SAND2010-7512P

Antineutrinos for nuclear reactor monitoring: current efforts in the Livermore Valley

Scott Kiff, Sandia National Laboratories

October 27, 2010

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Sandia National Laboratories

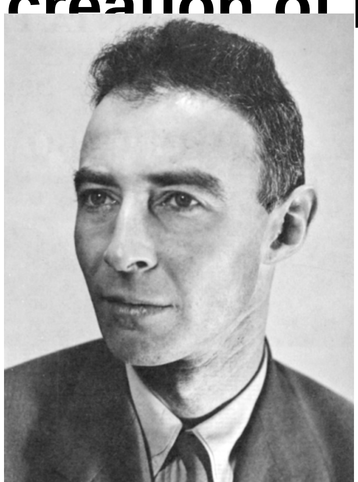
- **Multifaceted laboratory**
  - **Nuclear Weapons**
    - **Safe, secure, reliable stockpile**
  - **Energy and infrastructure**
    - **Clean, abundant, and affordable energy and water**
  - **Nonproliferation**
    - **Reduce WMD proliferation and threat of accidents**
  - **Homeland security**
  - **Defense systems**
    - **Maintain US military technical superiority**
  - **Science, technology, and engineering**

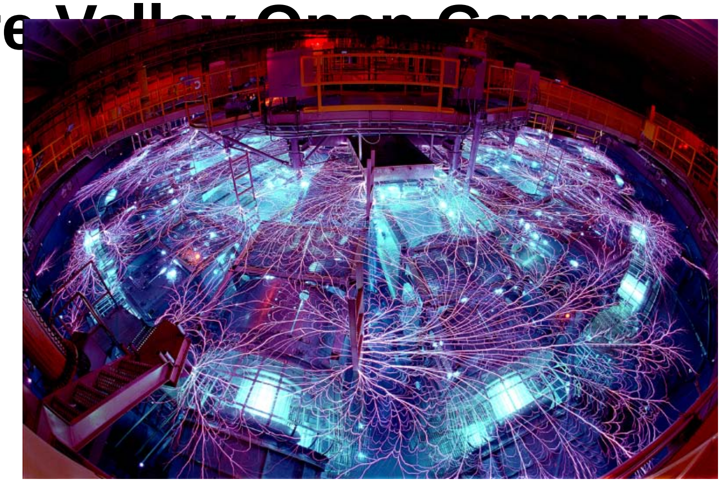
- **~8500 full-time staff**
  - **7500 Albuquerque**
  - **1000 Livermore**

Work/life balance: eye candy

From Z (division) to Z (machine)

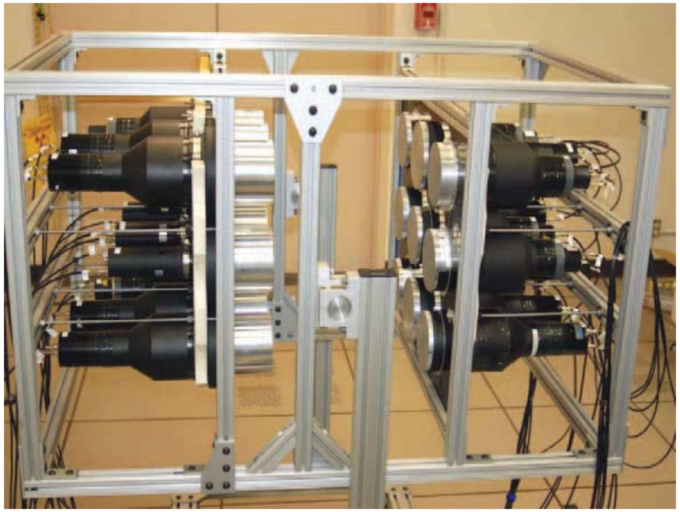
- 1945: Los Alamos Z Division moves to Albuquerque
- 1949: Sandia (Albuquerque) founded to turn physics packages into deployable weapons
- 1956: Livermore site opened
- 1974: technical advisor for WIPP
- 1997: started Z-pinch research for basic science and stockpile stewardship
- 2010: creation of Livermore Valley Open Campus





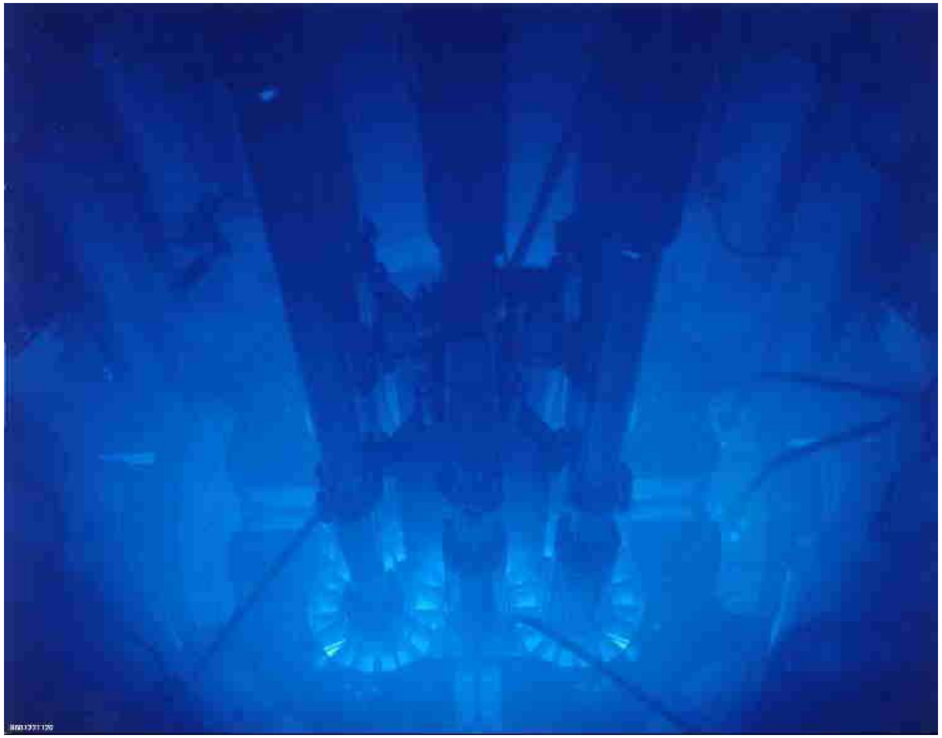
Projects in Rad/Nuc Detection Systems

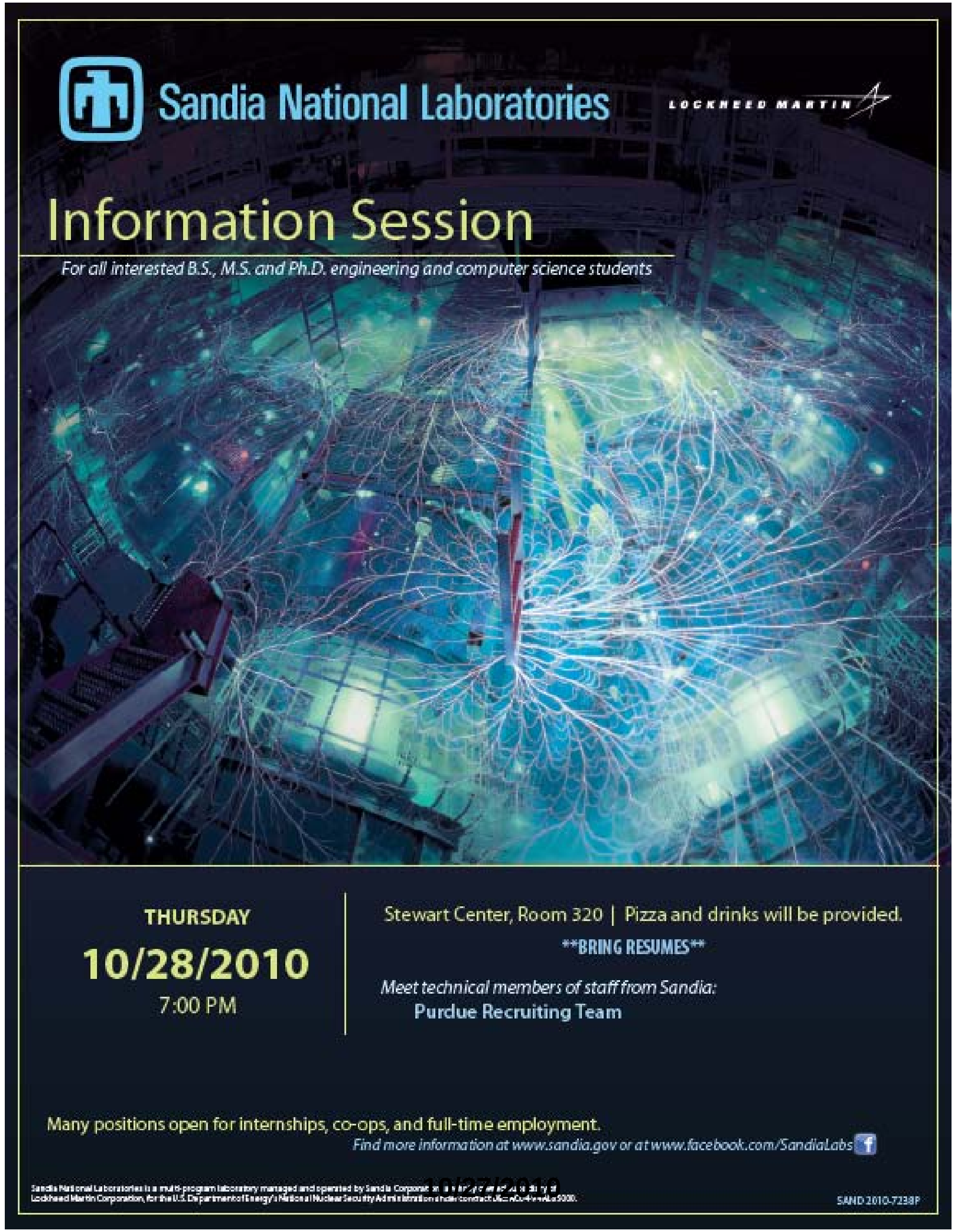
- **Neutron imaging systems**
  - **Neutron Scatter Camera**
  - **Coded Aperture**
- **Antineutrino detection systems**
- **And more…**



Some Sandia Opportunities for Nuclear Engineers

- **Pulsed power**
- **Nonproliferation**
- **Advanced fuel cycles**
- **Materials development**
- **Homeland security**
- **Waste transport/storage**

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THURSDAY
10/28/2010
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Stewart Center, Room 320 | Pizza and drinks will be provided.
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Project Team/Collaborators

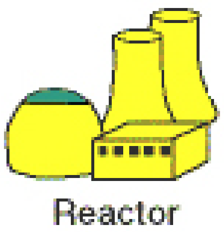
- **Sandia National Laboratories**
  - David Reyna (co-PI)
  - Belkis Cabrera-Palmer
  - Jim Lund
- **Lawrence Livermore National Laboratory**
  - Adam Bernstein (co-PI)
  - Nathaniel Bowden
  - Steven Dazeley
  - Greg Keefer
- **University of Chicago**
- **Oregon State University**
- **UC Davis**
- **Louisiana State University**

