Lawrence Livermore National Laboratory

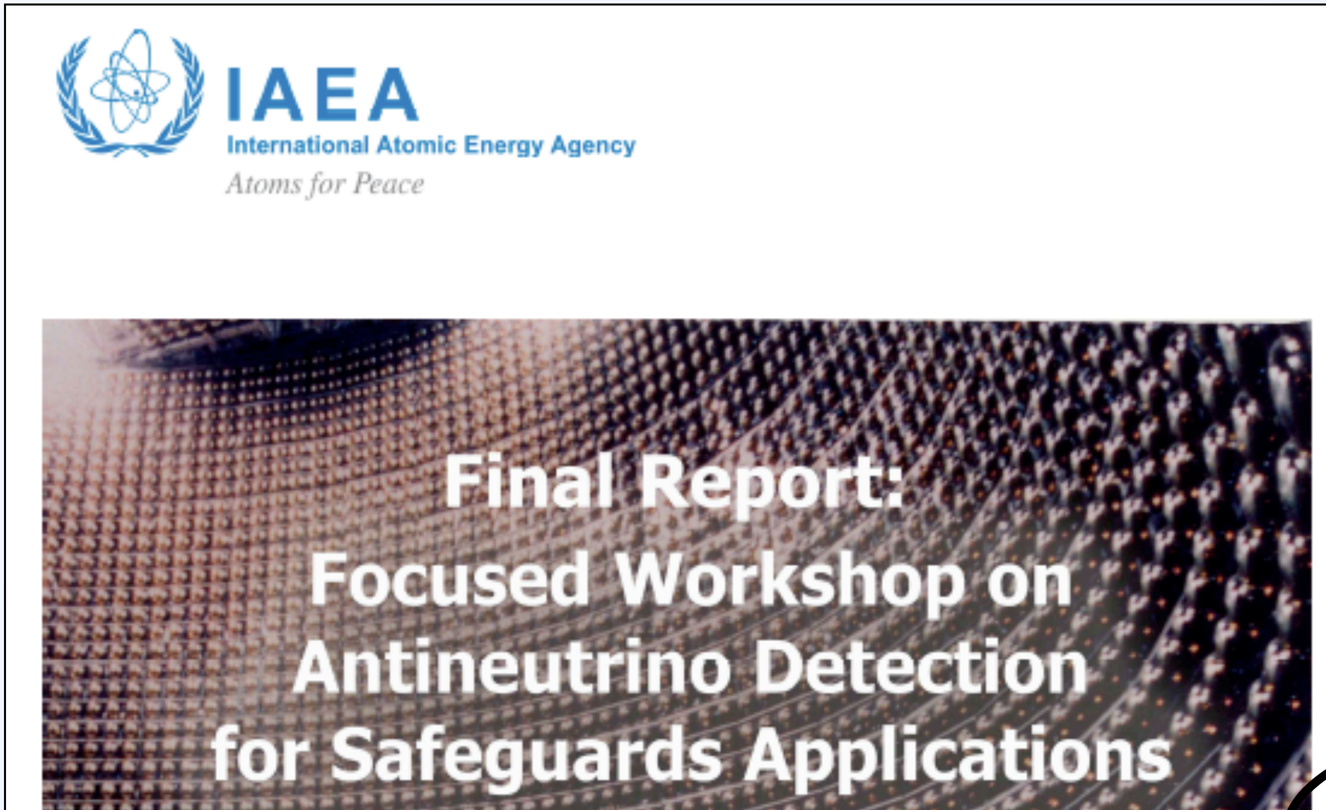
LLNL/SNL Scintillator Detector Development

N. Bowden, A. Bernstein, S. Dazeley, G. Keefer
Lawrence Livermore National Laboratory
D. Reyna, B. Cabrera-Palmer, S. Kiff, J. Lund
Sandia National Laboratories

LLNL-PRES-422580

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory in part under Contract W-7405-Eng-48 and in part under Contract DE-AC52-07NA27344.

IAEA Topics of Interest



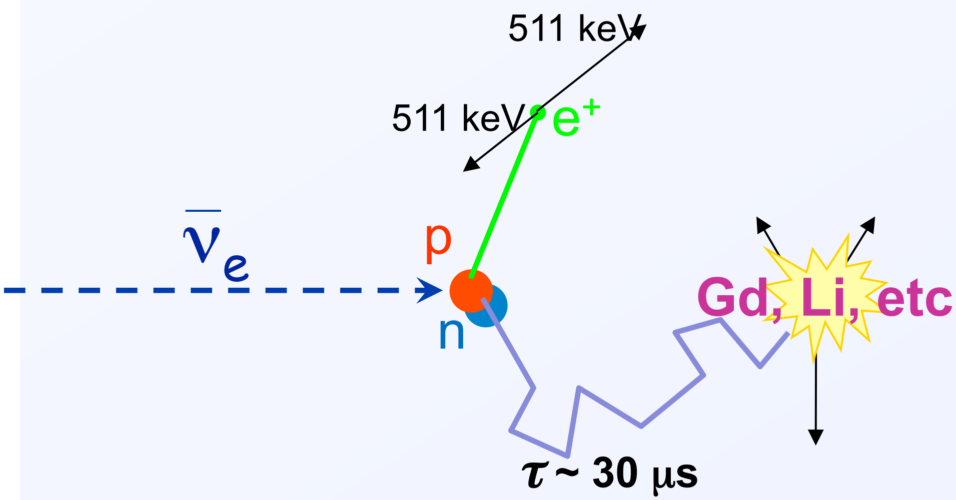
Result of 2008 Experts Meeting at IAEA HQ:

Interest in application for:

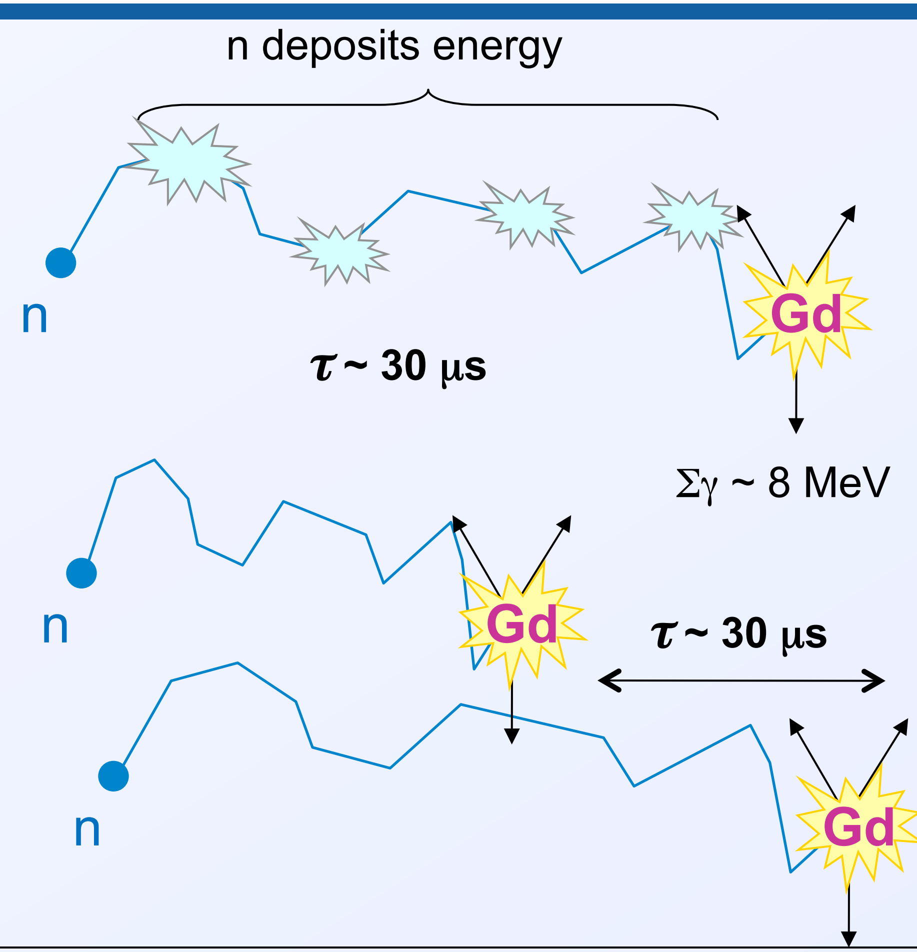
- Shipper-receiver differences,
- **Bulk Process/ Online Refuel Reactor Verification**
- Research reactor power
- Safeguards by Design, Integrated Safeguards
- **Aboveground Detection**

The Signal: Inverse Beta Decay

Cosmogenic Neutron Background:



- Positron
  - Immediate
  - 1- 8 MeV (incl 511 keV γs)
- Neutron
  - Delayed (τ = 28 μs for Gd)



- **Aboveground Detection will require: 1) Signal vs. Background discrimination**
  2) Background insensitivity

Candidate Particle ID technologies

Identification of inverse β-decay products or background

Reject fast n →

Organic liquid scintillator:
→identifies proton recoils via PSD
→not preferred due to flammability, dead volume in segmented geometry

Segmented liquid or plastic scintillator (could be Gd-based):
→segmentation identifies pair (e+-like,n)

BOTH reject fast n and identify n capture →

Single crystal Li doped organic scintillators
→identifies proton recoils
→identifies thermal neutron capture in ^{6}Li

Identify neutron capture ↓

Sheets of ^{6}Li: ZnS (Ag) layered with an organic scintillator:
→identifies thermal neutron capture in ^{6}Li via PSD

Inorganic scintillator grains (LGB) mixed with plastic scintillator:
→ identifies thermal neutron capture in ^{6}Li, ^{10}B,via PSD

Inorganic Neutron Capture Scintillator ($Li_6 Gd(BO_3)_3$:Ce) grains mixed with Plastic Scintillator

