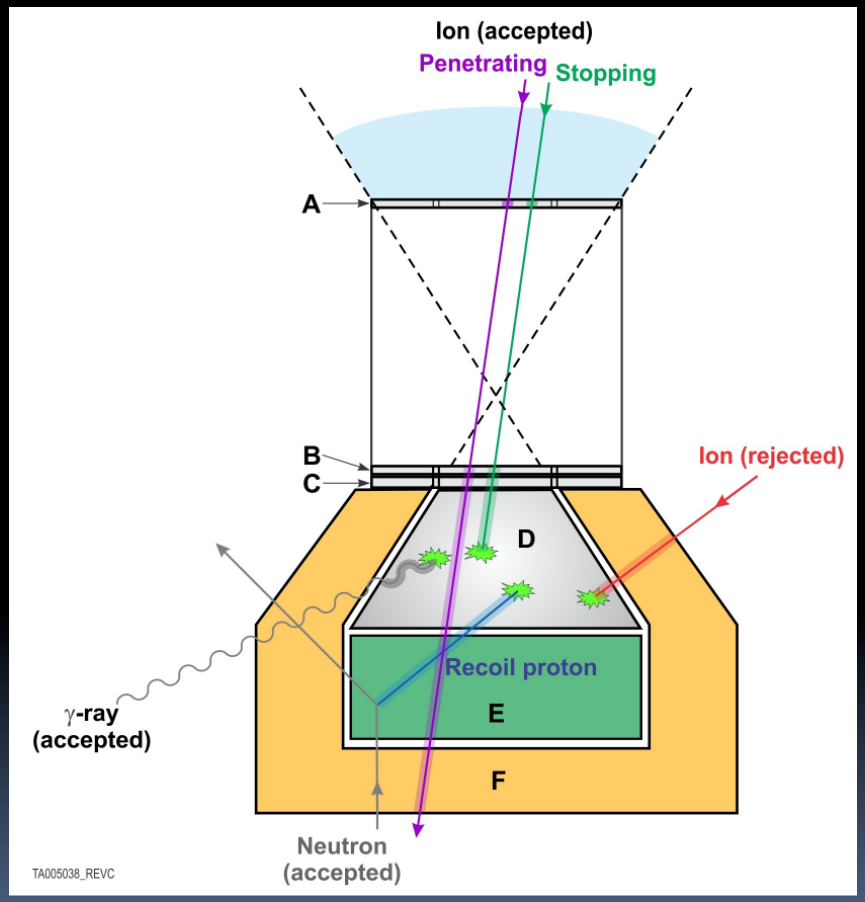
REFINEMENT OF MSL-RAD DOSE RATE MEASUREMENTS IN CRUISE AND ON THE MARTIAN SURFACE

