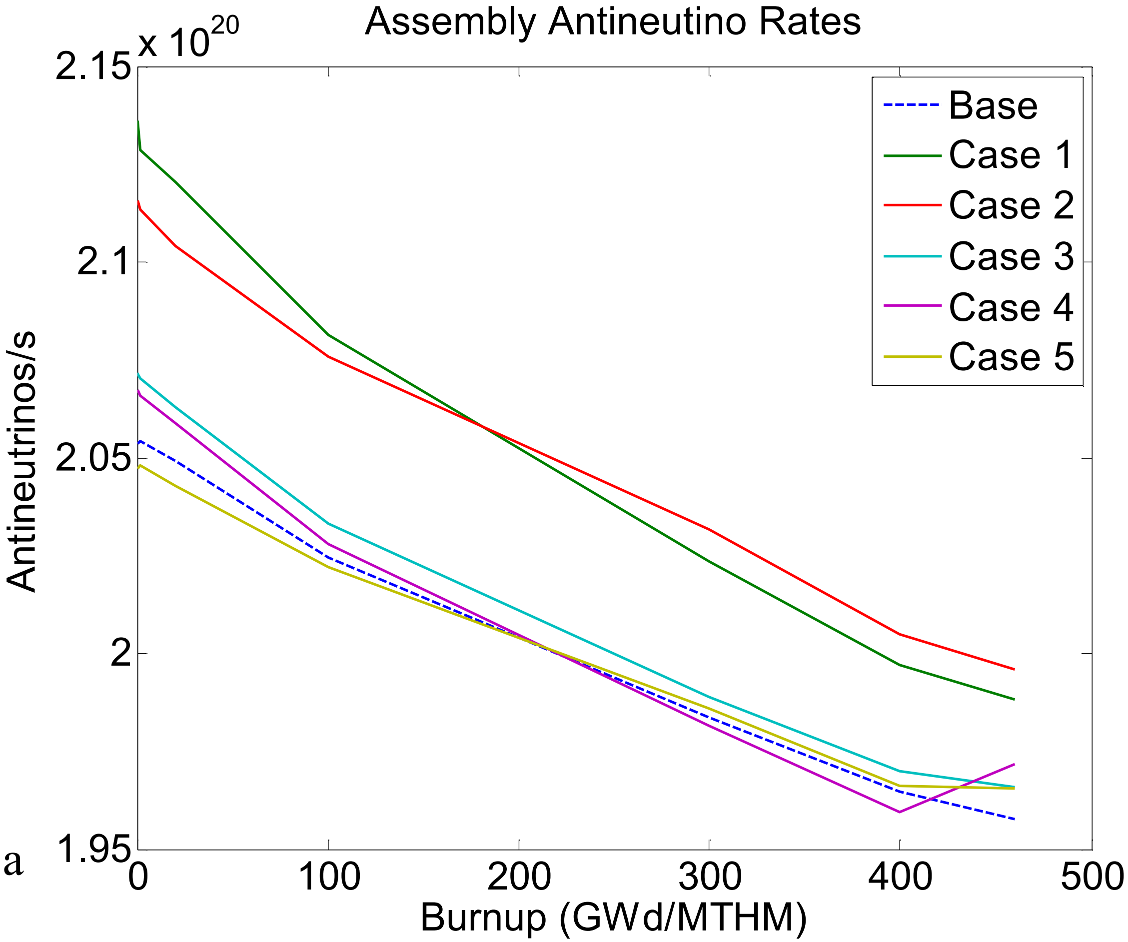
Reduce **background** to ~10 c $keV^{-1} kg^{-1} d^{-1}$

Lower **electronic threshold** to 100 eV

Safeguards study: effect of swapping fuel elements in core (T. Saller, NERS)

#	Case Description
1	Replace all WG-MOX 4.0% with fresh LEU 4.5%
2	Replace all fresh WG-MOX with fresh LEU 4.5%
3	Replace all fresh WG-MOX with fresh RG-MOX
4	Add in CR-B (towards periphery, 8 assemblies)
5	Add in CR-A (towards inside 4 assemblies)

Replacing a single fresh WG-MOX assembly with RG-MOX has between a 0.045% and 0.021% difference depending on the power at that location.



Summary: antineutrino safeguards and reactor monitoring

- Antineutrino 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
- Compact antineutrino detectors could provide continuous, non-intrusive, unattended measurements suitable for safeguards
- Current efforts focus on detectors that are more practical to field (smaller, greater standoff distance, aboveground) than first-generation detection systems