Technical talk outline

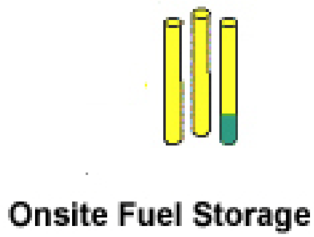
- Reactor safeguards
- First-generation instruments
- IAEA support
- Second-generation instruments
- Future possibilities
- Summary

Nuclear safeguards considerations

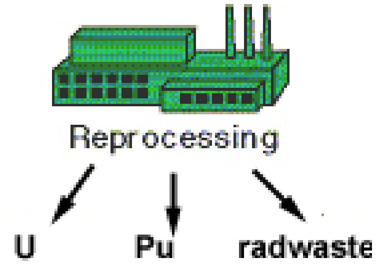
(1-1.5 years)



(months to years)



(months)



(forever)

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

1 'Gross Defect' Detection

2 Item Accountancy

3. Containment and Surveillance

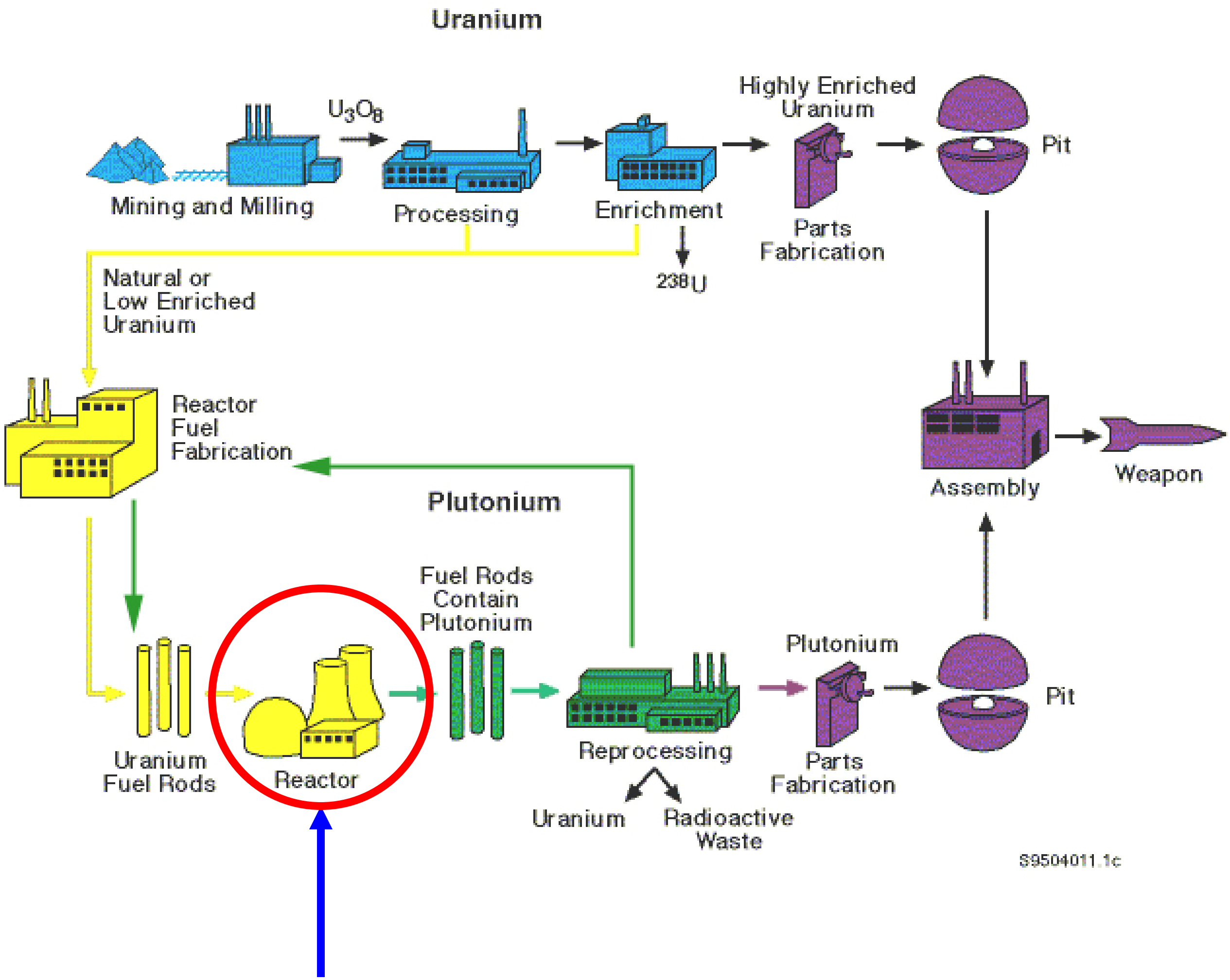
1 Check Declarations

2 Verify with **Bulk Accountancy**:

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

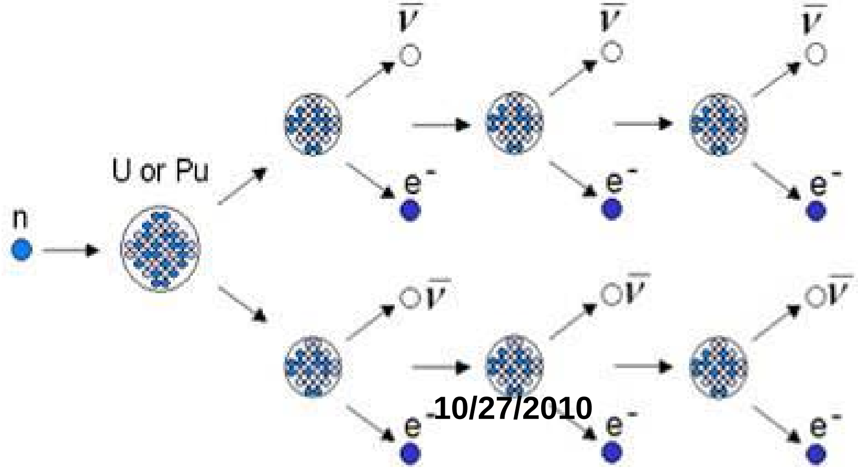
Antineutrino Safeguards and Monitoring

- 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

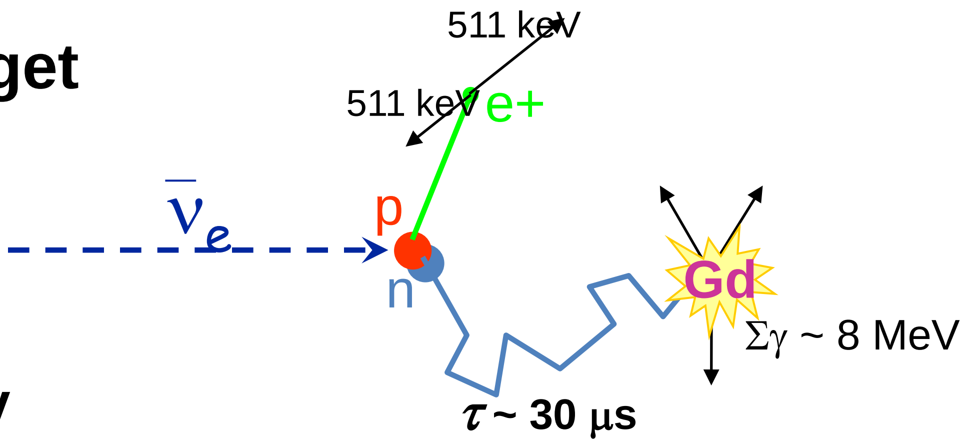
Using antineutrinos to monitor nuclear reactors

- **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**

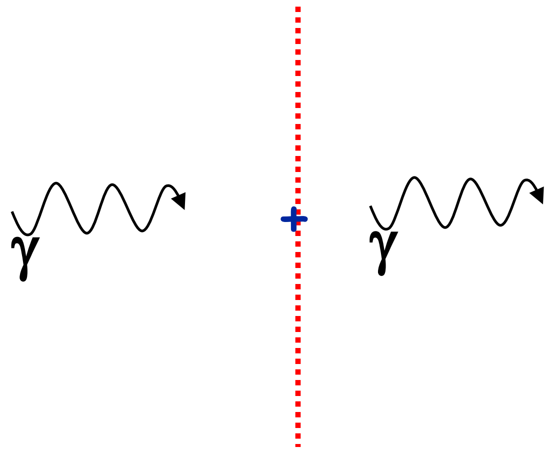


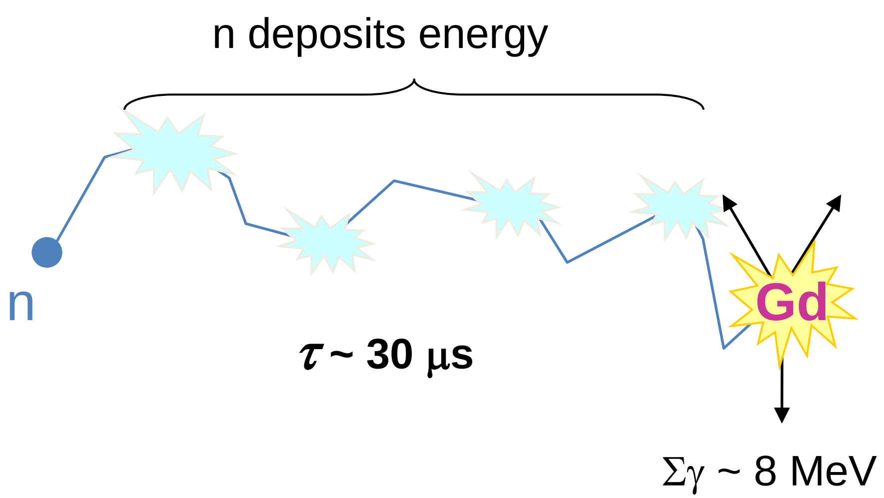
- **Two reaction products is advantageous**
  - **Positron interacts immediately**
  - **Neutron diffuses and captures (usually 10s of μs later)**
  - **Detecting two events is coincidence is a unique signature that provides large reductions in backgrounds**

Backgrounds come in two flavors

- 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**





Deployment Goals and Design Principles

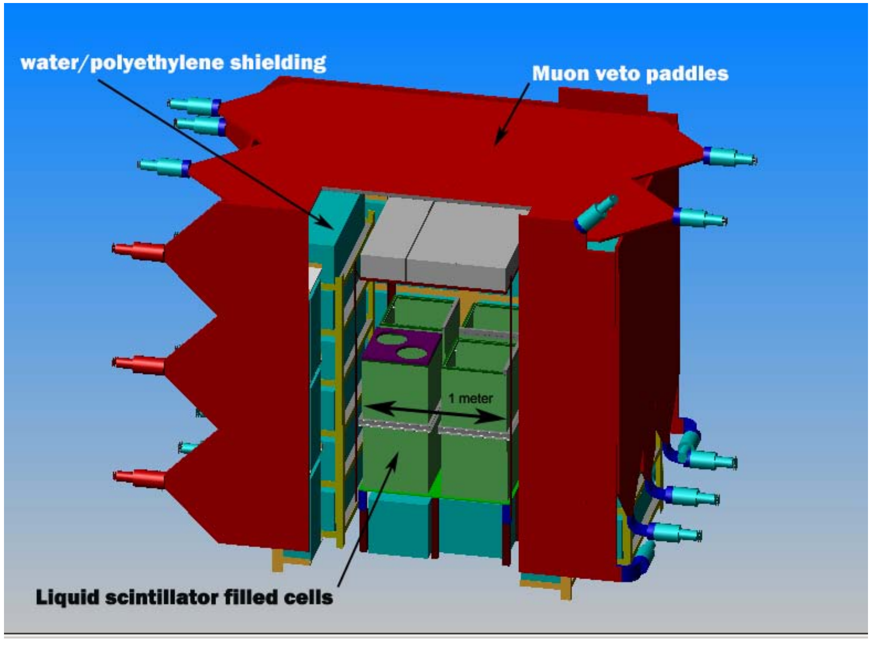
- **Demonstrate a reactor monitoring system with the following properties:**
  - **Automated and Unattended**
  - **Non-intrusive to reactor operations**
  - **Simple (~ 3 people vs. 10-100 for physics expt.)**
  - **Inexpensive (< 10 PMTs vs. 100-1000 for physics expt.)**
  - **Well known detection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

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

What does an ideal antineutrino detector look like?