Crystal index is well matched to that of plastic

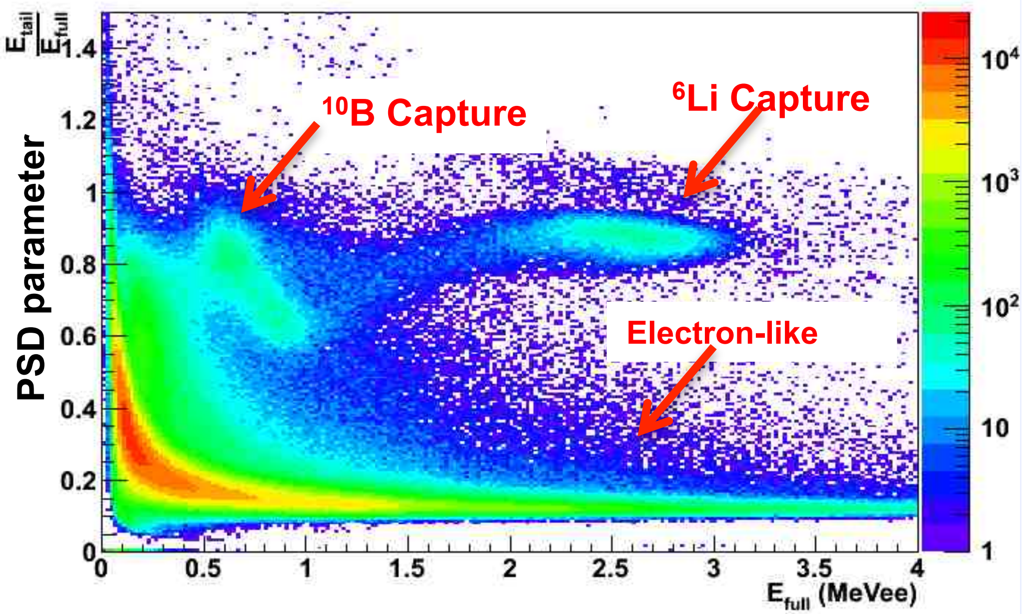
Neutron captures on ^{6}Li and ^{10}B are bright and distinct via PSD (Li especially, ~2.5 MeVee)

Fairly efficient neutron capture: Esc.: H :Gd :B :Li
(1% b.w. crystal loading) 13%: 12% :43% :21% :11%

***But*, current manufacturing technique yields poor optical properties: effective optical attenuation length is only ~ 20cm. Have successfully tested 40cm detector**

Currently, rather expensive ($2/cm^3)

We continue to investigate improvements to the production technique. New inorganic scintillators that contain only Li also warrent consideration.

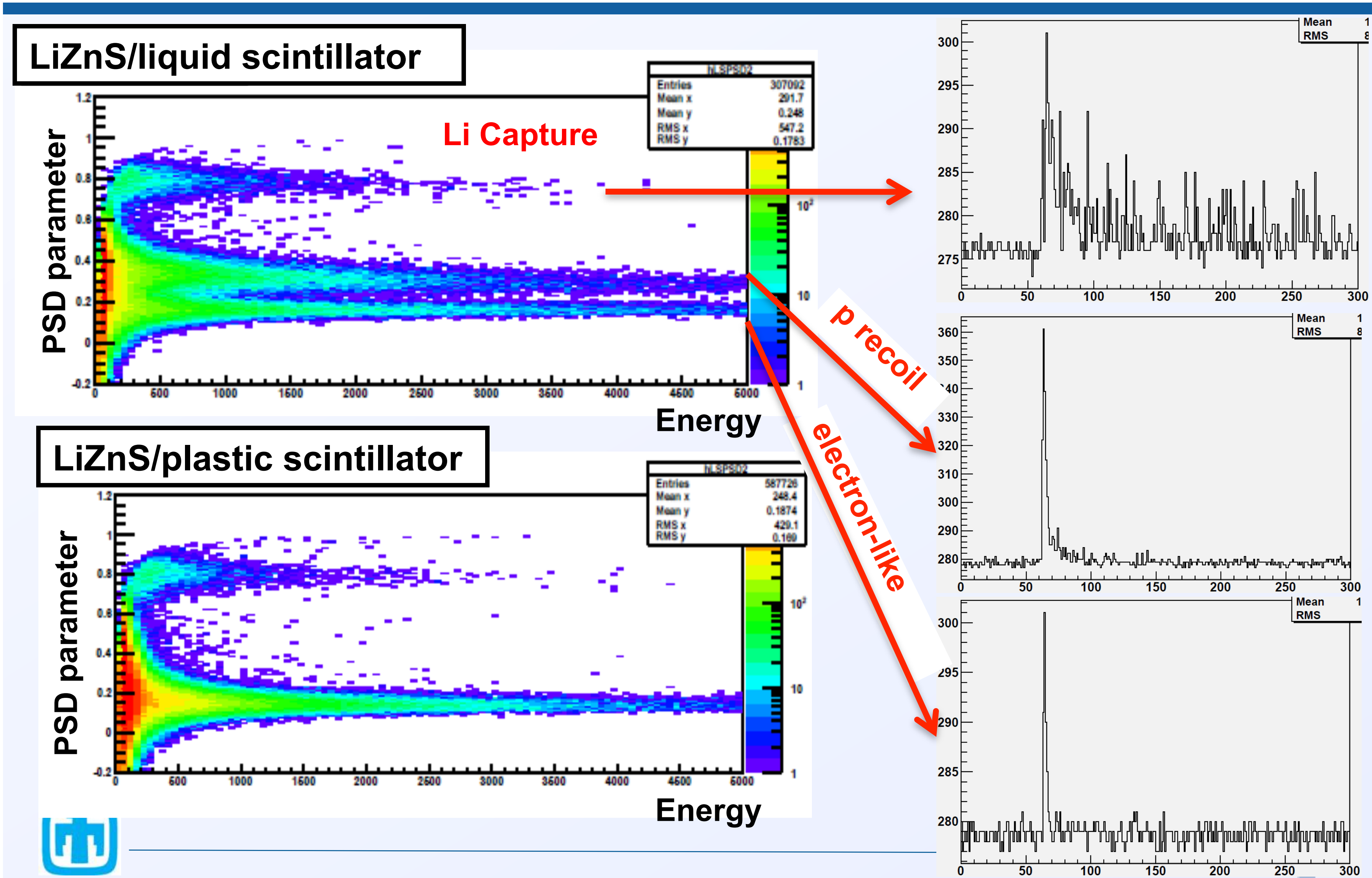


ZnS:Ag/^{6}LiF:
An inorganic scintillator mixed with a neutron capture agent

- ZnS:Ag is a polycrystalline inorganic crystal scintillator
  - Reduced quenching of heavy ion depositions from ^{6}Li neutron captures
  - Time constant is long (~200 ns), allowing good PSD
  - Fairly easy to obtain, since widely used in neutron radiography
  - *BUT*:
    - ZnS:Ag is not transparent to its own scintillation light so only thin layers can be used, and it is a poor optical reflector
    - The inhomogeneous mixture of Li and scintillator means that not all of the energy of the capture reaction is lost in scintillator
- Three configurations studied:

LiZnS sheets grease coupled to plastic scintillator bar (5cm x 5cm x 50cm)	**LiZnS sheets immersed in a liquid scintillator cell (5cm x 5cm x 50cm)**	**LiZnS sheets grease and air coupled to acrylic (to study optics) (12cm x 12cm x 50cm)**

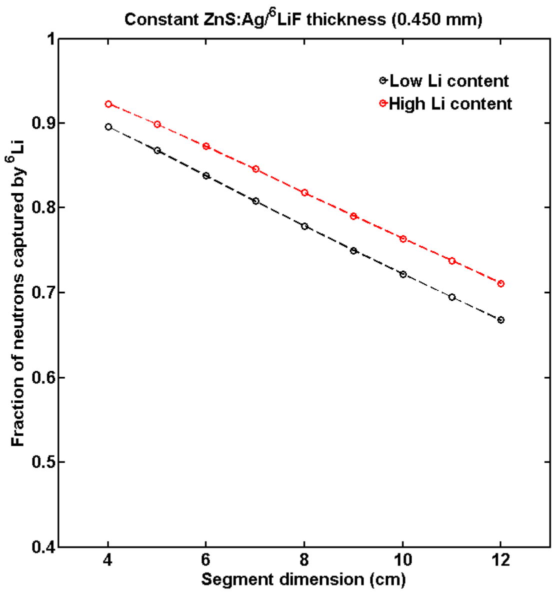
LiZnS in combination with organic scintillator clearly provides Particle ID capability



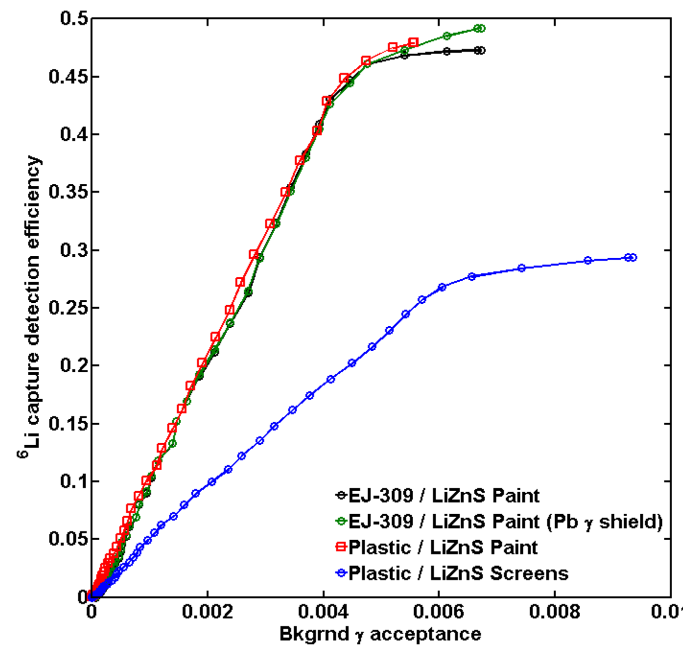
Good Neutron Capture Efficiency can be achieved

