COMPARISON OF BORON-LOADED PLASTIC SCINTILLATORS FOR ISS-RAD

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CPDS Overview

- JSC operates 4 “CPDS” units.
  - CPDS = Charged Particle Directional Spectrometer.
  - “IV-CPDS” (inside, single telescope).
  - “EV-CPDS” (outside, 3-axis telescope).
- Standard silicon detector telescopes.
- Flying on ISS for nearly 10 years.
- Telescopes very similar to MARIE.
CPDS Instruments

Figure from 2007 WRMISS talk by Kerry Lee.
RAD as CPDS Replacement

- CPDS’s are old, 2/4 not operational.
- RAD for MSL was built by a collaboration of SwRI and CAU Kiel.
  - Charged particle telescope similar to DOSTEL.
  - Also neutral detectors (gamma & neutron).
  - Detailed MSL-RAD talk given last year.
- SwRI is building ISS-RAD with support from CAU Kiel team.
RAD Sensor Head (RSH)

- Thin silicon detectors for $dE/dx$.
- CsI stops protons up to 95 MeV & medium-energy heavy ions (e.g., Fe up to ~ 400 MeV/nuc). Replaced by BGO for ISS-RAD.
- BC-432 plastic for neutron detection (1.8 cm × 6 cm).
  - Hermetic anticoincidence also made of BC-432.
  - Scintillators read out with p-i-n diodes.
ISS Measurement Requirements

- Charged particle requirements similar to those for MSL-RAD, e.g., detect charged particles from $Z = 1$ to $Z = 26$.
- Neutral particle requirement is different: must measure neutrons down to $0.5$ MeV whereas MSL-RAD lower limit is $\sim 5$ MeV.
  - MSL RTG power source limits measurement at lower energies (too much background).
  - Plastic scintillator + photodiode method insensitive below about $5$ MeV anyway.
“Fast” Neutron Solution

- Considered several options for 0.5 – 10 MeV neutron detection.
- Settled on a separate detector in conjunction with a RSH that is ≈ same as on MSL.
- The two subassemblies – RSH and FND – will share a common housing and interface to ISS.
- FND will use a boron-loaded plastic scintillator with PMT readout.
  - Use double-pulse technique to identify neutrons and measure their energies.
  - Excellent background rejection.
A Brief History...

- 1986: 1\textsuperscript{st} boron-loaded plastic scintillator reported by Los Alamos group + inventor of BC-454, Chuck Hurlbutt.
- Previous flight instruments with boron-loaded scintillators:
  - LANL’s Neutron Spectrometer on Mars Odyssey.
  - APL’s Gamma-Ray and Neutron Spectrometer on Mercury MESSENGER.
Neutron Weighting Factor

- Can’t go much below 5 MeV with plastic scintillator + pin diode approach.
Neutron Weighting Factor

- FND adds sensitivity where $w_R$ is large.
Double-pulse method

- Neutrons are moderated by interactions with hydrogen in the plastic (recoil protons), producing a light flash.
- Neutrons that lose ≈ all their energy scatter until they escape or are captured by a $^{10}$B nucleus.
- $n + ^{10}$B → $^7$Li + $^4$He with 94% chance of coincident $\gamma$
  - $^7$Li has $E = 0.84$ MeV, $\alpha$ has $E = 1.47$ MeV, $E(\gamma) = 0.48$ MeV
  - Second pulse from capture reaction products, mostly from the $\alpha$. 


Background Rejection

- For a scintillator with 5% boron by weight (20% of which is $^{10}\text{B}$), average time for capture is ~ 2 μs.
  - Average time of ~ 10 μs for 1% boron.
  - Depends slightly on detector size.

- In electronics, set up two adjustable windows:
  - Time between 1$^{\text{st}}$ and 2$^{\text{nd}}$ pulse.
  - Amplitude of 2$^{\text{nd}}$ pulse.