- **High hydrogen density**
  - **Antineutrinos interact with hydrogen only**
  - **Need a lot of atoms due to small cross section**
  - **Plastic, organic liquids**
- **A high neutron capture efficiency & record of interaction**
  - **Gd: high cross section, big gamma burst to mark event; can be used as a scintillator dopant**
  - **Li: good cross section; deposits energy locally via heavy charged particles; can be found in common scintillators**
- **Timing to resolve positron and neutron**
- **Pulse shape discrimination—more to follow**
- **Good energy resolution—this is generally incompatible with organic scintillator requirement**

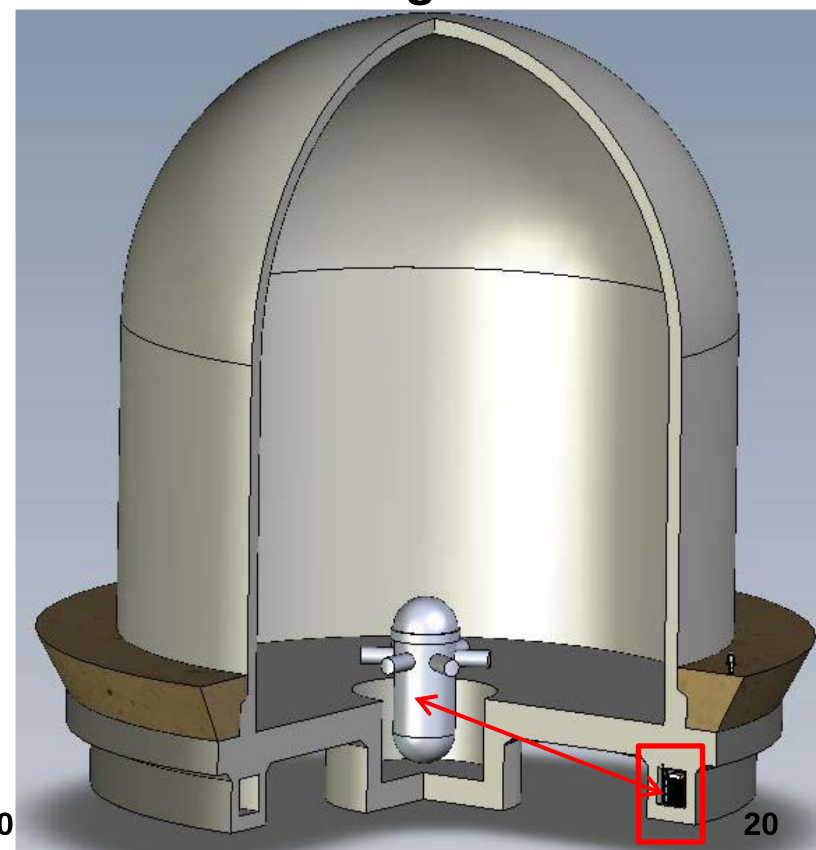
The first Livermore detector: Sandia's SONGS1



- 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
  - Could use capture on H (releases 2.2 MeV gamma)
  - Problem #1: 2.2 MeV is lower than prominent 2.6 MeV gamma background
  - Problem #2: H capture cross section is fairly low, so neutrons have a high probability of escape before capture

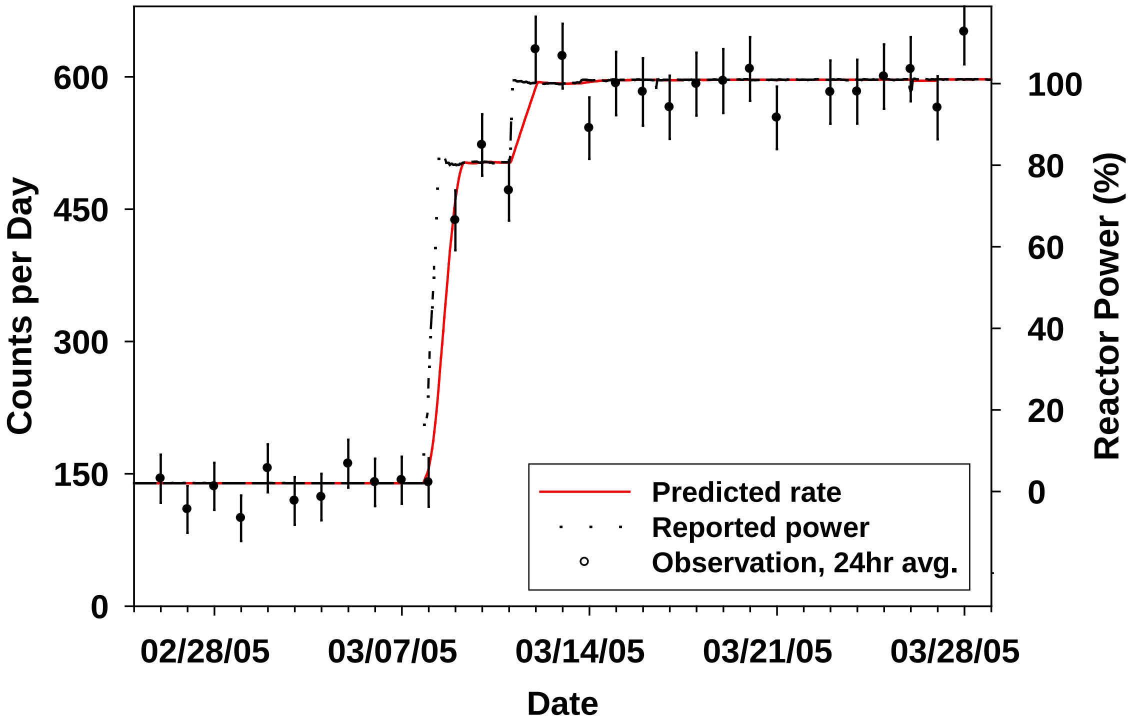
Deploying the first detector at a nuclear power plant

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

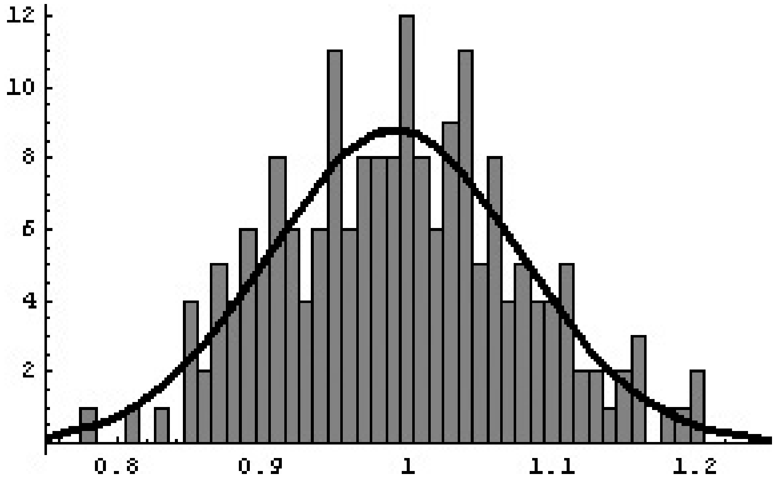


First result: reactor on/off using antineutrino rate

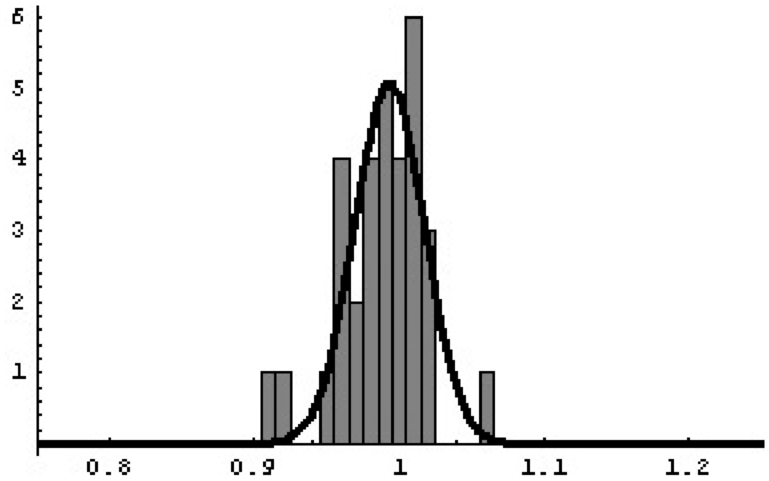
- **Operate detector through transition between full power and shutdown for refueling**
  - **Can measure background rate and background+reactor rate**
- **Large reactor power changes can be observed using only antineutrinos**



Relative Power measured using only antineutrinos



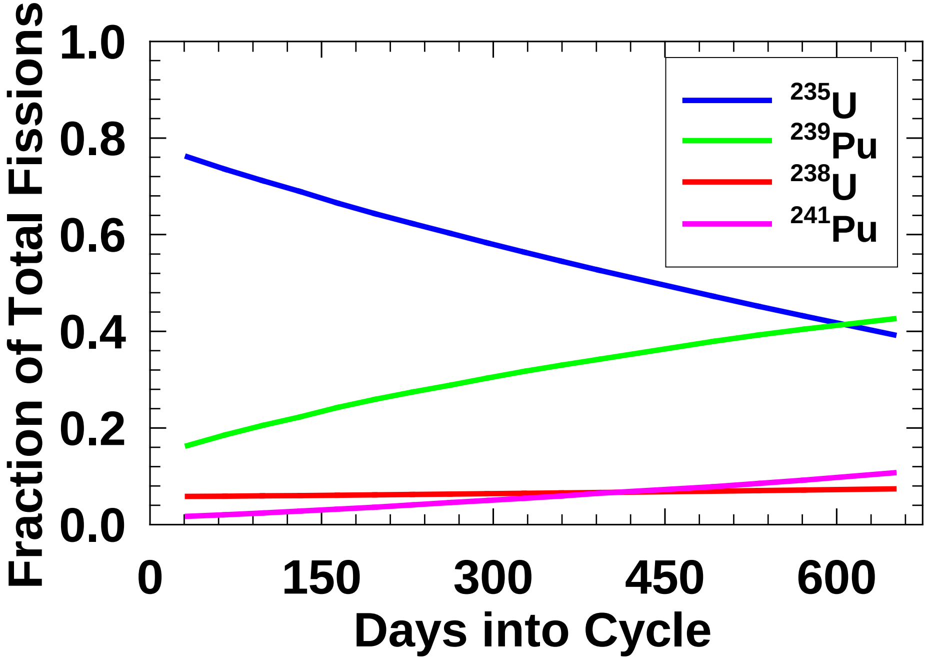
Daily average
8 % relative uncertainty
in thermal power estimate
(normalized to 30 day avg.)