- Two questions to address:

How often will a neutron capture on Li, in an inhomogeneous geometry?
Via MCNP/GEANT4, 12cmx12cm organic scintillator bars coated with LiZnS yield ~70% Li capture efficiency ($\tau \sim 100\mu s$)

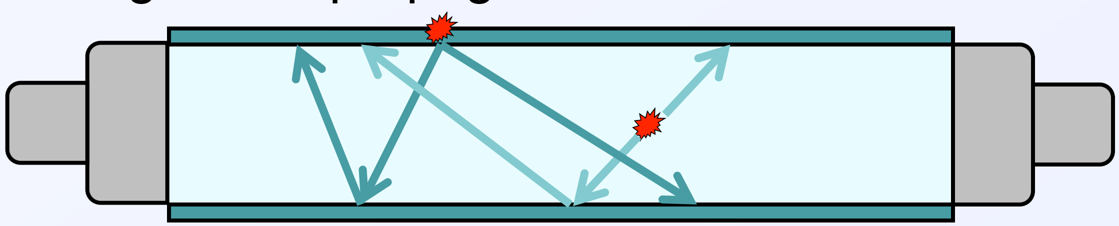


Given that a Li capture occurs, how often is it detected?
Via comparison to 3He tube of known efficiency, find that this approaches 50% for 50cm detectors

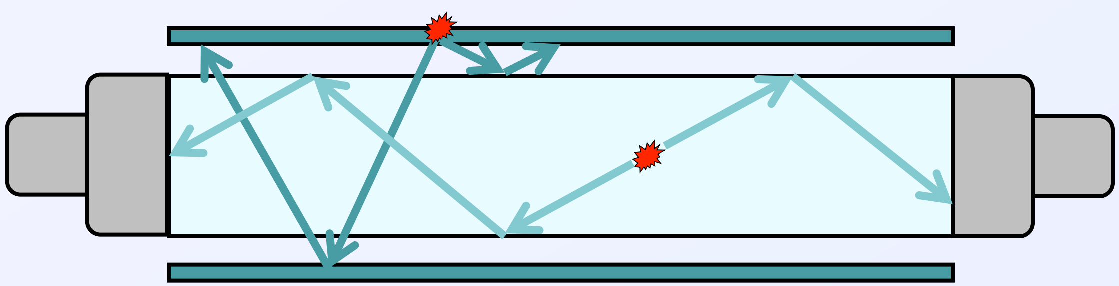


Large scale implementation is not straightforward

- Poor optical properties of LiZnS complicates implementation in long bars:
  - Direct coupling of LiZnS severely attenuates both ZnS and organic scintillation light as it propagates down a bar

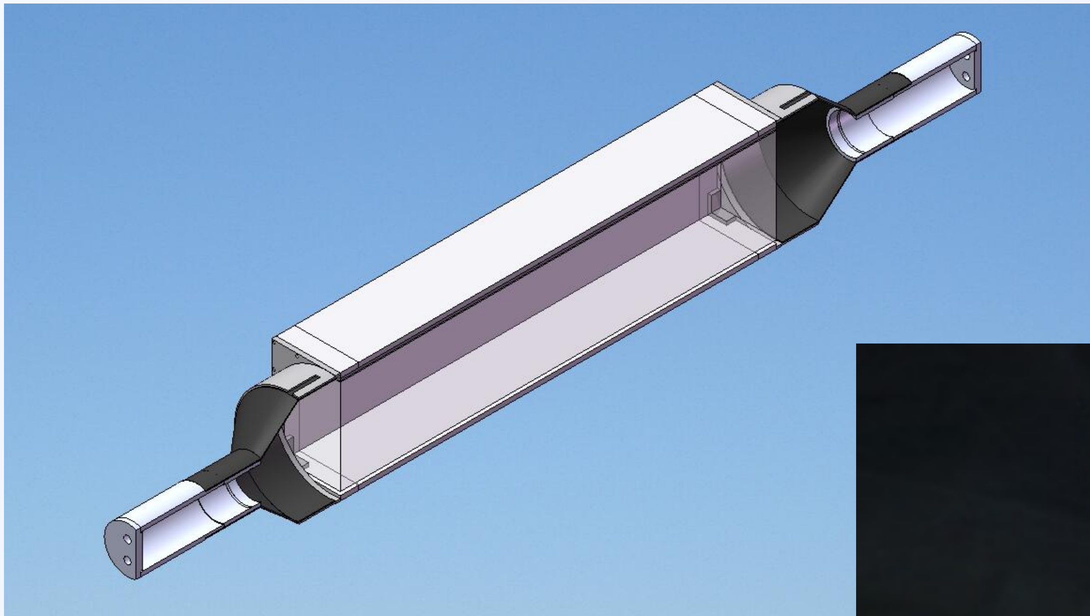


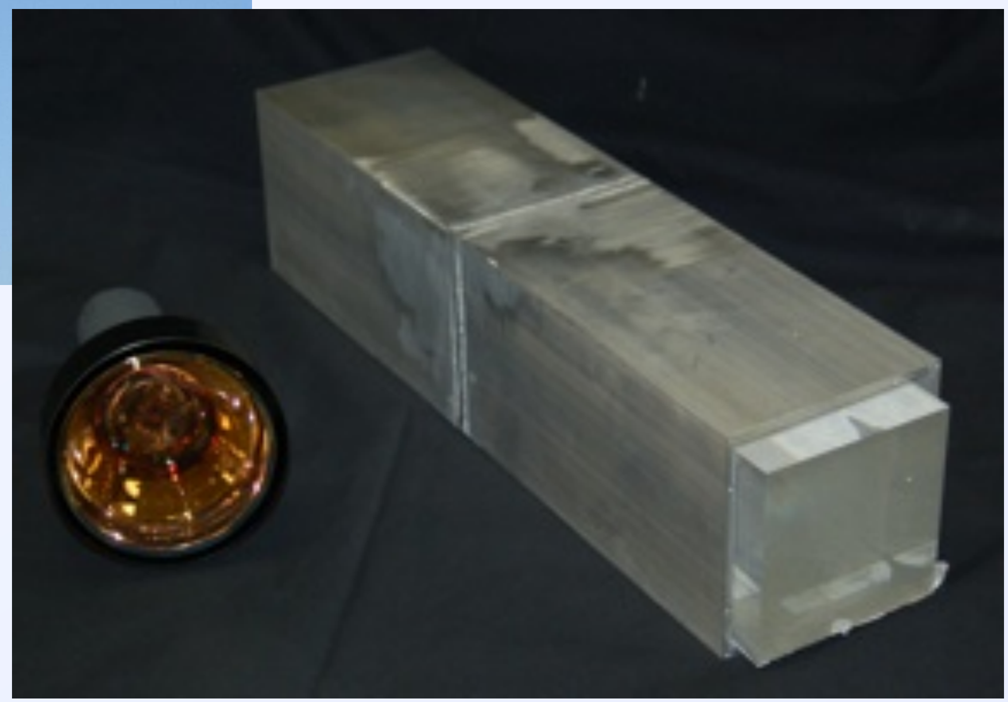
  - Indirect coupling of LiZnS (e.g. air gap) results in good organic collection, but poor collection of ZnS emissions. Light that enters the organic bar leaves after one pass, unless absorbed and re-emitted

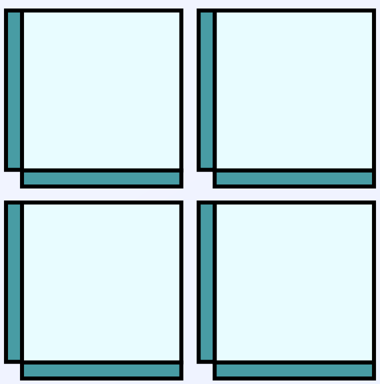


- Practical length limited to ~60 cm

Geometry to be implemented at SONGS

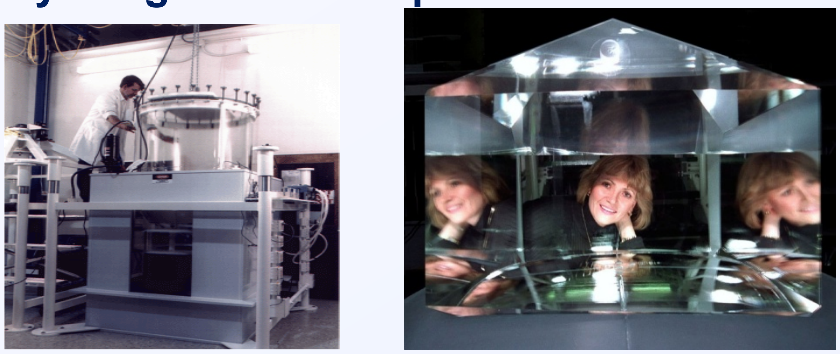




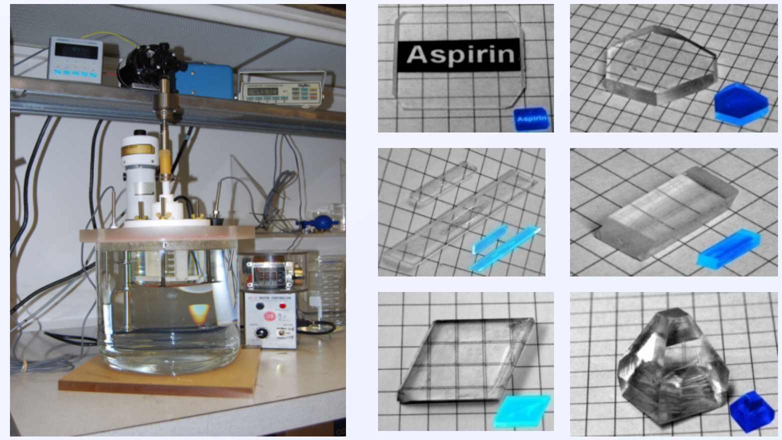


A future possibility?
Single Crystal Organic Scintillators

LLNL has unique capabilities for synthesis, crystal growth and optical characterization

