Jon Coleman, on behalf of the project
In the beginning: The ND280 ECal

- Electromagnetic Calorimeter consists of:
  - Active scintillator bars read out with WLS + MPPCs
  - Sandwiched with lead sheets
  - Magnetic field using UA1 Magnet Yoke
  - Major Liverpool involvement in design and construction
  - Survived the 2011 Earthquake
The ND280 ECal

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Detecting inverse $\beta$-decays

• Needed to modify the ECal
• Different signatures and environment than T2K
• Three main challenges:
  • Neutron detection
  • Trigger & DAQ
  • Aboveground operation
Neutron Detection

- Replacing lead with Gadolinium
- Provides ability to capture neutrons
  - Gd has second highest capture cross-section
- Produces characteristic 8 MeV γ-ray cascade
  - Compton scattering in detector
Trigger & DAQ

- Based on Trip-T chips (DØ and T2K)
- Front- and backend readout uses T2K hardware with modified firmware

- Changing from beam trigger to neutron trigger
  - Uses number of bars above threshold and total energy

- FIFO buffer of integration cycles stores data pre-trigger
  - Read-out upon trigger
Aboveground Operation

• Muon veto:
  • Implemented on trigger level
  • Reduces data rate and avoids deadtime

• Muon tracking:
  • Analysis level
  • Uses detector layout to identify tracks
Mobile Container Lab

• Full-scale prototype:
  • 1.7m x 1.7m x 0.8m
  • c. 1 ton active mass
  • c. 2000 channels

• Housed in climate controlled 20 ft. ISO shipping container

• Transport using standard HIAB truck
Mobile Container Lab

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## Liverpool Prototype Detector

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Solution</th>
<th>✔️</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inert construction</td>
<td>Plastic scintillator</td>
<td>✔️</td>
</tr>
<tr>
<td>Non-liquid</td>
<td>Plastic scintillator</td>
<td>✔️</td>
</tr>
<tr>
<td>Easy operation</td>
<td>Low voltage SiPMs (&lt; 120 V)</td>
<td>✔️</td>
</tr>
<tr>
<td>Cheap</td>
<td>Extruded plastic</td>
<td>✔️</td>
</tr>
<tr>
<td>Portable</td>
<td>Detector &amp; services in ISO container</td>
<td>✔️</td>
</tr>
<tr>
<td>Robust</td>
<td>Proven T2K ECal design</td>
<td>✔️</td>
</tr>
<tr>
<td>Aboveground operation</td>
<td>Integrated cosmic ray veto</td>
<td>✔️</td>
</tr>
<tr>
<td>Easy deployment</td>
<td>ISO container only requires 3-phase power plug</td>
<td>✔️</td>
</tr>
</tbody>
</table>

The Wylfa Magnox Power Plant

- Detector deployed 2014-2015
- Was last operating Magnox reactor in UK
  - Magnox design has been exported
  - Originally, two cores, one active during deployment
  - Final shutdown end of 2015
- Detector deployed c. 60m from reactor
  - Position outside inner security barrier (ISB)
  - Close to 3-phase power outlet
The Wylfa Magnox Power Plant

Detector Deployment
Challenges of Power Plants

• Not a research reactor

• Due to safety and security protocols:
  • Limited access
  • No standard connection to detector (dial-up modem!)
  • Need to write safety case
  • ‘dirty’ power

Resolvable Problems
Event Signatures

**Positron**
- Contained track
- Concurrent in time
- $E_{\text{max}} \approx 8 \text{ MeV}$
- Immediately after inverse $\beta$-decay

**Neutron**
- 8 MeV $\gamma$ cascade upon capture
- Multiple Compton scatters (many small hits)
- Spatially diffuse hits coincident in time
- Ca. 10 $\mu$s after positron
Event Selection

• Positron:
  • Continuous track/cluster
  • Short length
  • Only single positron in event

• Neutron:
  • Ratio of bars and total energy
  • Cluster size
  • Based on source measurements
Event Display

Neutron
Positron
Result: Preliminary Observation

- Reactor turn-on after refuelling
- 1.6 GW\textsuperscript{th} power
- At 60m distance
- Using self-contained mobile laboratory (20 ft. ISO container)
Return to Liverpool