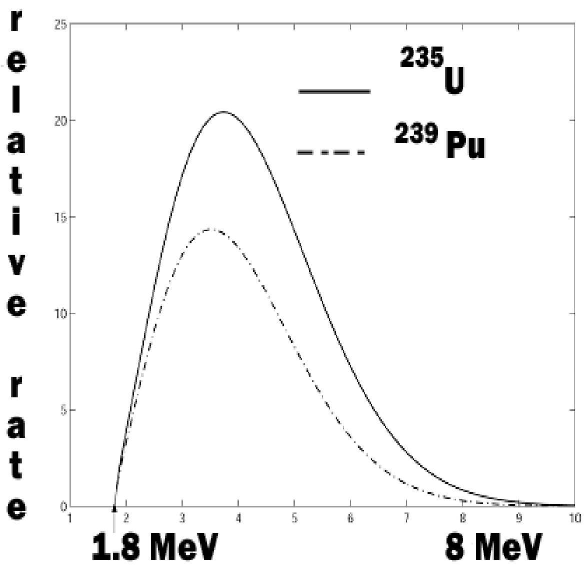


Weekly average
3% relative uncertainty
in thermal power estimate
(normalized to 30 day avg.)

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

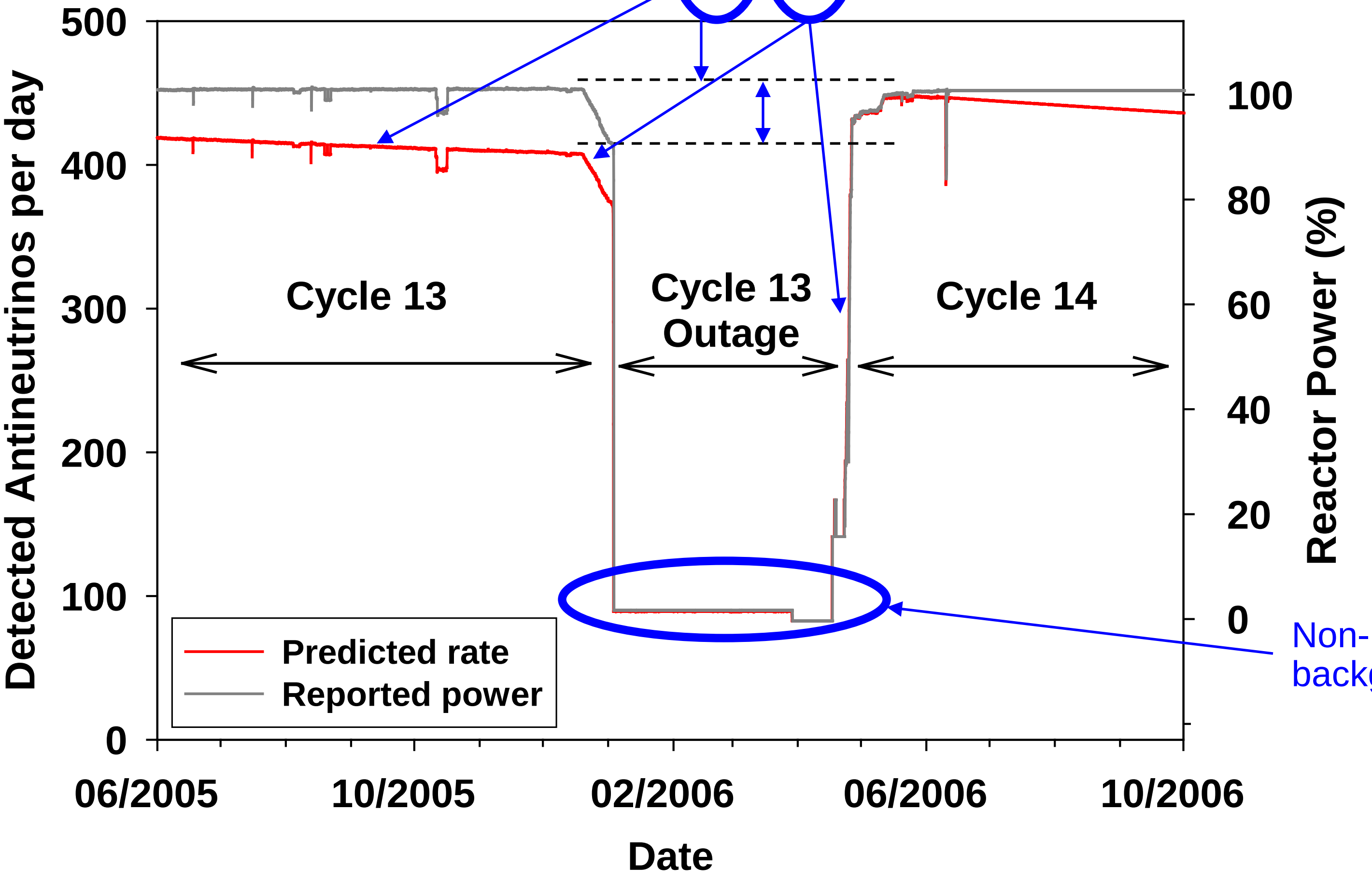




Predictions for our Dataset

Detector and reactor constants

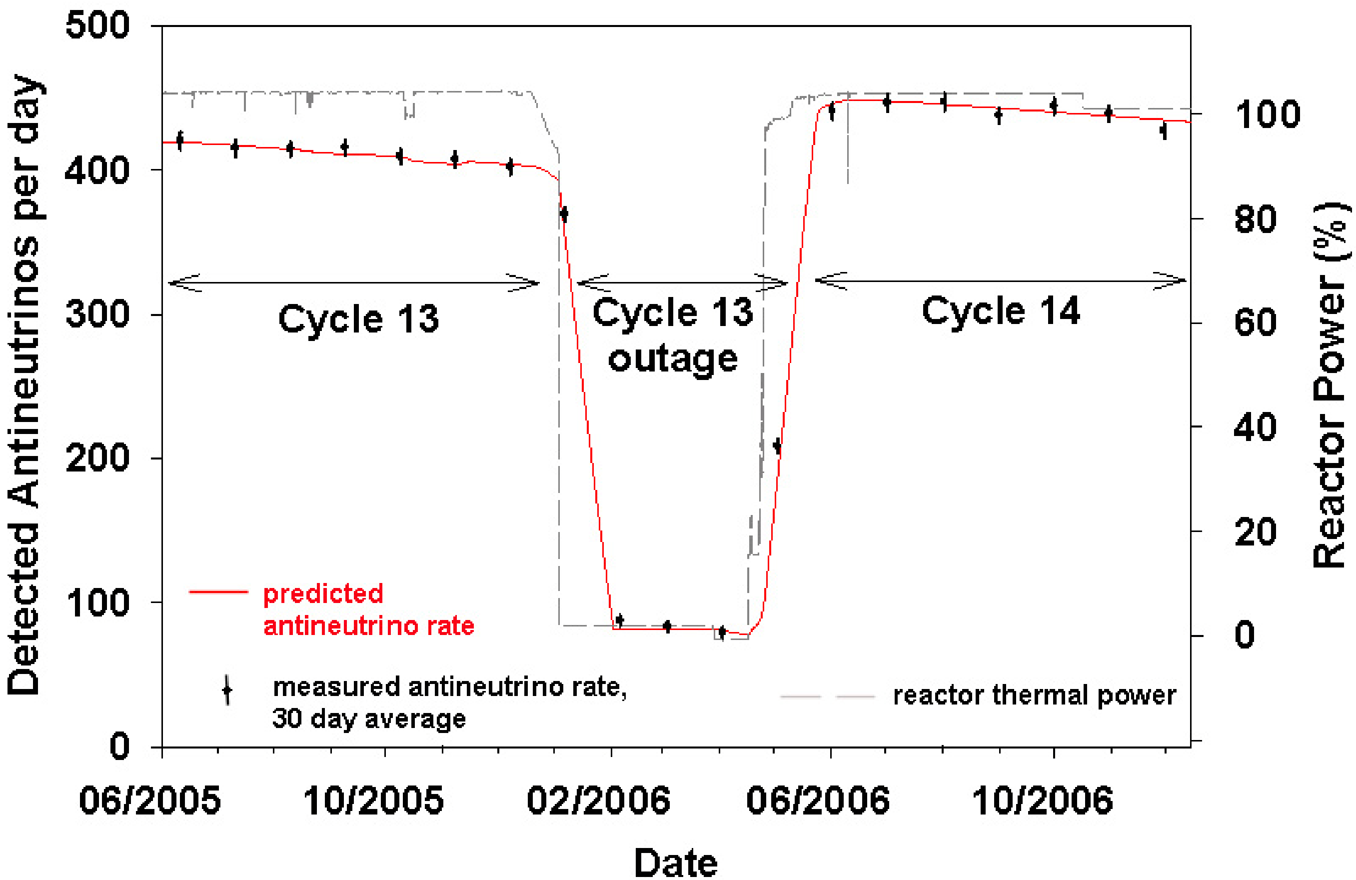
$$N_{\bar{\nu}} = \gamma(1+k)P_{th}$$



Non-neutrino background

Fuel evolution measurements with SONGS1

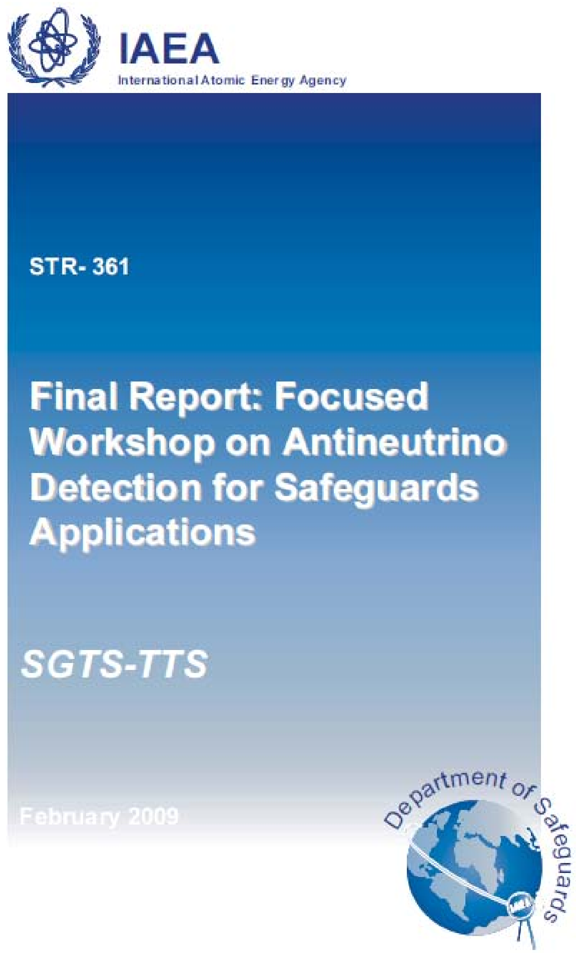
- **Refuel: replace 250 kg of ^{239}Pu with 1500 kg $^{235}U \rightarrow$ 12% change in detected antineutrino rate**



Aboveground placement of antineutrino detectors

- SONGS1 showed great promise as a potential reactor monitoring tool
  - 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
- Below-grade location is great because:
  - Shielding from cosmic rays
  - Does not interfere with daily plant operations
  - Close to reactor core
- Below-grade location is not great because:
  - Access is difficult
  - Not every power plant has a location as suitable as the tendon gallery
- Aboveground detectors must be developed for a viable safeguards instrument

Project motivation: IAEA recommendations



7 Future Developments for Incorporation of Antineutrino Detection Technology into Safeguards

This report illustrates the rapid development in the last five years of antineutrino detectors for the monitoring of reactors for safeguards purposes. The technology has reached a level of maturity where integration in the safeguards regime can be realistically envisaged.