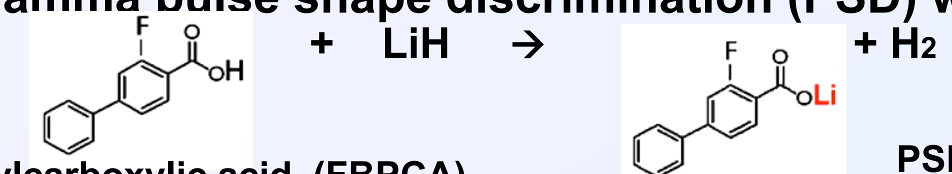


Technique used for rapid growth of NIF KDP crystals

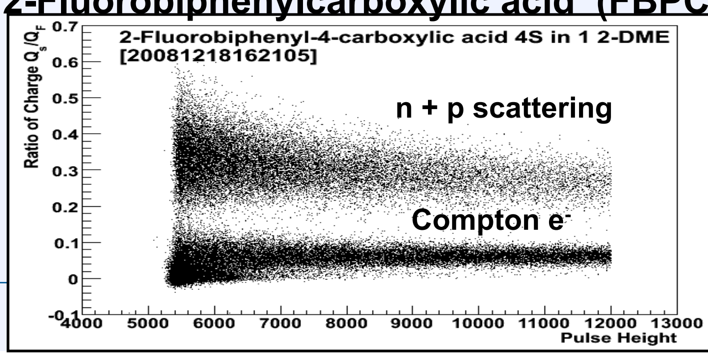


Adapted for growth of large varieties of new organic crystals

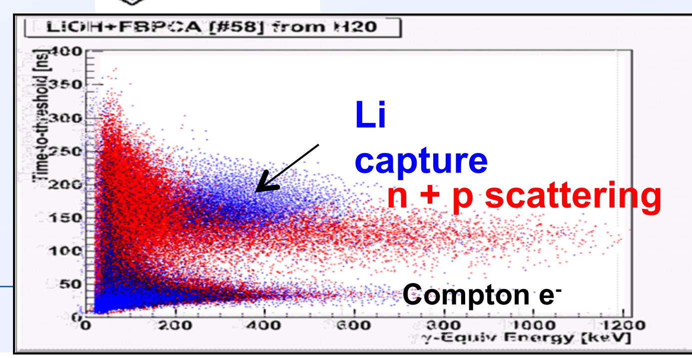
Investigating combination of *recently discovered* organic scintillators that have efficient neutron/gamma pulse shape discrimination (PSD) with capture agent:



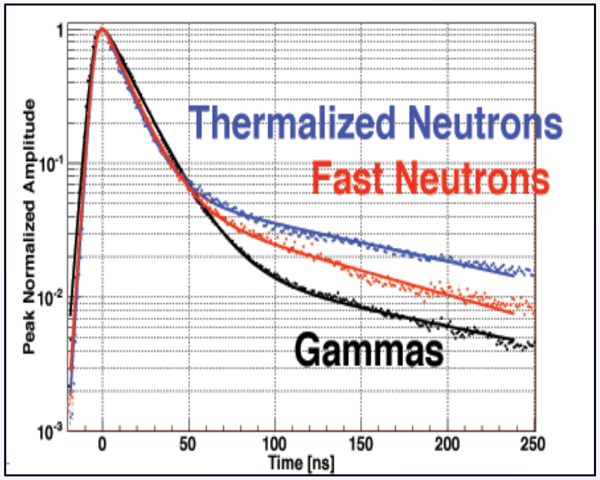
PSD in 2-Fluorobiphenylcarboxylic acid (FBPCA)



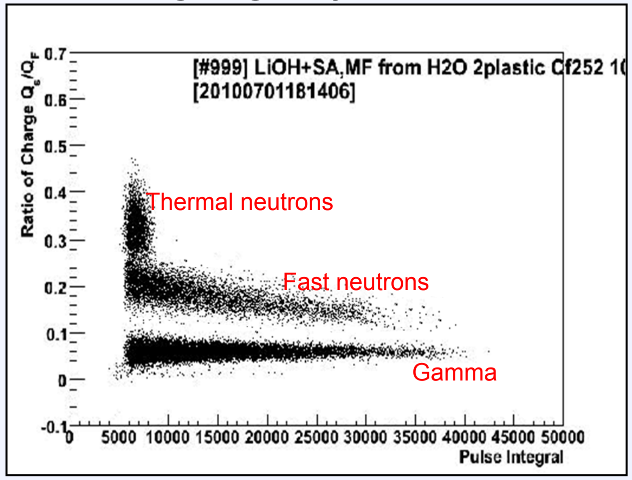
PSD in Li-salt of BPCA



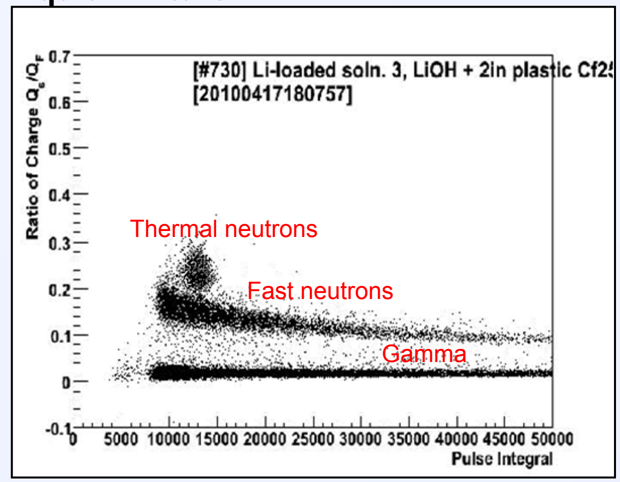
New scintillator materials with triple pulse shape discrimination (PSD) of *electron*, *proton recoil* and *neutron capture* studied in solid and liquid states



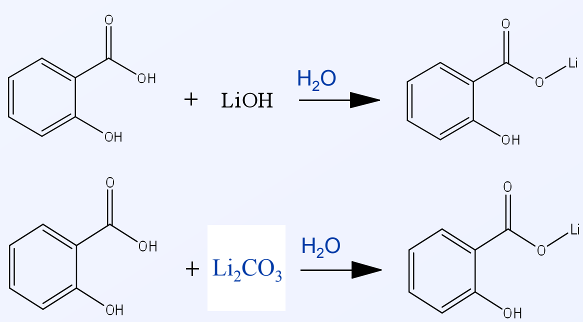
Triple PSD measured in a Li-containing single crystal



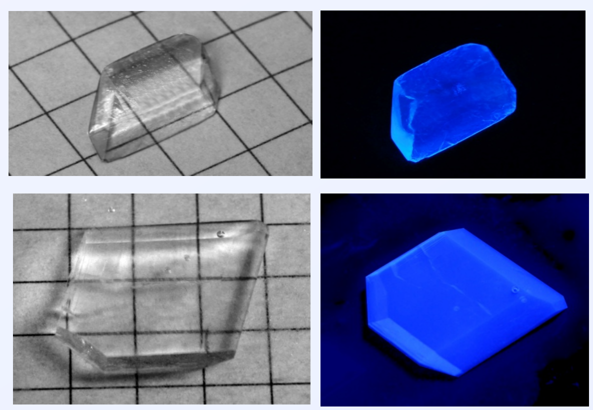
Triple PSD obtained in a Li-containing liquid mixture



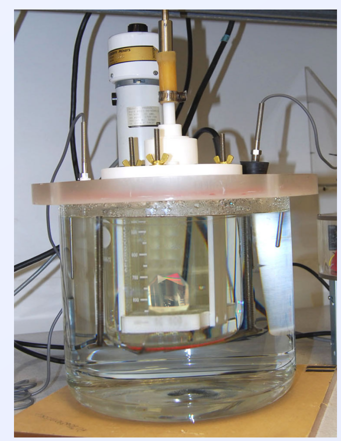
New compounds are synthesized by incorporation of Li in earlier discovered scintillators with PSD