Cary Zeitlin, Southwest Research Institute
On behalf of the MSL Science Team

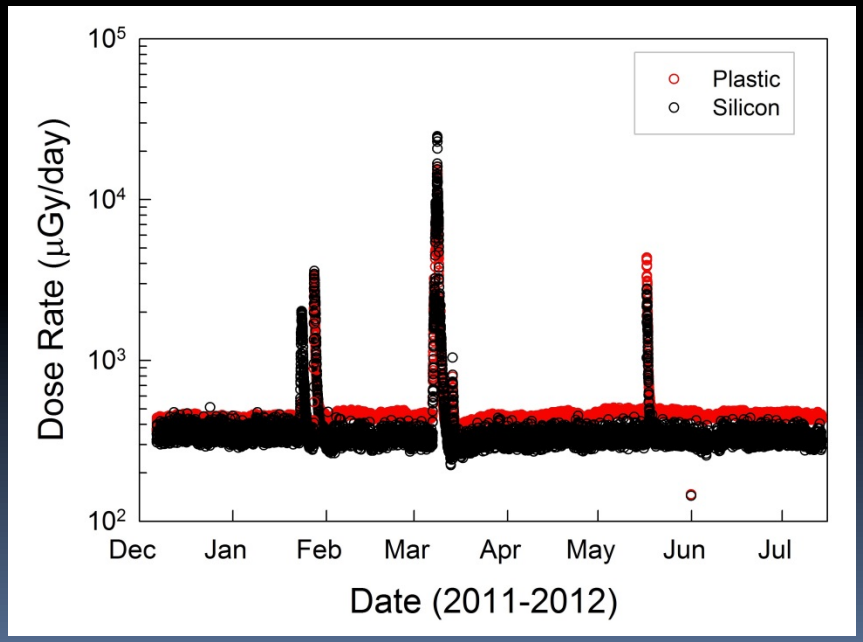
RAD Sensor Head Overview

- 3-element silicon detector telescope (A, B, C).
- CsI scintillator (D).
- Plastic scintillators (E, F).
- D and E detect neutrals (veto if other detectors hit).
- D and E → 3 diodes each for light collection.
- Hits in F reject charged particles from the side or from below.



Published Cruise Results

GCR flux model	Pions/included in transport	Dose rate (mGy/day)	Dose equivalent rate (mSv/day)	<Q>
Badhwar-O'Neill 1996	No	0.429	1.69	3.95
	Yes	0.507	1.70	3.53
Badhwar-O'Neill 2011	No	0.366	1.72	4.69
	Yes	0.445	1.80	4.05
RAD measurement		0.481 ± 0.080	1.84 ± 0.33	3.82 ± 0.25



- GCR dose rate, dose eq. rate, and <Q> were based on B only.
- 17% uncertainty in dose rate, 6.5% in <Q>, 18% in dose equivalent rate.
- GCR dose rate in E was 0.461 ± 0.092 mGy/day (± 20%).
  - Supports B detector result.

Can We Improve Accuracy?

- Accuracy affected by:
  - Threshold settings.
  - Onboard calibration.
  - Background from Curiosity's radioisotope thermoelectric generator (RTG).
  - Silicon to tissue conversion for B dose.
- Hard to understand without context, so next several slides are very detailed.

Dosimetry Triggers

- B dosimetry == hit above ~ 60 keV in B.
- E dosimetry == coincidence of hits in 2 of 3 diodes.
  - Coincidence requirement rejects events where signal is from direct hit, not scintillator.
    - Without coincidence, high rate of RTG γ's.
- No directional requirement.

Data Processing Level 2

- Onboard "L2" processing:
  - Applies calibration, determines "detector energy" according to the "gain selection" algorithm.
  - Performs temperature corrections.

Level 3 Processing

- L3 processing:
  - Data compression.
  - Histograms, including dosimetry.
  - Decides which pulse height records to store.
    - Not all can be sent to Earth due to telemetry limits.
    - Priority scheme selects most important events.
    - Get ~ 100% of particles in telescope FOV but small fraction of dosimetry triggers.
      - Have to use dosimetry histograms.