7.2 Medium Term:

If the above near-term goals are met, it is the opinion of the workshop conferees that antineutrino detectors will have demonstrated utility in response to the stated inspector needs in some specific areas of reactor safeguards. To further expand the utility of antineutrino detectors, several useful medium term (5-8 year timeframe) R&D and safeguards analysis goals are proposed.

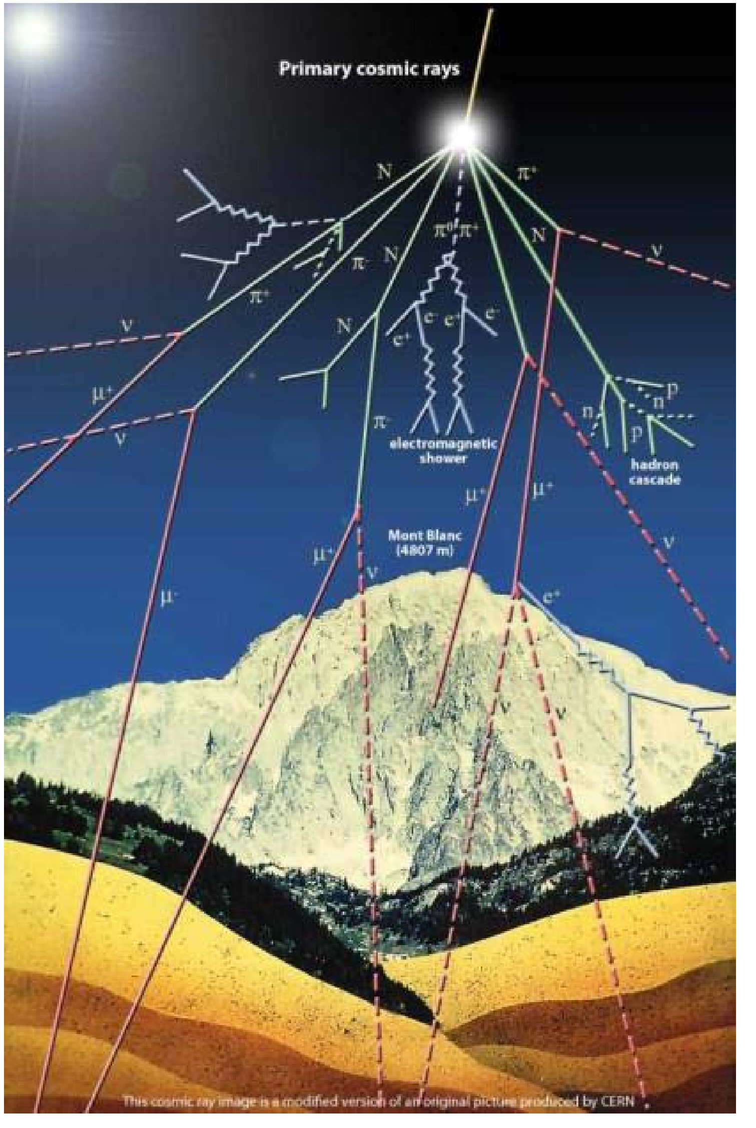
1. Above ground deployment. Above ground deployment will enable a wider set of operational concepts for IAEA and reactor operators, and will likely expand the base of reactors to which this technology can be applied;
2. Provide fully independent measurements of fissile content, through the use of spectral information. This will allow the IAEA to fully confirm declarations with little or no input from reactor operators, purely by analysis of the antineutrino signal;
3. Develop improved shielding and reduced detector footprint designs, to allow for more convenient deployment. Current footprints are of order 2-3 meters on each side; modest reductions in footprint would expand the general utility of antineutrino detectors. In this regard, a possible deployment scenario is envisaged where the component parts of the detector, shielding and all associated electronics are contained within a standard 12 metre ISO container, facilitating ease of movement and providing physical protection to the instrument. It should be noted that due to size and weight restrictions of ISO containers (approximately 25,000 kg net load) the

So, we have two current projects to explore viability of aboveground placement

- **Water Cerenkov detector**
  - A big tank with 1 ton of water
  - Insensitive to high-energy neutron scatters
  - Doped with Gd for collection of inverse beta decay neutrons
- **Segmented (advanced) scintillator detector**
  - Explore new dopants (Gd replacements)
  - Segmenting has advantages for event acceptance/rejection
- **Both detectors require a substantial shield from cosmogenic neutrons and muons**

Our primary aboveground challenge: increased backgrounds

- **Without overburden, an aboveground detector is exposed to:**
  - **An increased muon rate**
  - **Hadronic component**
  - **Electromagnetic component**
  - **Secondaries produced by all of the above, in the detector and its surroundings**

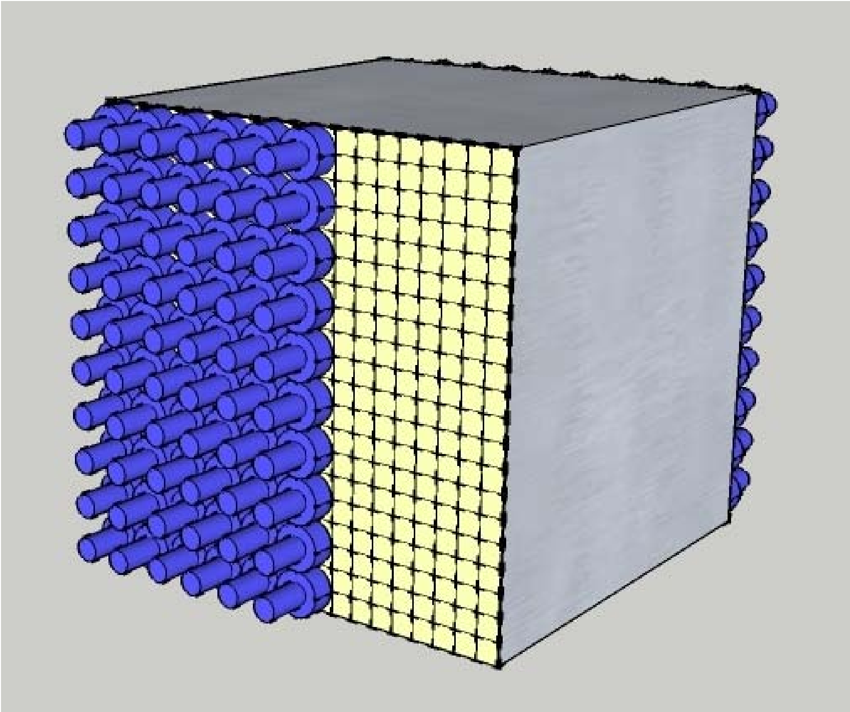


Segmented scintillator design ideas

- **Explore neutron capture agents**
  - Gd is a great capture agent, but high-energy gammas escape detector without detection (lower efficiency)
  - Gd capture products (gammas) do not leave behind a unique signature (i.e., all gammas look the same to the organic scintillator)
- **Explore segmentation benefits**
  - Instead of one or a few big detection elements, how about many smaller segments?
  - Event topology may be used to define events (positron annihilation photons) or reject background (spatial distribution isn't what we expect to see in a true event)
- **Consider pulse shape discrimination**

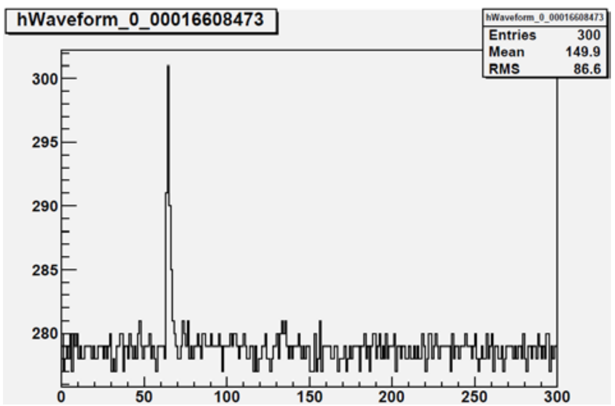
The segmented scintillator array

- **~1 m^3 of organic scintillator**
  - **Antineutrino target**
- **Interleave neutron capture agent**
- **Double-ended PMT readout for better light collection**

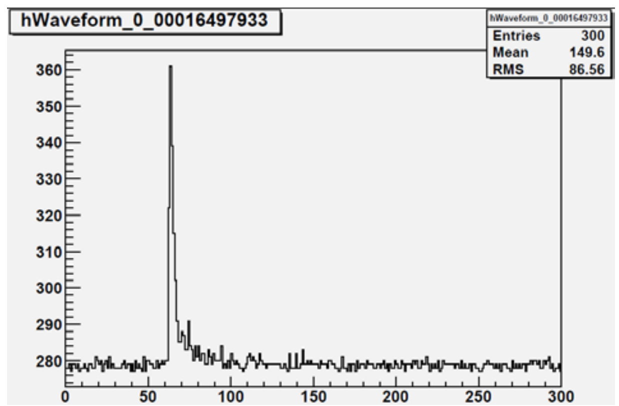


Pulse shape discrimination (finally!)