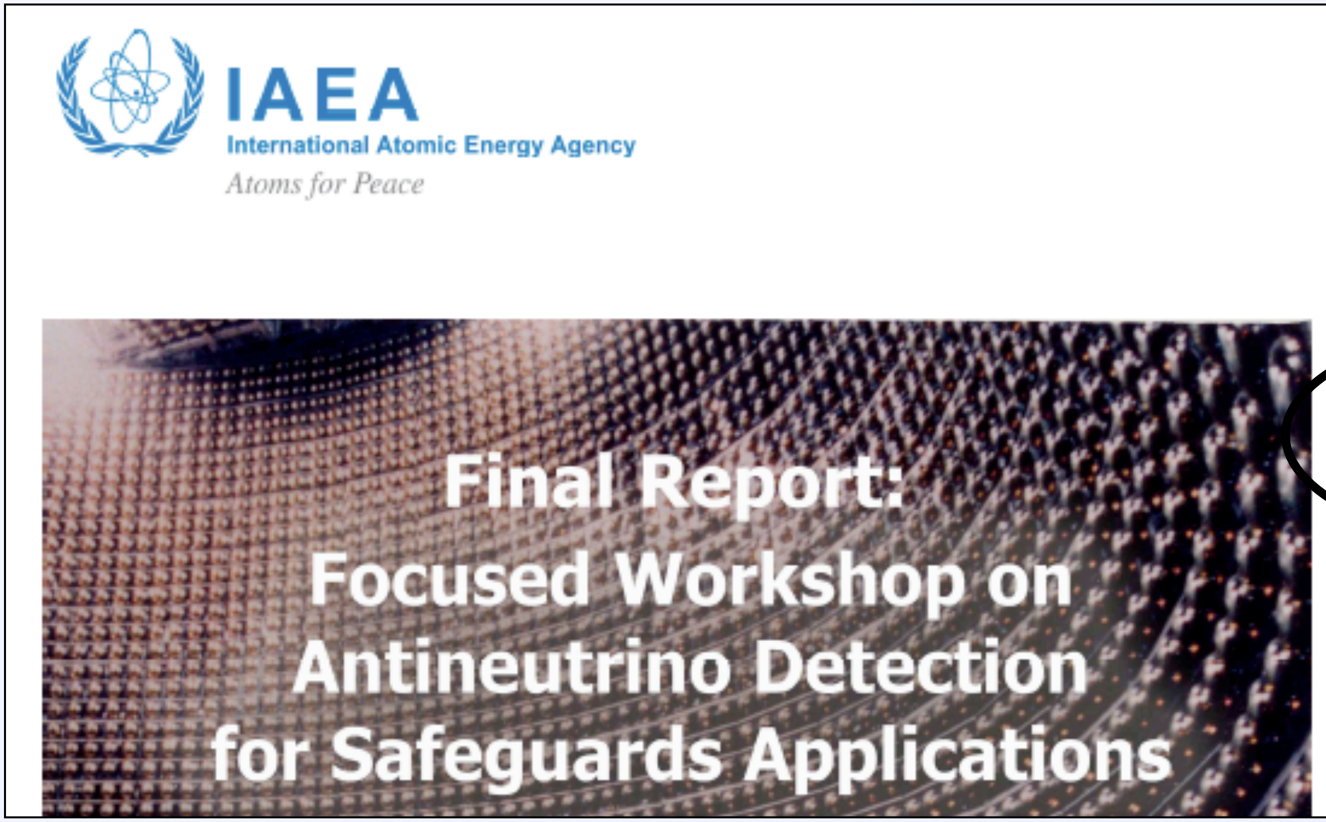
First crystals of the most efficient triple PSD materials grown at a small scale



Growth of larger crystals (10-cm scale) is planned for the next year



IAEA Topics of Interest



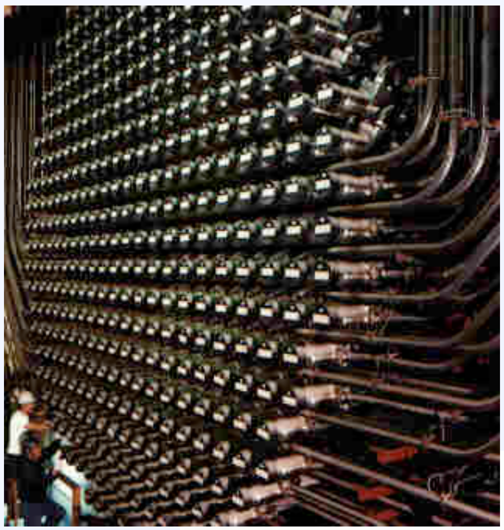
Result of 2008 Experts Meeting at IAEA HQ:

Interest in application for:

- Shipper-receiver differences,
- **Bulk Process/ Online Refuel Reactor Verification**
- Research reactor power
- Safeguards by Design, Integrated Safeguards
- **Aboveground Detection**

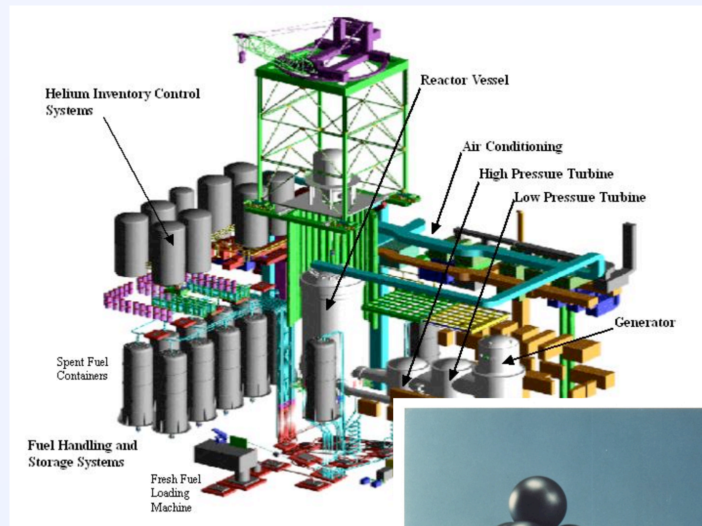
CANDU and Bulk Process Reactors (e.g. PBMR)

The daily movement of fuel bundles at a CANDU plant presents a safeguards challenge - item accountancy remains a primary strategy



Item accountancy is not possible on the "continuous" or finely divided fuel of a BPR – a Bulk Materials Accountancy approach will be necessary.

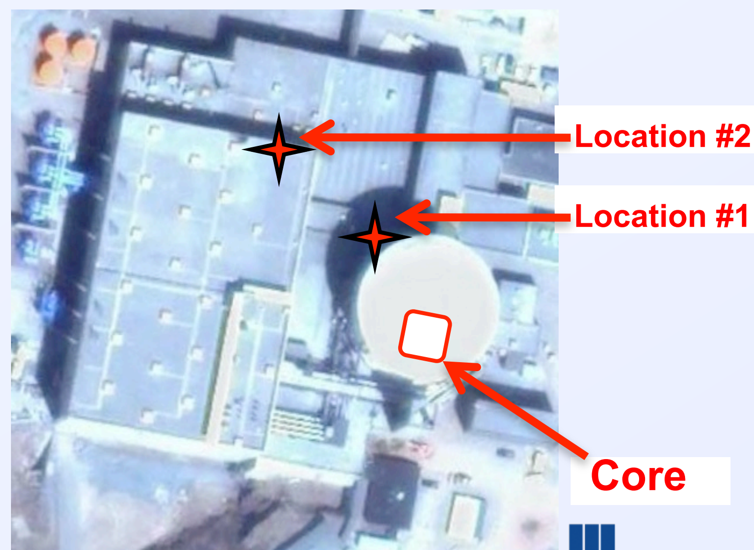
Loss of Continuity of Knowledge over the core contents would be difficult to recover



Pt. Lepreau CANDU6 Deployment
(in collaboration with AECL Chalk River)

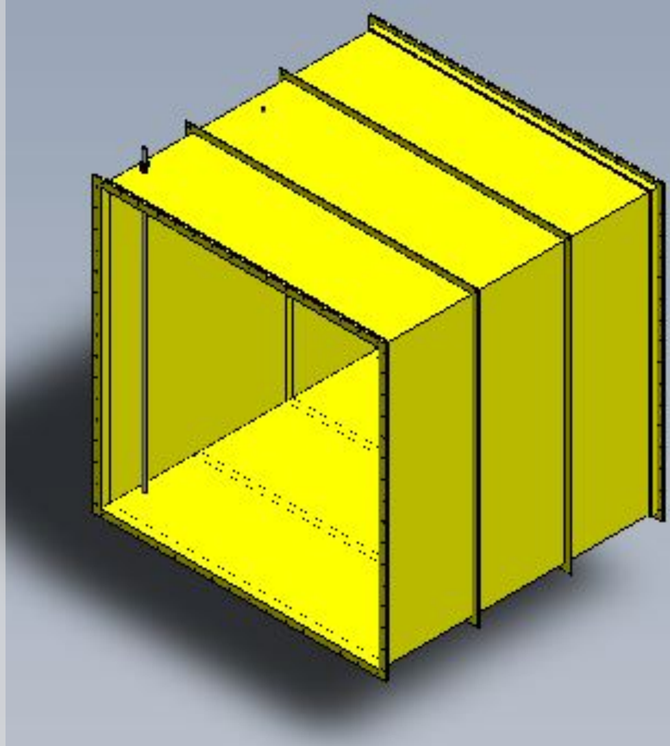
- We have negotiated access to the Point Lepreau Generating Station (PLGS) CANDU6 reactor (2.2 GWth, 0.64GWe)
- Two potential deployment locations were identified:

	Location #1	Location #2
Distance from core	37m	75m
Depth below grade/ Overburden	6m ~10m.w.e.	15m ~10-30 m.w.e.
Access	Inside RCA, escort required at all times	Outside RCA, no escort
Contamination	20-5000uSv, large contribution from ^{60}Co plated onto piping.	(none)
Reactor Correlated activities	D_2O processing	Turbine operation (ambient temperature)
Antineutrino flux relative to SONGS1	29%	8%



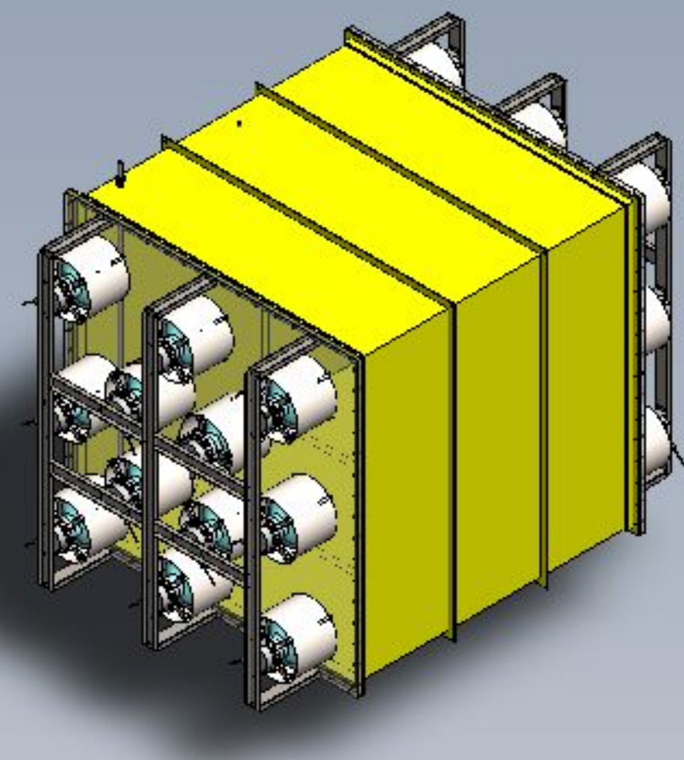
Detector Features

- To compensate for reduced flux, target will be 4m^3 of BC-525 (0.1% Gd);
  - expect ~20% overall efficiency
  - Per m^2 of footprint, ~10x as efficient as SONGS1
- Double ended readout using 24x10” R7081 PMTs
  - Acrylic windows, sealed via PTFE encapsulated o-rings
- Optical coupling and hydrostatic support via mineral oil
- Shielding from 6 interlocking water tanks (0.5m) and 2.5cm Borated Poly.
- 5cm thick muon veto on 5 sides.