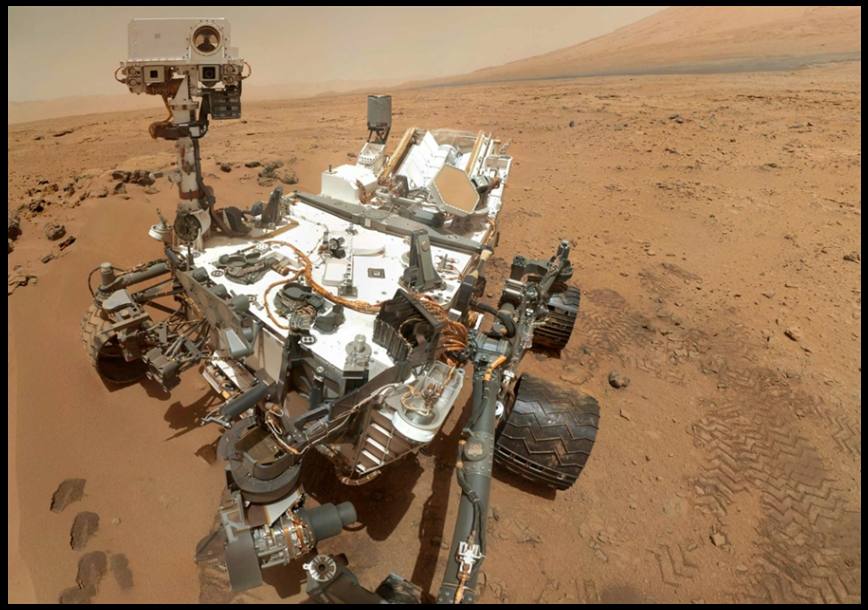
Calibration – Part of L2

- Onboard table has pedestals & gains.
- Level 2 applies these to get ΔE per channel.
- Each detector has 4 (Si) or 6 (scint's) readout channels with different gains.
  - Combine to get a single "detector energy."
    - A, B, C use ΔE from highest-gain unsaturated channel.
    - For D and E, combine signals from at least 2 of 3 diodes.
      - Improves resolution (reduce position dependence).

Dosimetry Histograms – L3

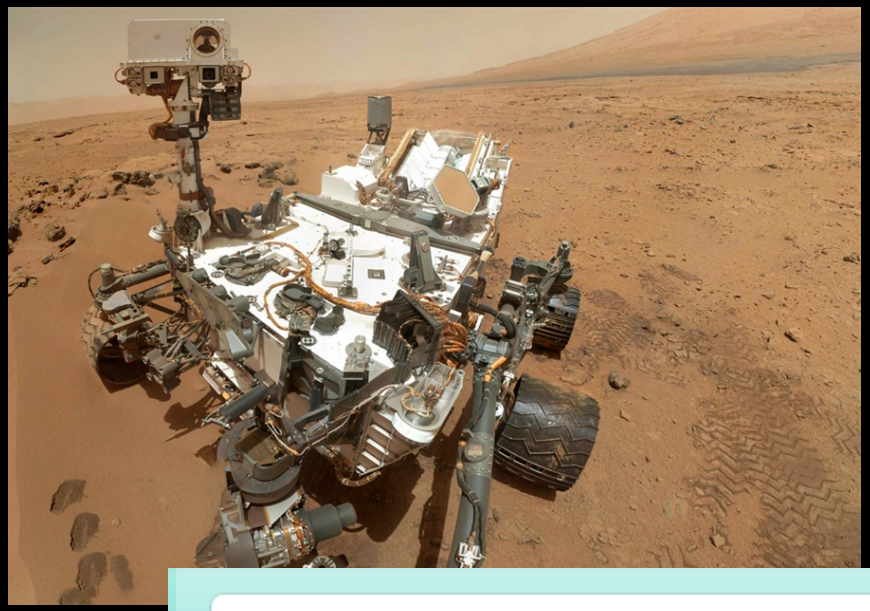
- On every B dosimetry trigger, the L2 ΔE is added to a running total.
- Separate running total for E triggers.
- Totals stored every 1/16th of an observation.
  - E.g., if observation duration is 32 minutes, totals are stored every 2 minutes.
- Data from the 1/16th intervals is not useful, too much scatter – we end up summing them.

RAD on Curiosity



- Curiosity is powered by a ^{238}Pu RTG → a constant background of neutrons and γ-rays.
- RAD is only ~ 1 meter from the RTG.