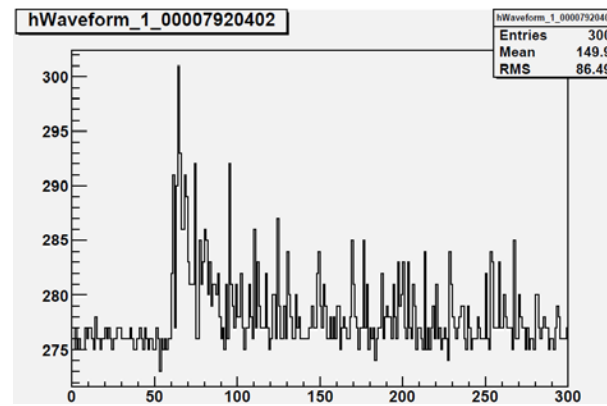
- It is possible for scintillation light to be emitted with different time profiles
  - Different particles, same scintillator
  - Different scintillators with distinct scintillation characteristics
- These differences in time profiles tell us whether:
  - The interaction was due to particle type A or B (electromagnetic or fast neutron scatters in liquid scintillator)
  - The interaction was in scintillation material C or D



Gamma ray, liquid scintillator



Neutron scatter, liquid scintillator



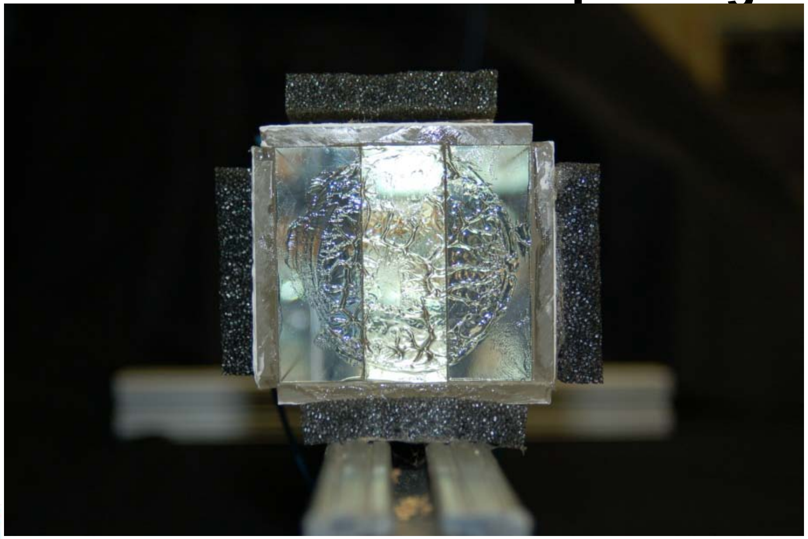
Neutron capture, ZnS/LiF

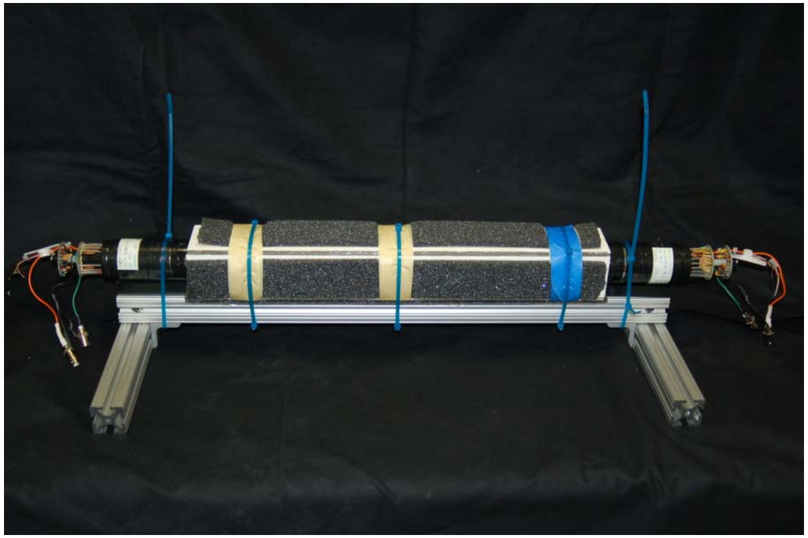
Neutron capture agents: ZnS(Ag)/LiF

- ZnS(Ag) is one of the oldest scintillators (Rutherford's backscatter experiments)
- When doped with LiF (enriched in ^{6}Li), there is now a high neutron capture cross section
  - Creates two charged particles (α and t) that interact locally in ZnS matrix
- ZnS scintillates with a very long time constant
  - ~200 ns vs. a few ns in the organics
  - Pulse shape discrimination is very easy now
  - Can uniquely identify neutron capture events

Incorporating ZnS(Ag)/LiF

- Since ZnS(Ag) is opaque to its own light, must use thin layers
- Purchased ZnS(Ag)/LiF in different atom ratios and material thicknesses
- Optically mated to an organic scintillator base material
  - Liquid scintillator: placed inserts along walls of a container
  - Plastic scintillator: optical grease

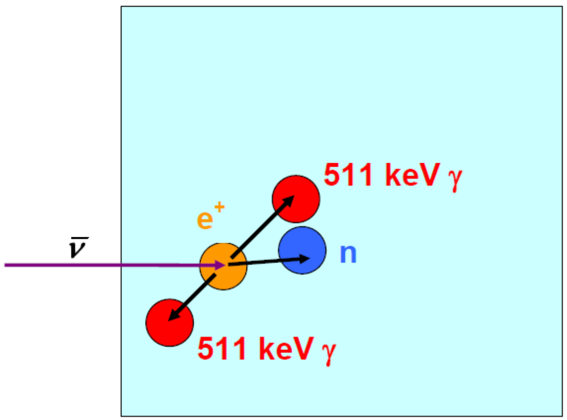




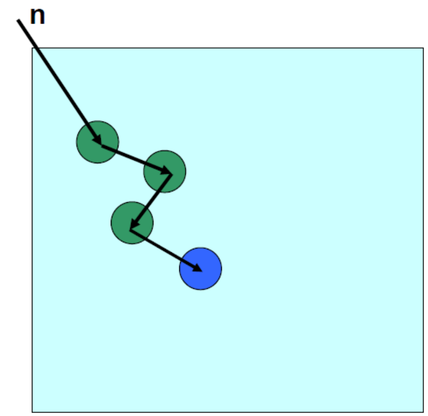
Segmentation benefits and challenges

- **Benefits:**
  - **Spatial cuts to identify positrons or reject backgrounds**
  - **Allows layering of ZnS(Ag)/LiF to increase neutron capture efficiency**
- **Challenges:**
  - **High segmentation is expensive (added PMTs, data channels)**
  - **High segmentation adds a lot of complexity (calibrating each channel, data analysis)**
  - **High segmentation tends to make optical transport more challenging (more optical interfaces/bounces to collect light)**

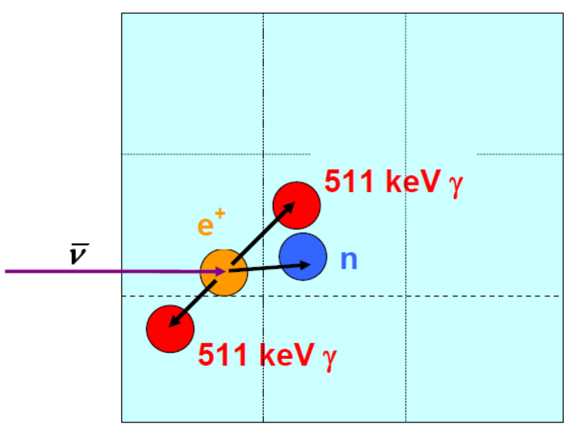
Segmentation concept: positron ID example



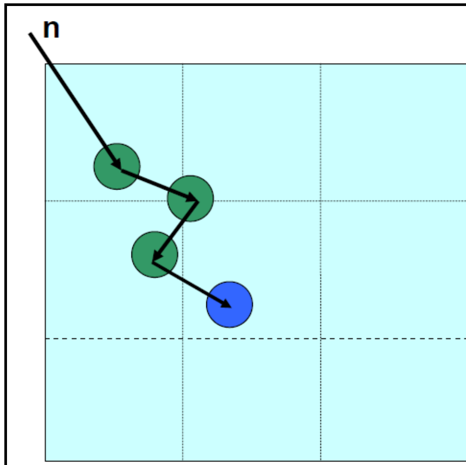
Event accepted? YES
Desired outcome? YES



Event accepted? YES
Desired outcome? NO



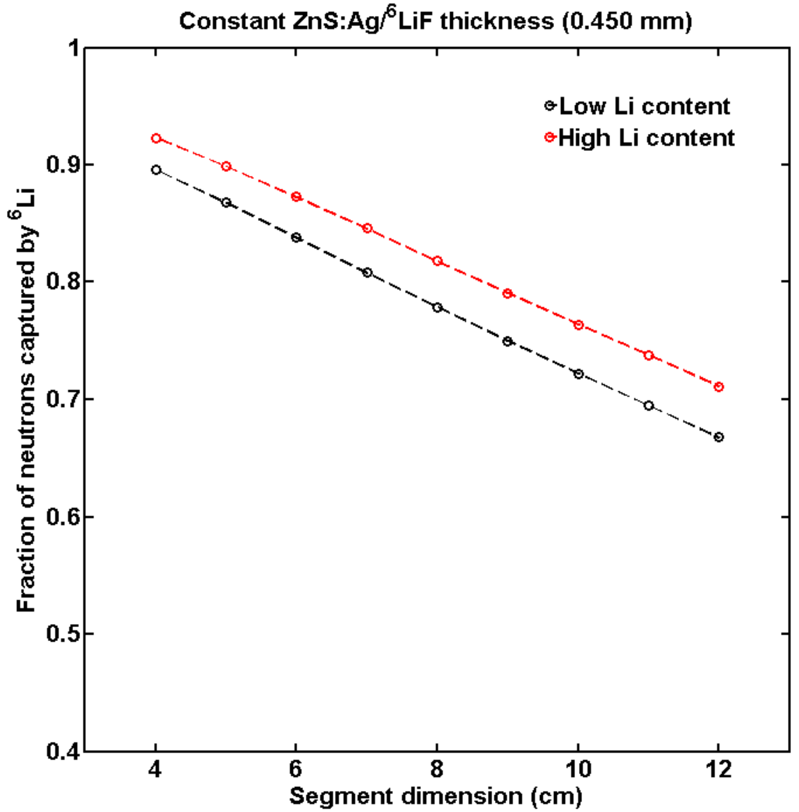
Event accepted? YES
Desired outcome? YES



Event accepted? NO
Desired outcome? YES

Predicting the neutron capture efficiency as a function of segment dimension

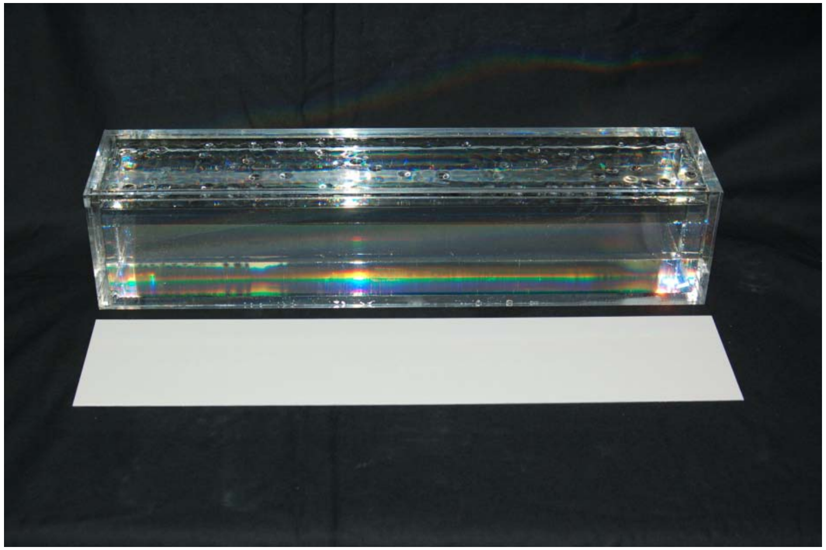
- Bigger segments: easier, cheaper
- Smaller segments: better neutron capture
- Use MCNP5 simulations to estimate capture efficiency vs. segment dimension