• After Wylfa shutdown:
  • Detector returned to Liverpool early 2016
  • Background studies started

• Upgrade programme under Innovate-UK grant with JCS Nuclear Solutions

• Collaboration with National Nuclear Laboratory
Reactor Simulation

- Collaboration with NNL:
  - Access to core data (usually not accessible)
  - Highly experienced with core modelling
  - Strongly involved in nuclear data bases used for understanding β-decay chains

- Can produce anti-neutrino flux predictions at detectors
  - On full pin-by-pin level

from Robert Mills
Reactor Simulation

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  - On full pin-by-pin level
The Vidarr Upgrade

Improving performance and future outlook
Mass Upgrade

• First generation system has space mass upgrade (allows re-use of frame)
• Additional c. 50% active mass
• Increasing layer count from 49 to 70
• Scintillator arrived end of 2017
Upgraded MPPCs

• First generation used T2K-type MPPCs
• Upgrade to newest MPPCs
• New MPPCs characterised

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Quantum Efficiency [%]</th>
<th>Gain</th>
<th>Dark Noise</th>
<th>Crosstalk</th>
<th>Dynamic Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT</td>
<td>30-40</td>
<td>$O(10^6)$</td>
<td>kHz - Hz</td>
<td></td>
<td>Large</td>
</tr>
<tr>
<td>T2K MPPCs</td>
<td>20-30</td>
<td>$3 \times 10^5$</td>
<td>$O(10^6)$</td>
<td>10%</td>
<td>100s photons</td>
</tr>
<tr>
<td>Latest MPPCs</td>
<td>40-60</td>
<td>$3 \times 10^6$</td>
<td>$O(10^4)$</td>
<td>2%</td>
<td>100s photons</td>
</tr>
</tbody>
</table>
New Electronics

- 64-channel analogue board
- 64-channel Fast ADC mezzanine board
- Optical fibre link to μTCA backend board (AMC)
- 3 AMC boards connected to DAQ computer via ethernet
New Electronics

- Made for new MPPCs
- ‘deadtime-less’
- Lower data taking threshold (1-2 PE)
- Higher time resolution (10s of ns)
- Longer coincidence buffer (up to 100 μs)
- Boards in production
Simulated Neutron Event

- High threshold: 700 keV
- Number of channels: Low

- Reduced threshold: 100 keV
- Number of channels: High
- Spatially separated hits
Detector Simulation

• Implemented full GEANT4 simulation of detector
  • Optical model of bar + MPPCs
  • Full detector model

• Used to model detector upgrade:
  • Studying performance of new MPPCs
  • Simulation of new electronics
  • Modelling of new triggers
Up[graded Detector

Based on operational experience & technology advances

• Additional mass and channels
• Improved MPPCs & new readout system
  • Leads to lower thresholds
• Full Detector and Reactor Simulations
• Improved Trigger
Acknowledgements


• **NNL**: R. Mills
  • **NNL staff are** funded by a multi-year strategic internal research and development project

• **Special thanks to:**
  **Magnox Ltd at Wylfa Power Station**: G Davies, A Roberts, A Tobias
Flux Calculation

Fission Yield Data (JEFF) -> FISPIN

Radionuclide Inventory -> FISPIN

FISPIN -> Bespoke Post-Processor

Bespoke Post-Processor -> Antineutrino Flux

Antineutrino Flux -> BTSPEC

Reactor Data

Decay Data (JEFF)
Known issues with anti-neutrino calculation

- BTSPEC code is 35 years old; physics from the 1970’s and 1980’s.
- JEFF-3.1.1 radioactive decay data only has beta spectra information for 670 nuclides of > 1000 needed (~90% of beta decays, but majority of anti-neutrinos >1.8 MeV from the 670).
- Uncertain if spectral data is experimental or theoretical approximation, no estimate of accuracy.
- In current work BTSPEC is used to generate 1500 bins of 10 keV width (i.e. maximum of 15 MeV) for all 670 nuclides.
• Work done so far used FISPIN to generate inventories for all 49248 rods in core during each day of irradiation with irradiation/cooling history.