RAD on Curiosity



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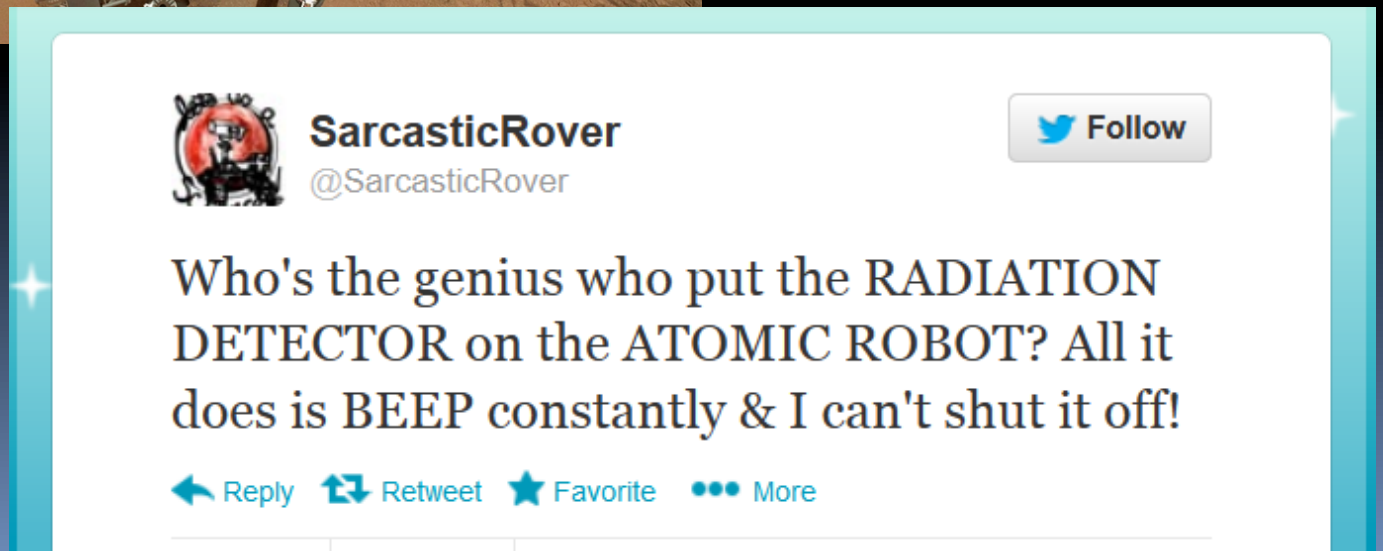