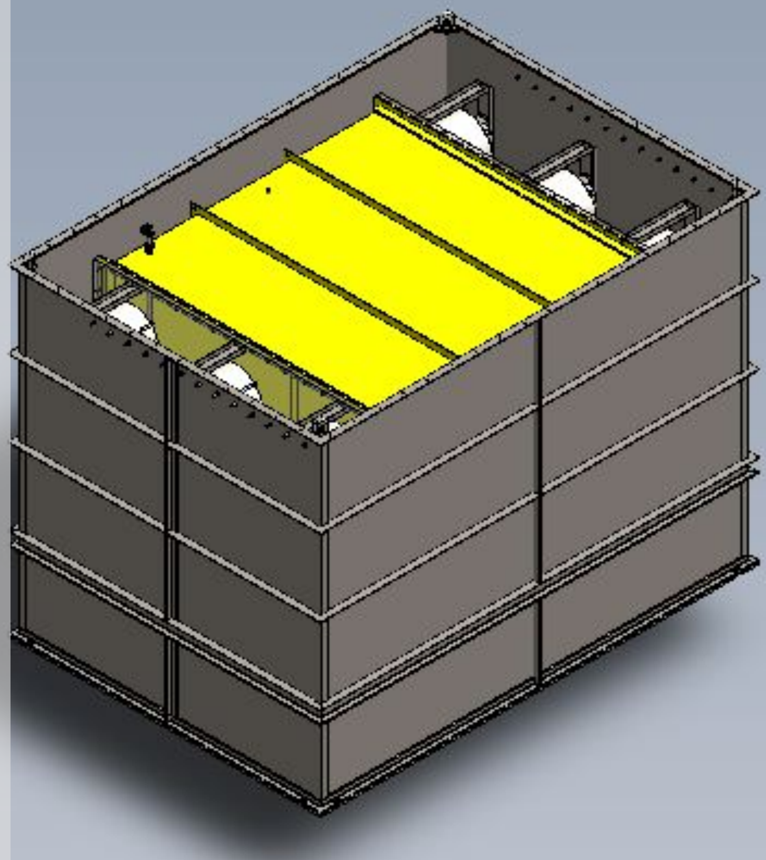
Detector Features

- To compensate for reduced flux, target will be 4m^3 of BC-525 (0.1% Gd);
  - expect ~20% overall efficiency
  - Per m^2 of footprint, ~10x as efficient as SONGS1
- Double ended readout using 24x10" R7081 PMTs
  - Acrylic windows, sealed via PTFE encapsulated o-rings
- Optical coupling and hydrostatic support via mineral oil
- Shielding from 6 interlocking water tanks (0.5m) and 2.5cm Borated Poly.
- 5cm thick muon veto on 5 sides.



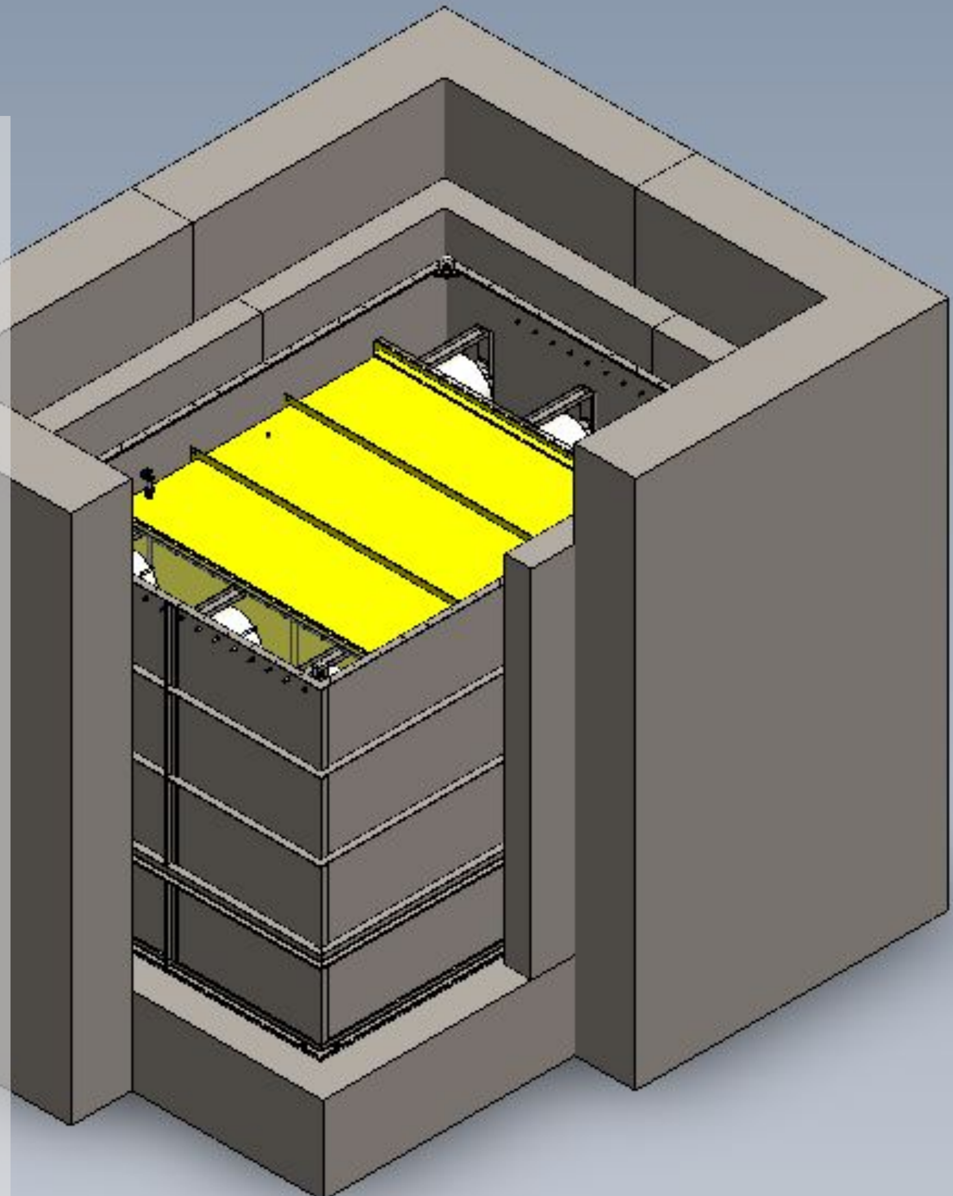
Detector Features

- To compensate for reduced flux, target will be 4m^3 of BC-525 (0.1% Gd);
  - expect ~20% overall efficiency
  - Per m^2 of footprint, ~10x as efficient as SONGS1
- Double ended readout using 24x10" R7081 PMTs
  - Acrylic windows, sealed via PTFE encapsulated o-rings
- Optical coupling and hydrostatic support via mineral oil
- Shielding from 6 interlocking water tanks (0.5m) and 2.5cm Borated Poly.
- 5cm thick muon veto on 5 sides.