- Capture-gating strongly rejects coincidence background from charged particles and $\gamma$’s.
  - No active anti-coincidence required in typical conditions.
Efficiency

- Multiple interactions required to thermalize incident neutrons.
- Larger scintillator = higher efficiency.
- Larger also means slightly longer average time to capture.
- MCNP model development underway at JSC.
Shielding

- Charged particle background is manageable with time & amplitude windows even in SAA.
- Ambient thermal neutrons possibly a problem → wrap scintillator in a material with large capture cross section, e.g., Cd or (more likely) Gd.
- Gamma & x-ray backgrounds also a concern but probably not too large inside ISS – Gd thermal neutron shield will also absorb γ’s.
Scintillator Tests at RARAF

- Radiological Research Accelerator Facility (RARAF) run by Columbia University
- Quasi-monoenergetic neutrons up to 14 MeV.
- We used 0.5, 1, 2, 3, and 6 MeV beams.
- Ran experiment August 3-5, 2011.
- Small cave → considerable “room background” from γ’s & scattered neutrons.
Scintillator Materials

- C. Hurlbutt now at Eljen Technology, got fresh samples from him:
  - Eljen EJ-254 with 5% boron by weight.
  - Eljen EJ-254 with 1% boron by weight.
  - Eljen EJ-200 with no boron.
  - Also, old piece of BC-454 (5% B) from St. Gobain.

- All samples are right circular cylinders, 5 cm diameter, 5 cm length.
- Each scintillator was connected to a PMT and read out by analog and digital electronics, prototypes of flight electronics.
Sensitivity Requirement

- Adding boron to plastic scintillator reduces transparency.
- Capture pulse is faint – 2.3 MeV released into $\alpha + ^7\text{Li}$, but light output only $\sim 100$ keVee due to quenching.
- We have to detect 0.5 MeV neutrons, light output from those $< 50$ keVee.
Event Data

- Data acq. triggers on single pulses, looks within a specific time window for a 2\textsuperscript{nd} pulse.
- Depending on neutron energy, see varying \% of 2-pulse events.
- More 2-pulse events seen at low energy due to higher probability of incident neutron being thermalized in plastic.
Time-to-capture Distribution

- $<\Delta t>$ between 1\textsuperscript{st} pulse (recoil protons) and capture pulse predicted to be 1.69 $\mu$s (Kamykowski).

- Filter data on 2-pulse events, apply amplitude window on 2\textsuperscript{nd} pulse, plot $\Delta t$ histogram.

- Expect exponential distribution, data fit better with exponential + const
  - Some residual background is not removed by pulse-height cut.

\begin{align*}
y & = P1 + P2 \times \exp(t \times P3) \\
<\Delta t> & = 1/P3 = 1.58 \text{ microseconds}
\end{align*}
Recoil Proton Energy

- Apply capture pulse amplitude cut and plot amplitude of $1^{\text{st}}$ pulse.
- See room background & 0.5 MeV neutrons.
  - Peak amplitude below that of capture pulse.
- This is BC-454 (5%) data.
- $\sigma/E \sim 30\%$. 

![Graph showing amplitude distribution.](image)
Energy vs. Peak Location

- Neutron peaks look Gaussian – broad, as expected.
- Peaks obey power law:
  - Fit of 0.5, 1, 2 MeV gives exponent of 1.79.
  - Reasonable agreement with $E^{1.6}$ predicted by Byrd & Urban.
  - May change as we improve calibration.
EJ-200 non-loaded scintillator

- Sanity check – look at EJ-200 to make sure we don’t see anything that looks like a capture pulse.
- Use 0.5 MeV data.
- Obviously no peak but a few events w/right amplitude.
- On closer inspection this is ~ same distribution as first pulse in BC-454.
  - “Second pulse” in this case is just a second 0.5 MeV neutron.
Conclusions

- All components performed well at RARAF.
- Data analysis just starting.
- 5% boron samples (EJ-254 and BC-254) are ~ identical.
  - This was not obvious given the different manufacturers.
- 1% EJ-254 should be most transparent, but scintillators with 5% boron appear good enough to see 0.5 MeV neutrons.
  - Shorter time window w/5% B → Less background
- Data from non-loaded EJ-200 will allow us to understand the backgrounds in the experiment.