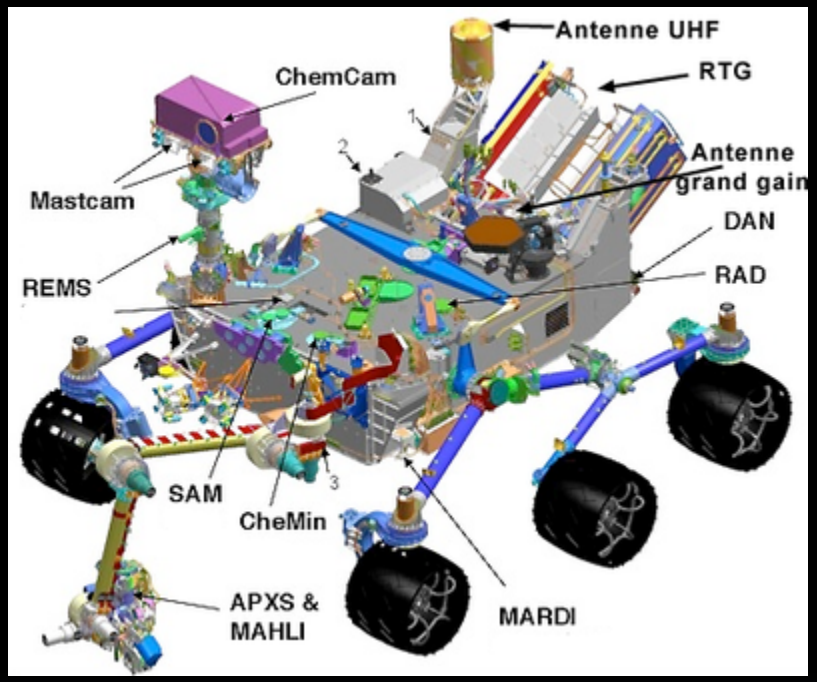
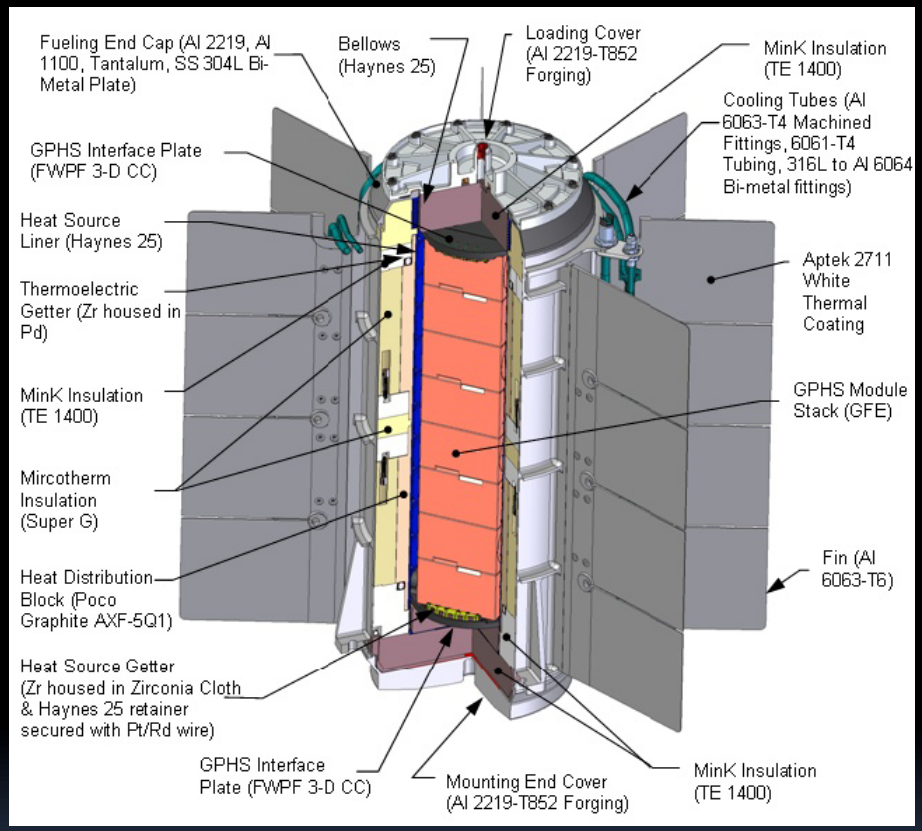