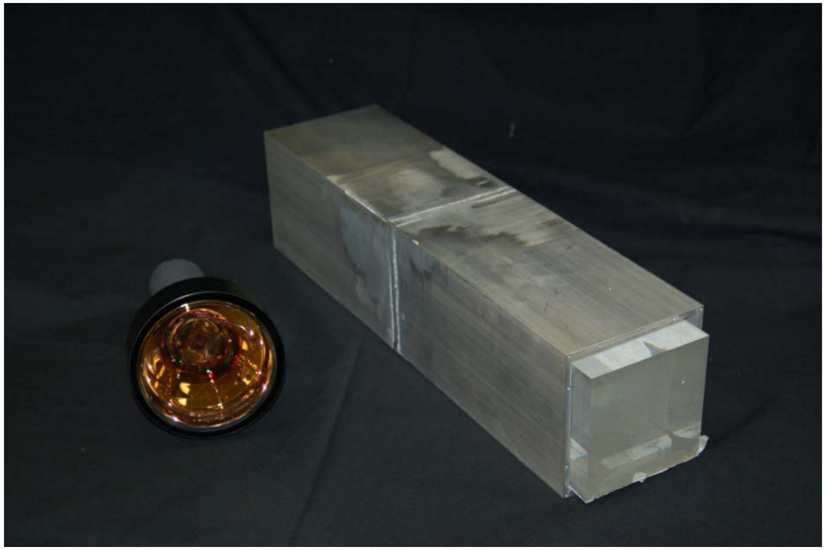


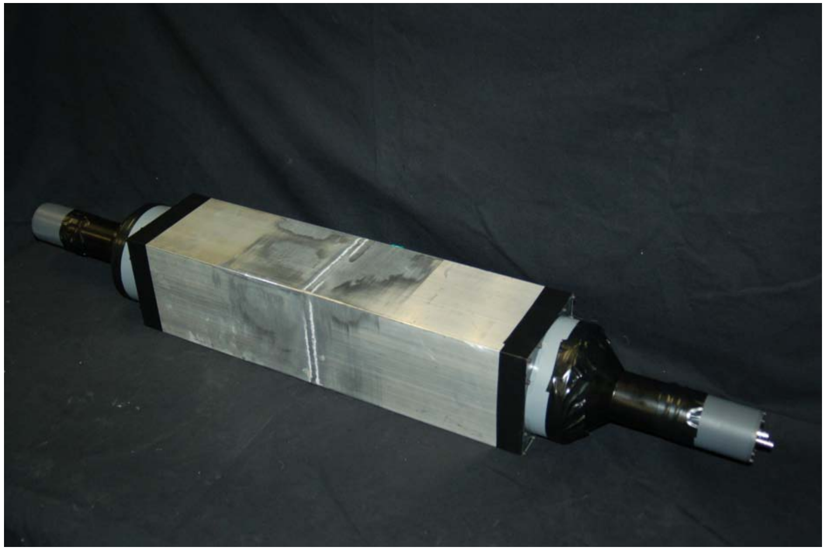
The length of a segment is important, too

- **Segment length affects:**
  - Number of segments (need to preserve total volume)
  - Cost (number of PMTs and data channels)
- **Segment length is determined by how well light is transported along the segment**
  - Total internal reflection (TIR): desired, not reality
  - ZnS(Ag)/LiF is not a great reflector, so more optical bounces degrades performance
- **Some crude lab experiments were used to estimate the maximum reasonable segment length**
  - Should be able to read out >60 cm

The segmented scintillator prototype

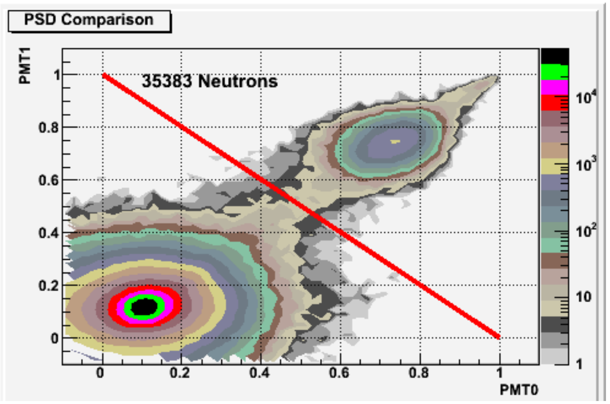


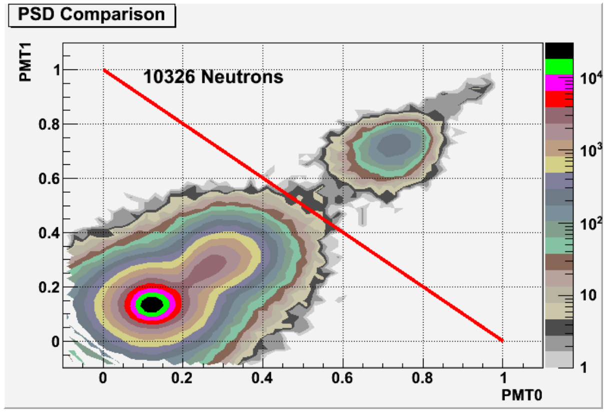


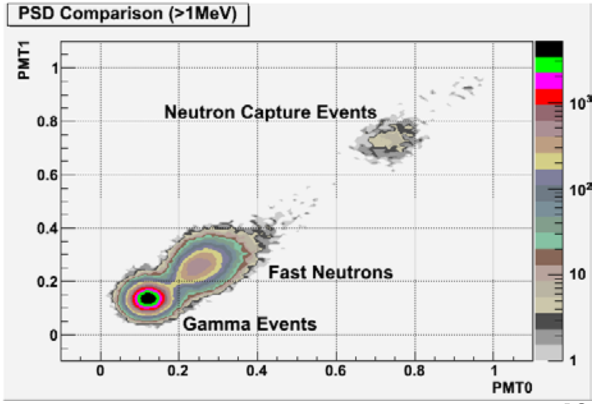


Pulse shape discrimination in segmented scintillator

- **For each PMT, calculate ratio (tail light)/(total light)**
- **Plot 2D histogram of PSD ratio for each PMT**
- **ZnS(Ag)/LiF neutron captures have more light in tail, so will be closer to unity**







The future: prototype testing at San Onofre

- **Single-segment characterization work is nearly finished**
- **Will soon begin data acquisition with four segments together**
  - **Estimate antineutrino-like background rates**
  - **Work on particle identification with multiple segments (positron)**
- **Move four-segment prototype to San Onofre in December/January to operate in reactor environment**

Summary

- (Sandia is a great place to work—check it out at www.sandia.gov)
- Antineutrinos provide a possible measurement tool supplementing the current nuclear safeguards techniques
- Early efforts (SONGS1) proved that antineutrino detection can be used to monitor reactor power, burnup
- Current efforts are focused on making aboveground measurements for ease of deployment

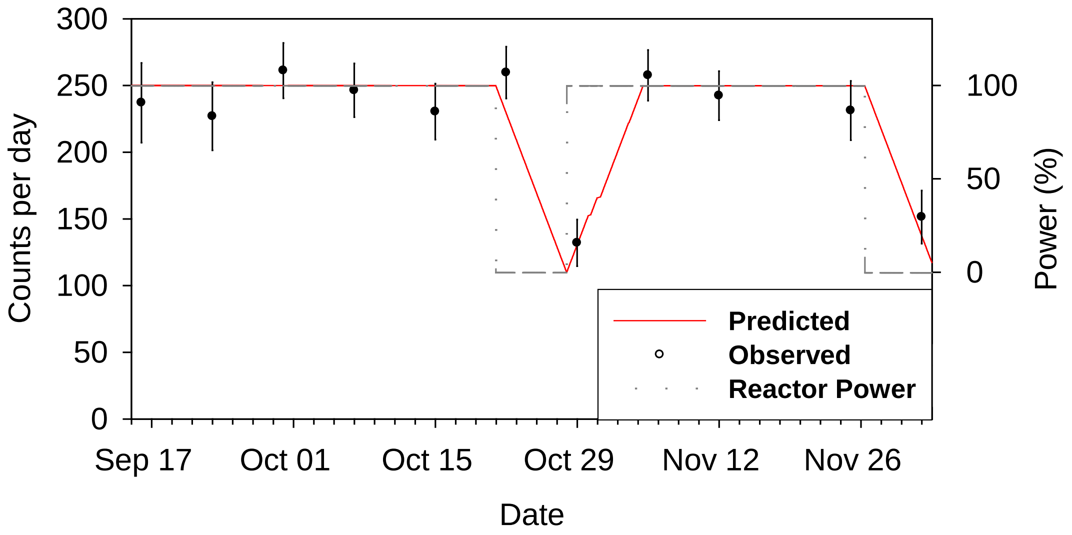
Extras!