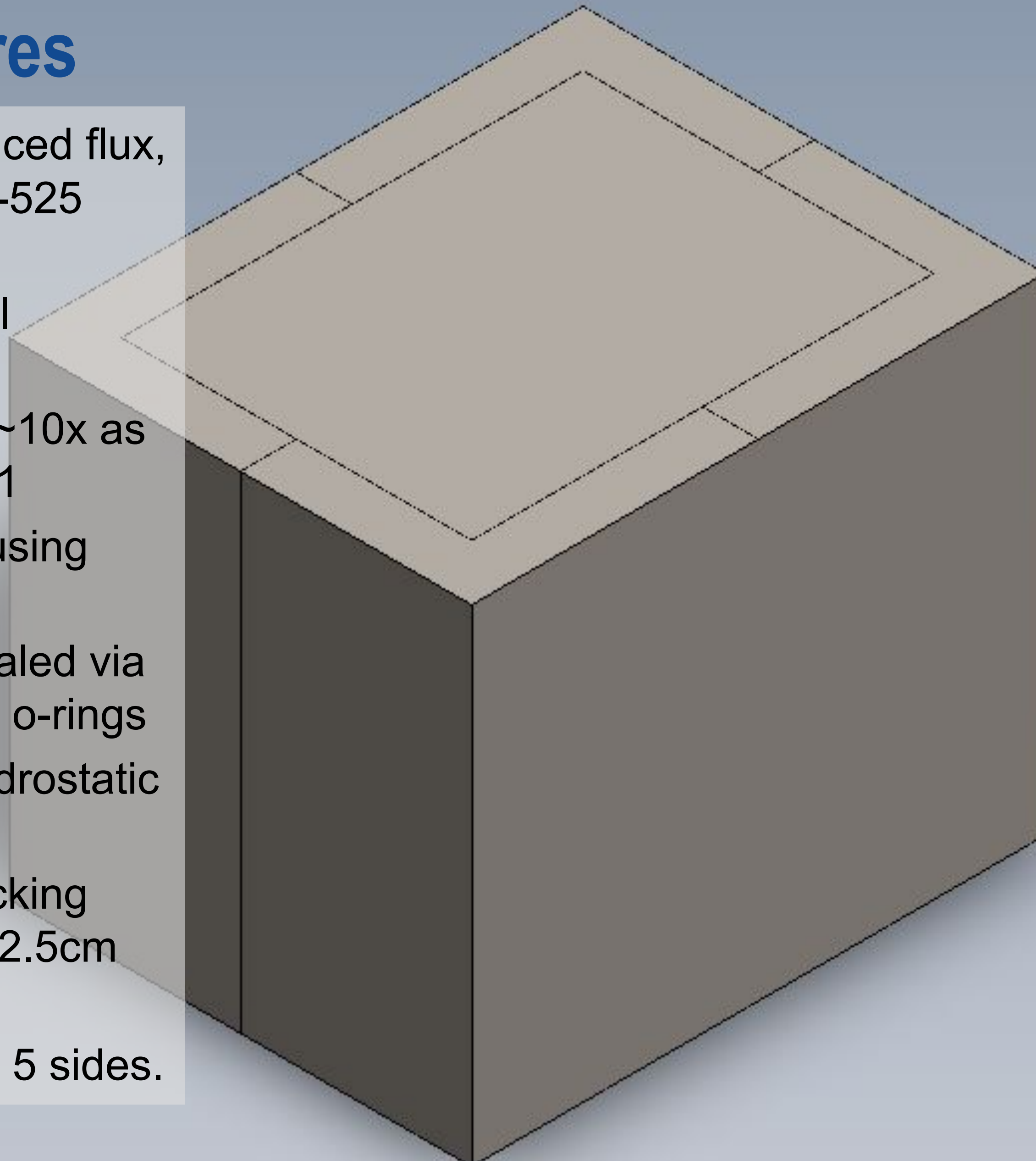
Detector Features

- To compensate for reduced flux, target will be $4m^3$ of BC-525 (0.1% Gd);
  - expect ~20% overall efficiency
  - Per m^2 of footprint, ~10x as efficient as SONGS1
- Double ended readout using 24x10” R7081 PMTs
  - Acrylic windows, sealed via PTFE encapsulated o-rings
- Optical coupling and hydrostatic support via mineral oil
- Shielding from 6 interlocking water tanks (0.5m) and 2.5cm Borated Poly.
- 5cm thick muon veto on 5 sides.



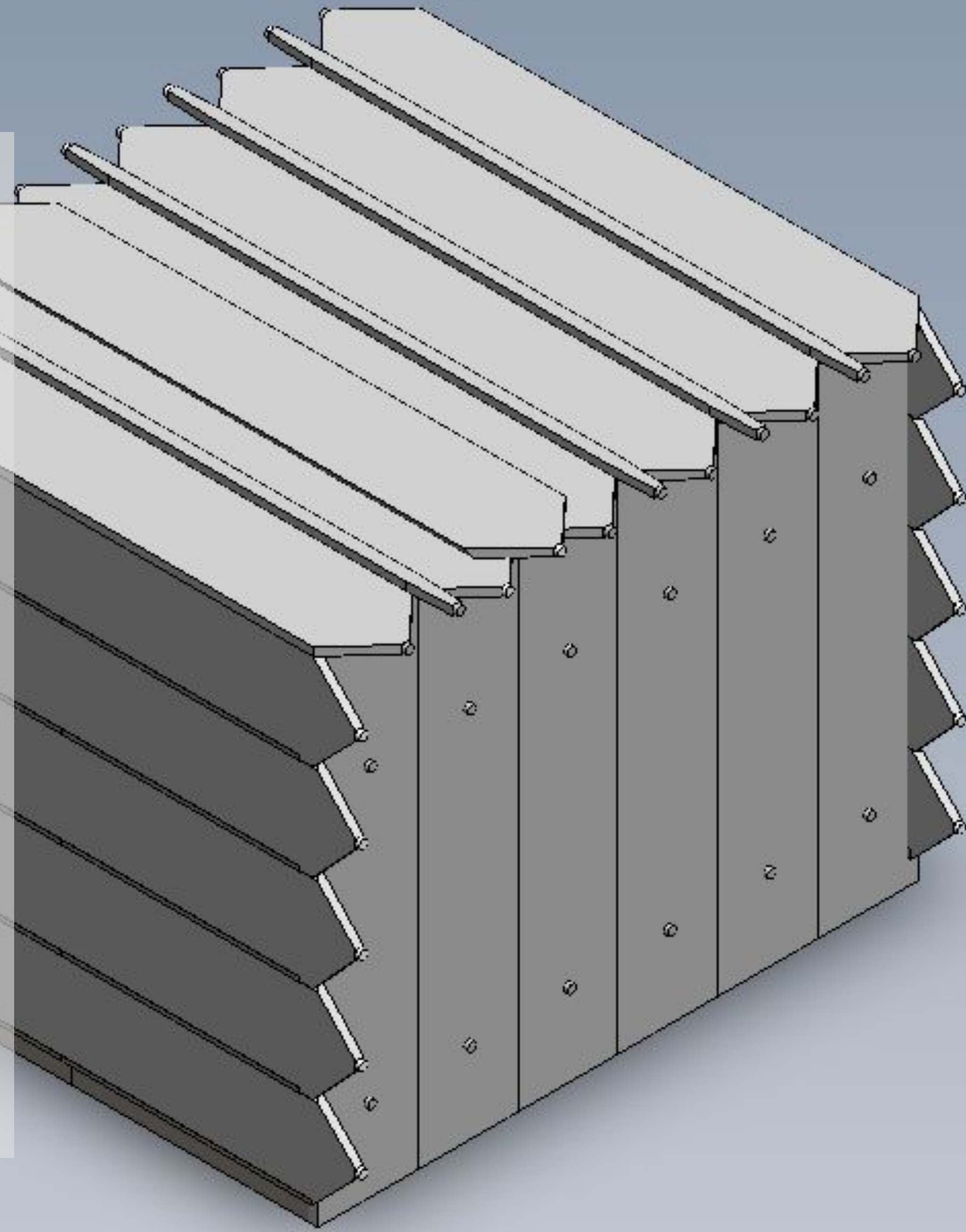
Detector Features

- To compensate for reduced flux, target will be 4m^3 of BC-525 (0.1% Gd);
  - expect ~20% overall efficiency
  - Per m^2 of footprint, ~10x as efficient as SONGS1
- Double ended readout using 24x10" R7081 PMTs
  - Acrylic windows, sealed via PTFE encapsulated o-rings
- Optical coupling and hydrostatic support via mineral oil
- Shielding from 6 interlocking water tanks (0.5m) and 2.5cm Borated Poly.
- 5cm thick muon veto on 5 sides.



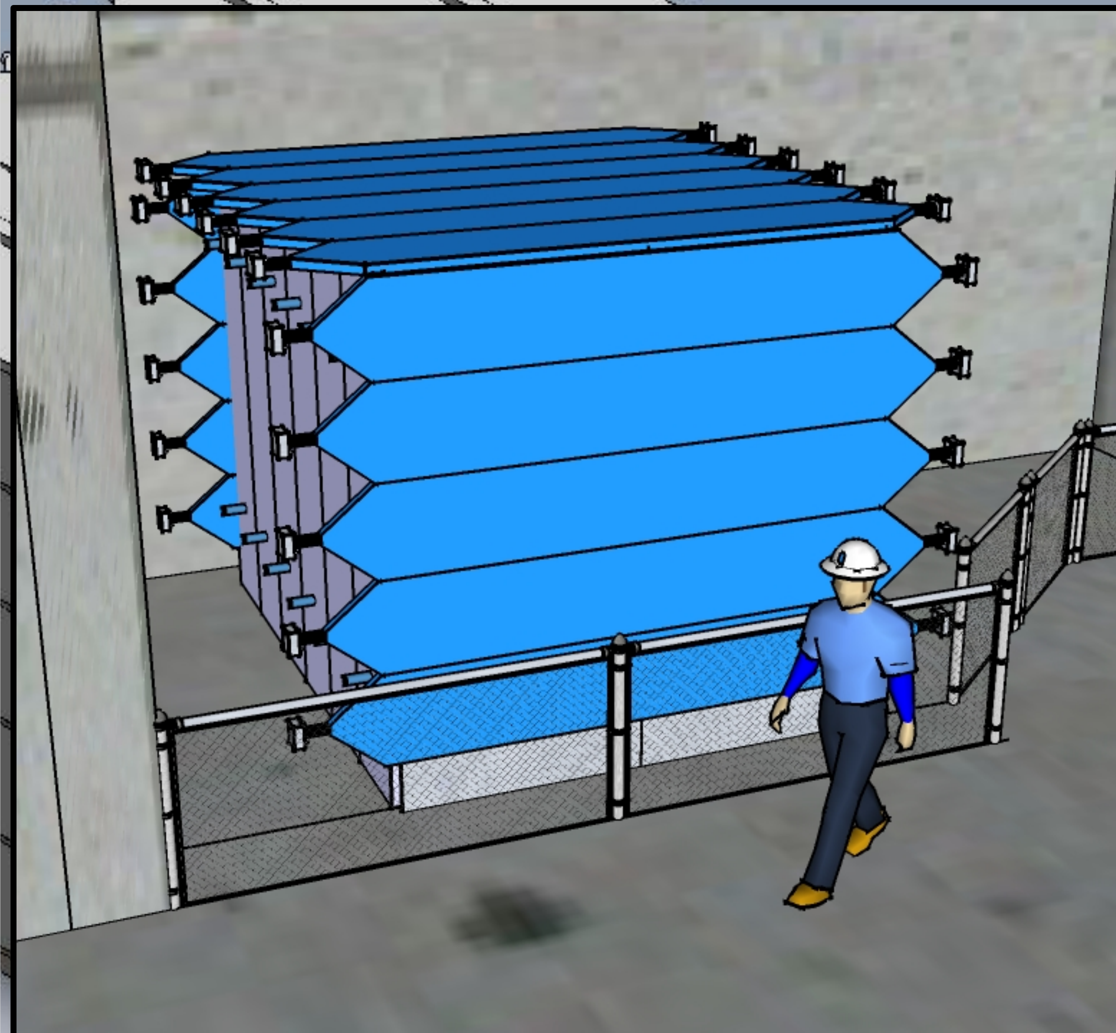
Detector Features

- To compensate for reduced flux, target will be 4m^3 of BC-525 (0.1% Gd);
  - expect ~20% overall efficiency
  - Per m^2 of footprint, ~10x as efficient as SONGS1
- Double ended readout using 24x10" R7081 PMTs
  - Acrylic windows, sealed via PTFE encapsulated o-rings
- Optical coupling and hydrostatic support via mineral oil
- Shielding from 6 interlocking water tanks (0.5m) and 2.5cm Borated Poly.
- 5cm thick muon veto on 5 sides.