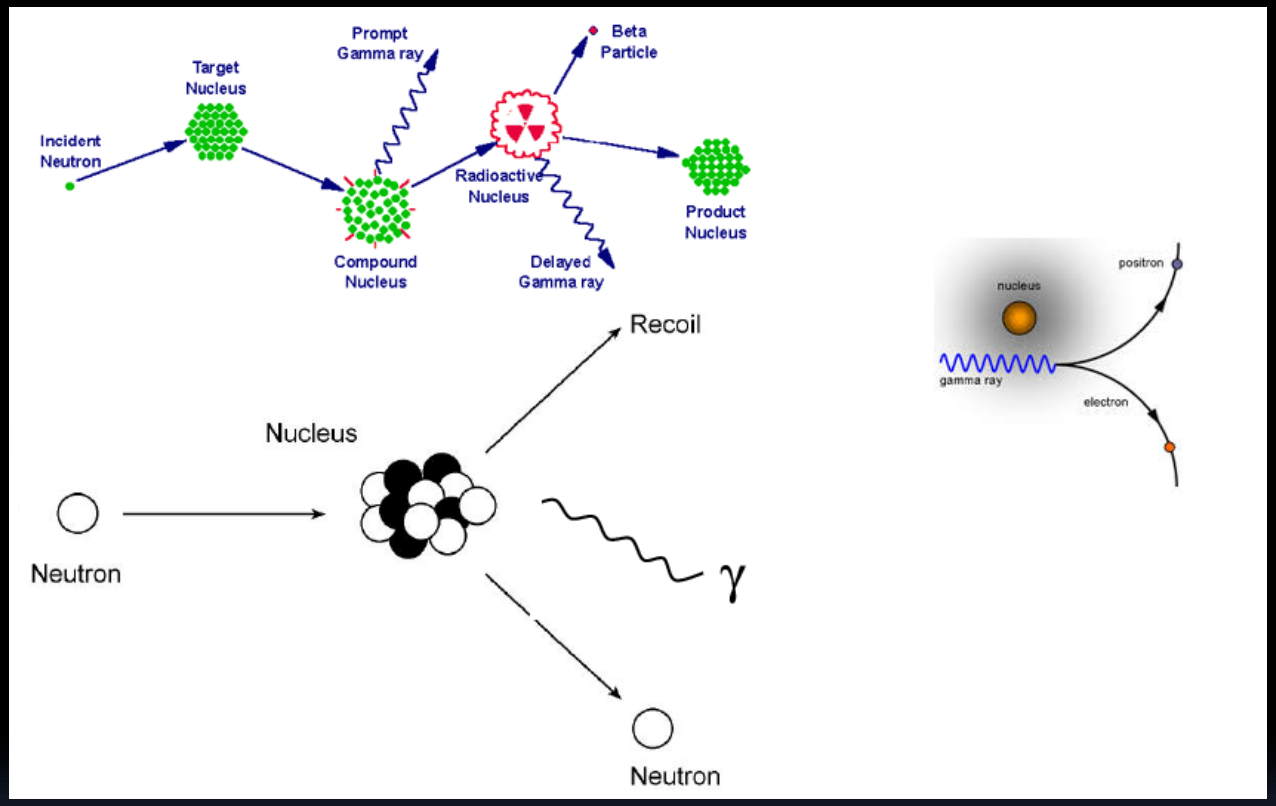
Curiosity's RTG





- RTG mostly above deck – lots of mass.
- Interactions → particles in RAD.
  - That part of the flux is same for cruise & surface.