Liquid scintillator vs. plastic

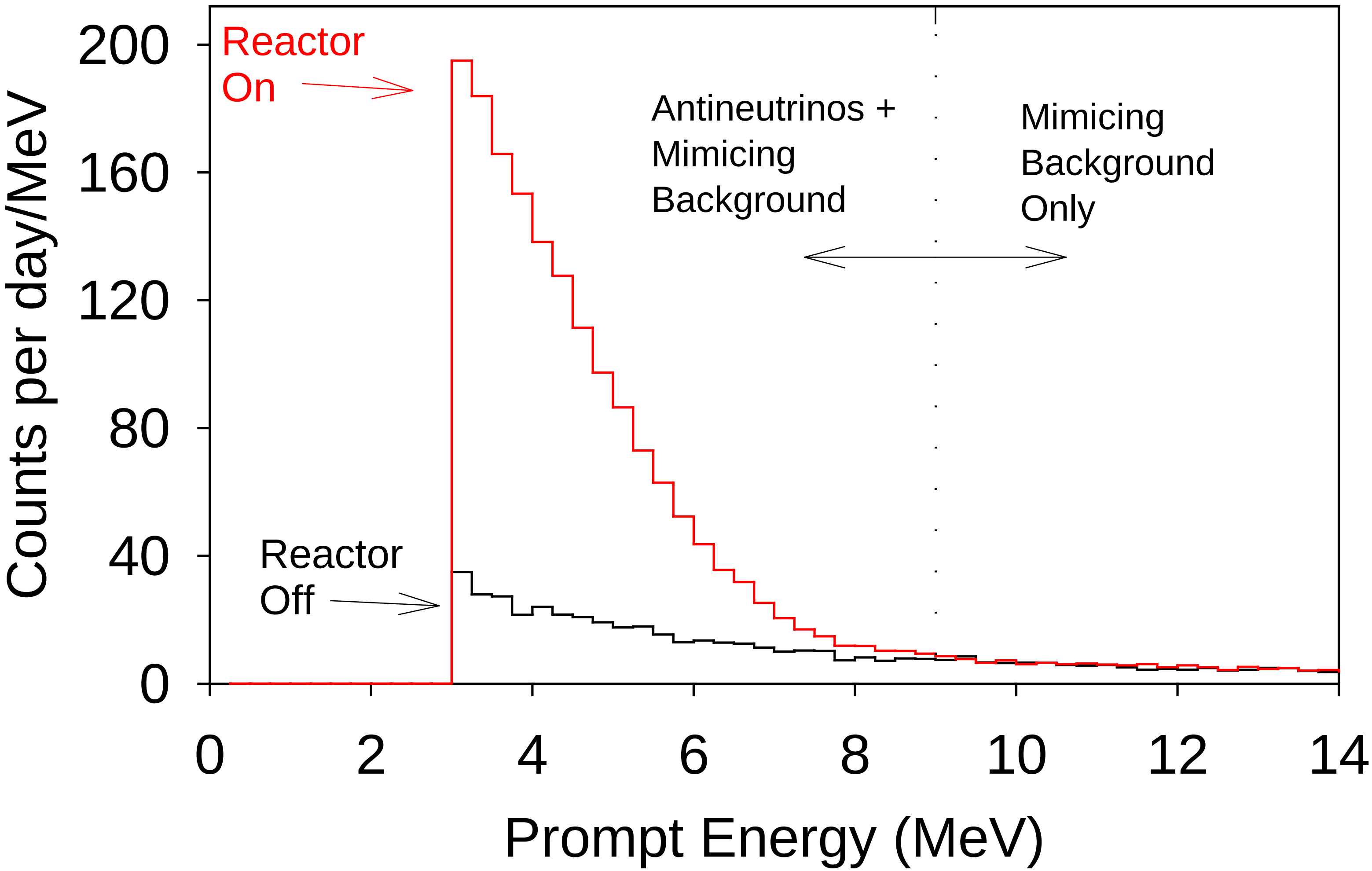
- Liquid scintillator is great because
  - Gd neutron capture agent can be added homogeneously
  - Pulse shape discrimination (more later—I promise!)
- Liquid scintillator is not great because
  - Need an expansion volume—adds complexity and optical interfaces
  - Not self-supporting—need a good container
  - Could leak
- Let’s try plastic scintillator instead!
  - Similar density, hydrogen content
  - Similar scintillation properties
  - No inherent PSD

SANDS

- **Remove ¼ of SONGS1 detector (1 cell)**
- **Replace with plastic scintillator/interleaved Gd sheets**



Clear indication of antineutrino detection

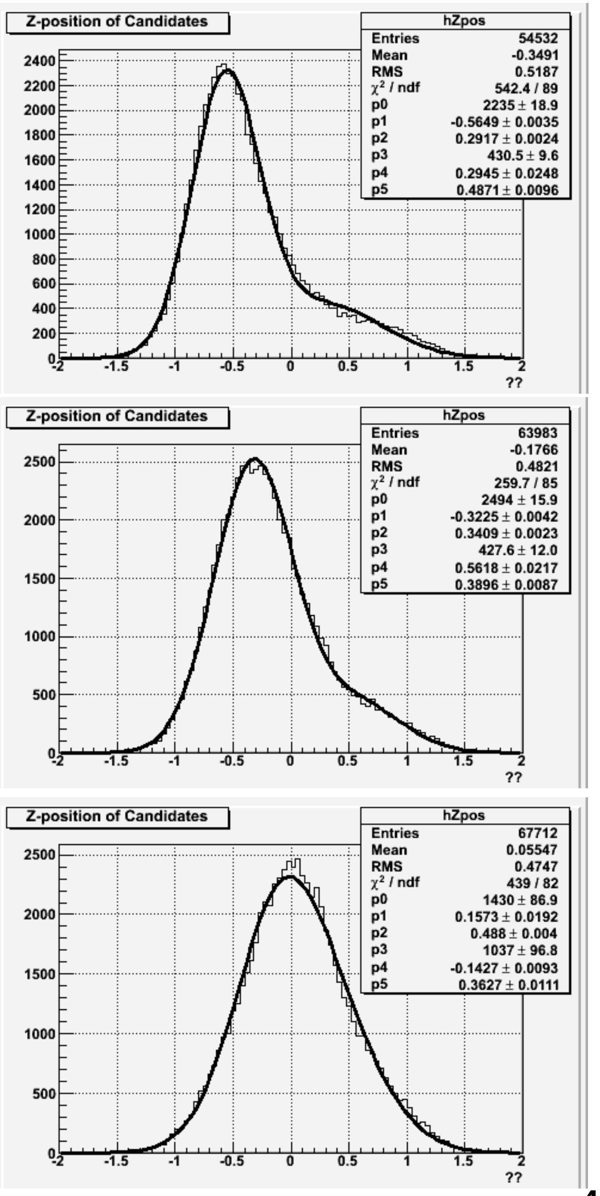


Data acquisition system: waveform digitizers

- **Advantages:**
  - High channel density
  - Electronic simplicity
  - Very flexible
- **Disadvantages:**
  - Non-instantaneous feedback
  - Data deluge (current water detector: ~1TB/month)

Collimated source testing

- **Because the light collection depends upon the distance between the event and the PMTs, the system response will vary along the segment length**
- **Want to determine efficiency profile**
- **Collimate a neutron source and use ratio of PMT light as a position estimator**



LGB: Separate detection media, single readout

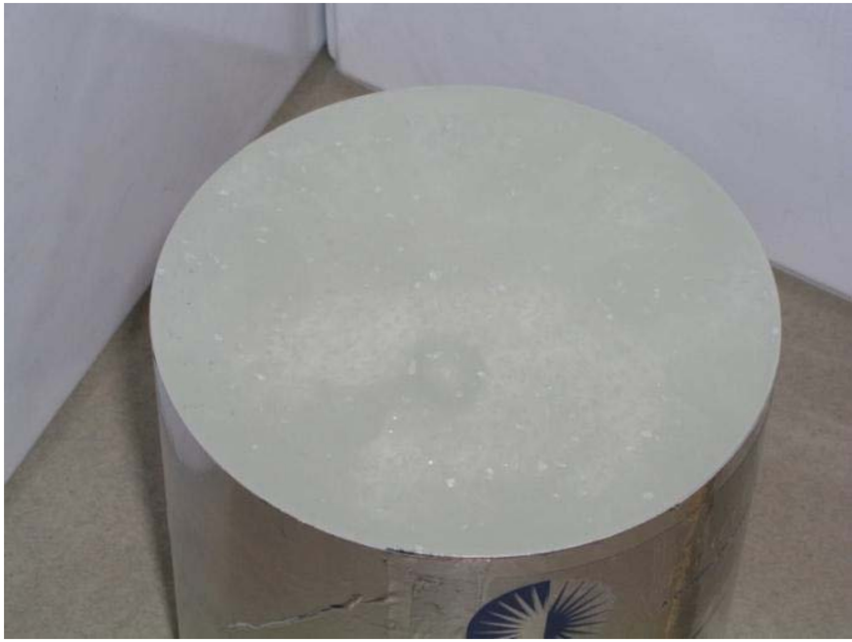
- **$LiGd(BO_3)_3$:Ce is being investigated at LLNL**
- **LGB is an inorganic crystal scintillator composed of neutron capture agents**
- **^{6}Li and ^{10}B neutron captures are bright compared to Li or B doped organic scintillators**
  - **Lower quenching of high dE/dx interactions than organics**
  - **Light yield from $^{6}Li + n \rightarrow {}^{3}H + {}^{4}He$ is ~40,000 photons**
  - **Light yield from $^{10}B + n \rightarrow {}^{7}Li + {}^{4}He$ is ~8,000 photons**

- **Time constant of inorganic scintillator is very long (~200 ns) compared to organics (~ few ns)**
- **To some extent, isotopics can be selected, e.g.**

$$^{6}Li^{nat}Gd(^{10}BO_3)_3{:}Ce$$

$$^{6}Li^{nat}Gd(^{11}BO_3)_3{:}Ce$$

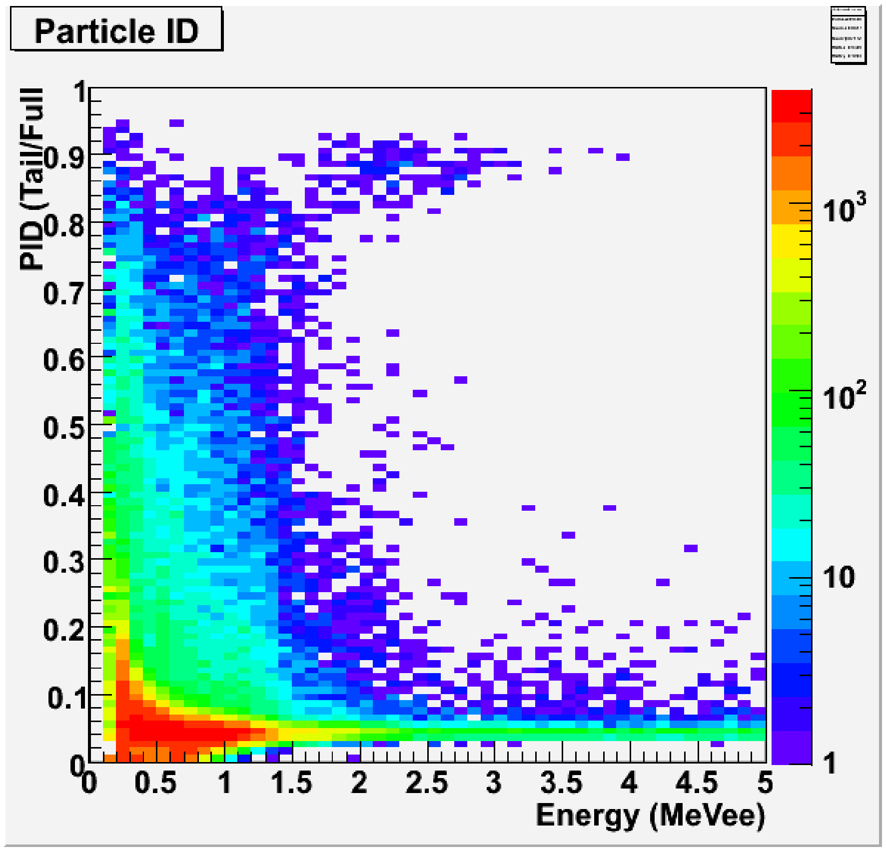
LGB as an antineutrino detection medium



- **Small grains of crystal (~1mm) mixed with plastic scintillator:**
  - **H for antineutrino target**
  - **e^+ in plastic scintillator**
  - **LGB for neutron capture (via PSD)**
  - ***BUT:* little to no fast n rejection**
- **LGB index (*n* = 1.65) is well matched to plastic (*n* = 1.58)**
- **5 inch right cylinder sample is 1% by weight LGB**
  - **0.1% by weight ^{6}Li**
  - **0.08% by weight ^{10}B**
  - **0.4% by weight ^{nat}Gd**
- **Good for uncorrelated background reduction; poor correlated proton recoil/capture background discrimination**

Neutron Capture Selection via PSD

Background



^{252}Cf + background