Detector Features

- To compensate for reduced flux, target will be 4m^3 of BC-525 (0.1% Gd);
  - expect ~20% overall efficiency
  - Per m^2 of footprint, ~10x as efficient as SONGS1
- Double ended readout using 24x10” R7081 PMTs
  - Acrylic windows, sealed via PTFE encapsulated o-rings
- Optical coupling and hydrostatic support via mineral oil
- Shielding from 6 interlocking water tanks (0.5m) and 2.5cm Borated Poly.
- 5cm thick muon veto on 5 sides.



Prototyping, Regulation, Schedule

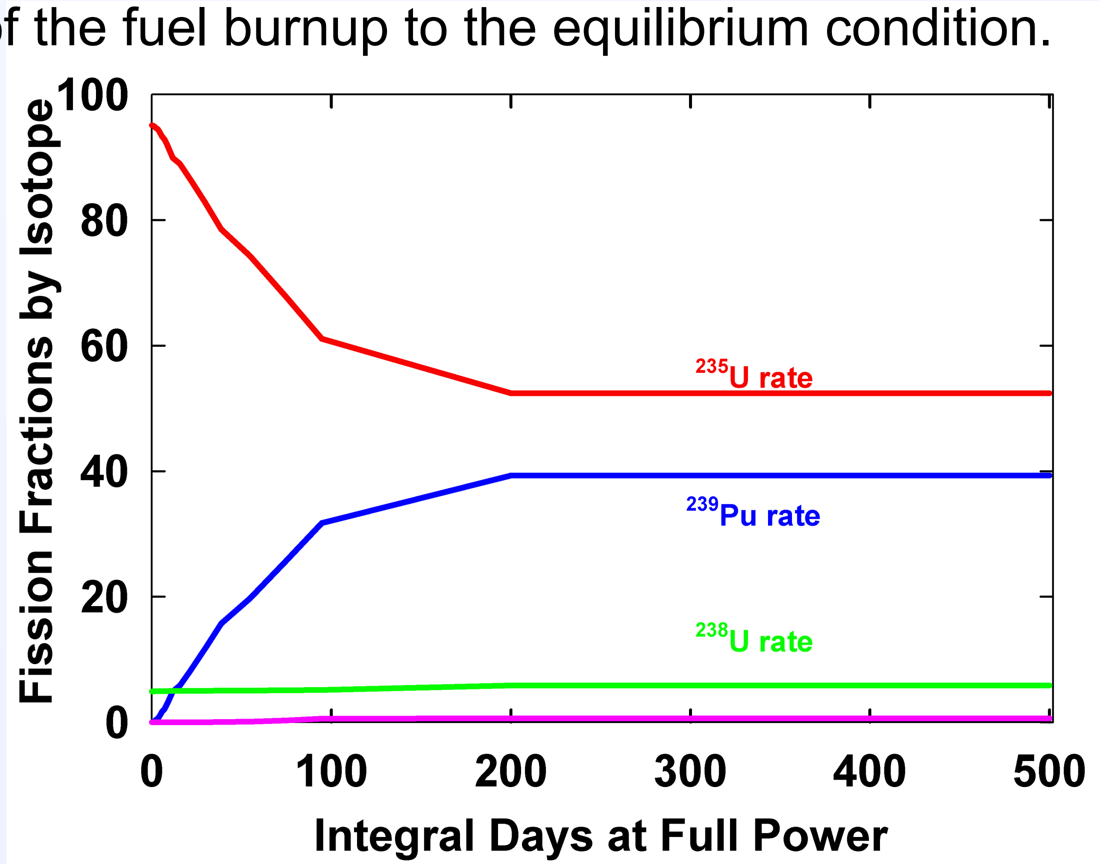
- A long term (1 year+) mechanical test of a double window cell has been conducting using SONGS1 BC525 liquid scintillator
- To be able to deploy at PLGS we have been required to perform:
  - Comprehensive Fire Safety Analysis
    - Minor recommendations included installation of local detection and fire retardant wrapping of cables above detector location
  - Third Party Review of Mechanical Design
- Upon completion of Mechanical Review, construction can begin
- Assembly and testing at Livermore late summer/fall
- Deployment Winter 2010-2011

Double ended cell, water leak test

Double ended cell, BC525, immersed in mineral oil

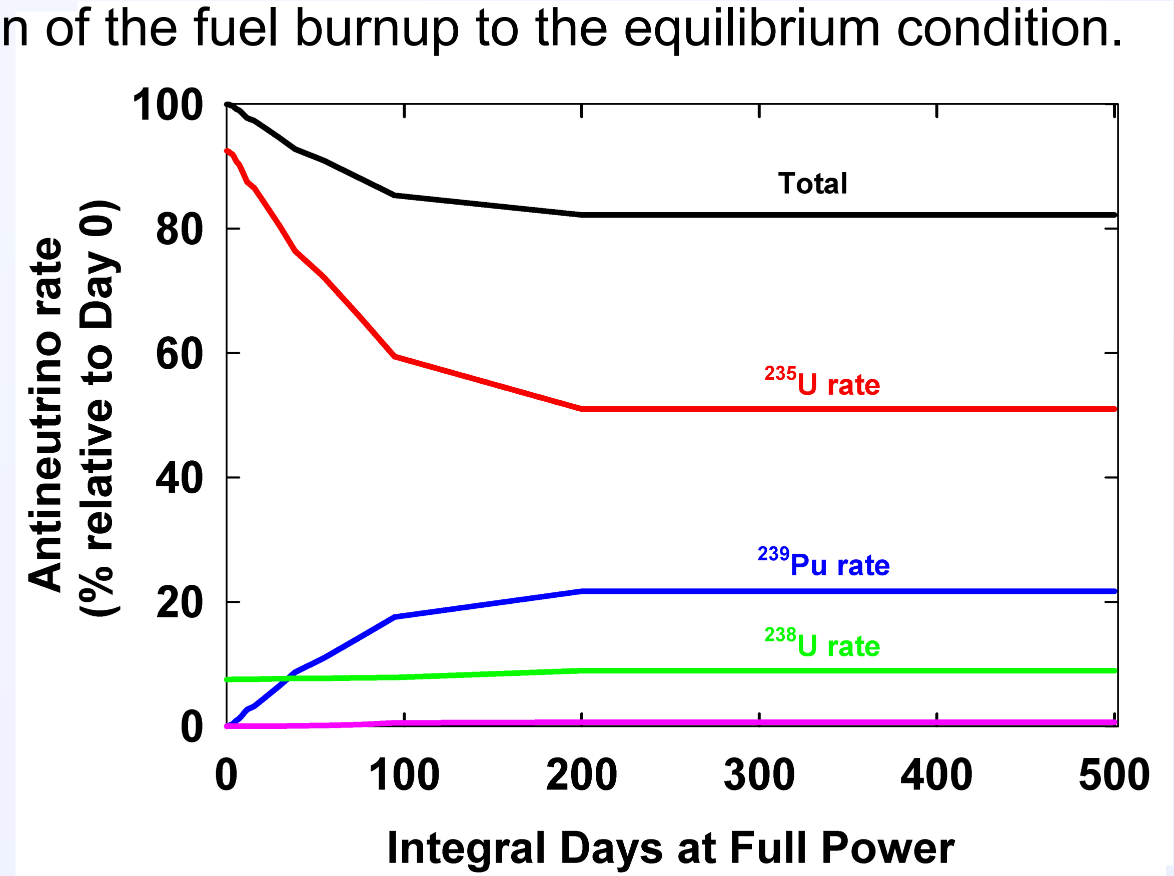
Expected Observation

- PLGS is currently being refurbished. For only the second (and likely last) time, it will have a fresh core load at restart
- Online refueling will begin at about FPD75; we expect to observe the evolution of the fuel burnup to the equilibrium condition.



Expected Observation

- PLGS is currently being refurbished. For only the second (and likely last) time, it will have a fresh core load at restart
- Online refueling will begin at about FPD75; we expect to observe the evolution of the fuel burnup to the equilibrium condition.



Conclusions

- Inorganic Li or B bearing scintillators can provide neutron capture ID, strongly suppressing much correlated and most uncorrelated background.
- These can be combined with organics to provide an antineutrino target and positron detection, but scaling up to cubic meter size is not straightforward.
- Online refueled and Bulk Process Reactors present distinct safeguards challenges – antineutrino detection could provide a unique capability to track the core loading of these types.
- A detector will be deployed at a CANDU plant to observe the fuel evolution at fresh startup and operation at equilibrium thereafter.