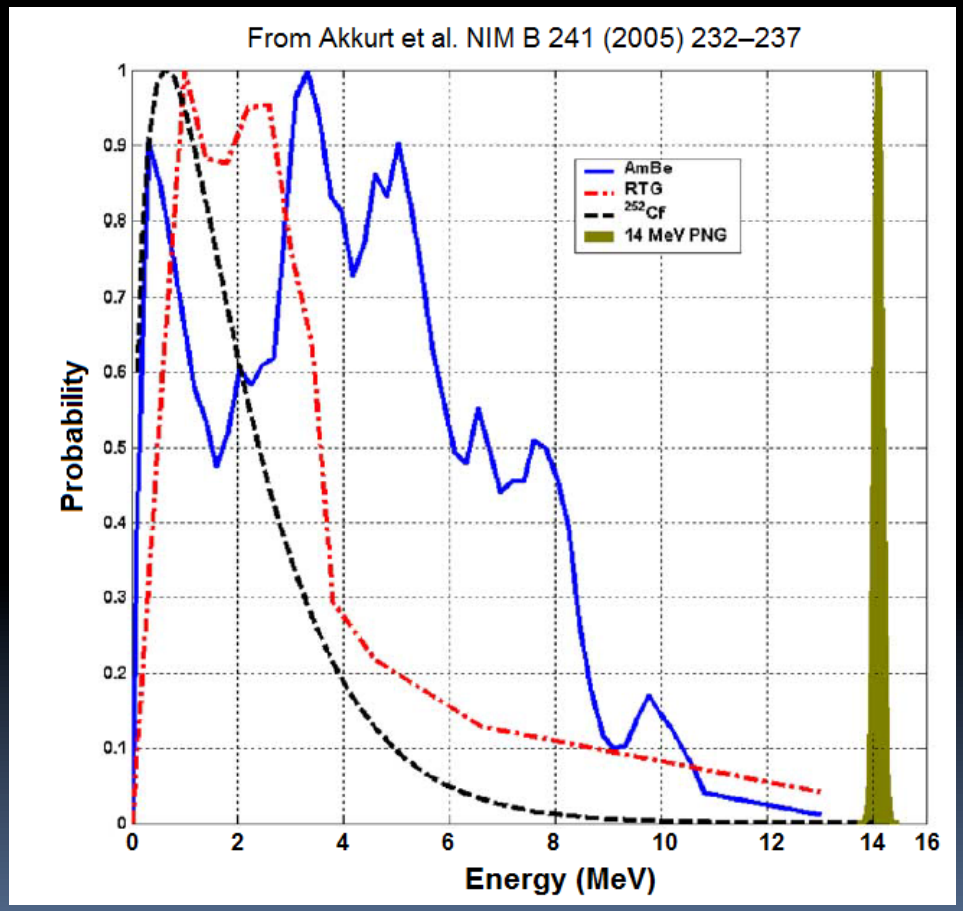
RTG Neutrons → Particles in RAD



- Direct neutrons, but detection efficiency is low.
- Other ways RTG creates particles in RAD:
  - n+nucleus interactions produce prompt γ's, delayed γ's, β's.
  - γ's with enough energy can pair produce.

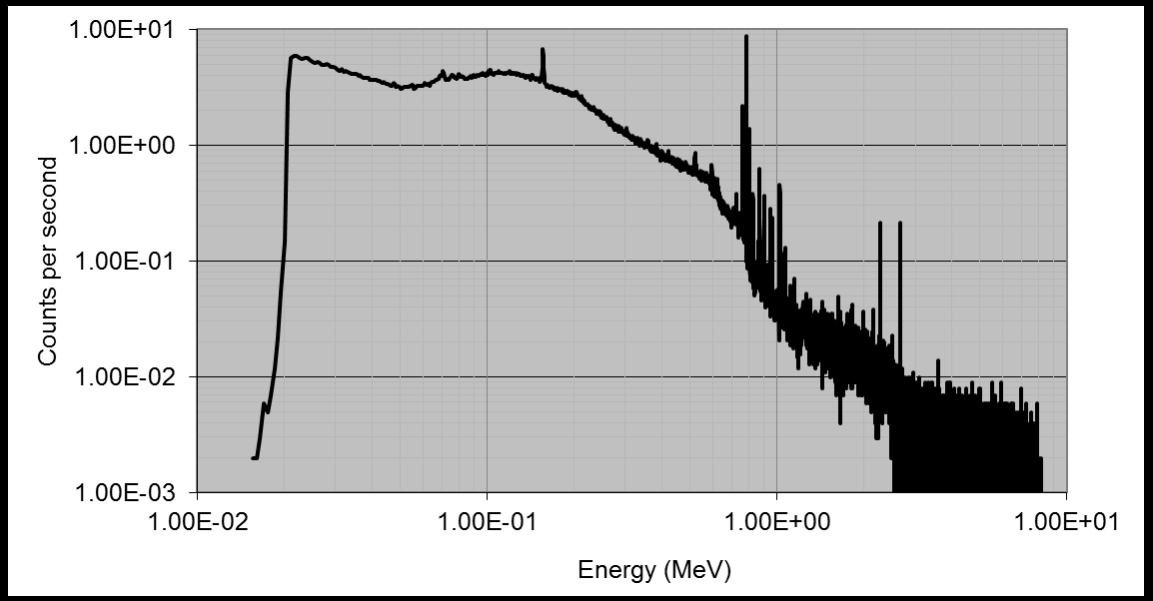
Direct Neutrons from RTG

- Large majority of RTG neutrons have E < 4 MeV.
- E neutron detection efficiency falls off below ~ 5 MeV due to low gain.
- Rover body, etc., provide some shielding.



Thanks to E.S. for the Akkurt paper.

RTG Gamma Data from Cape



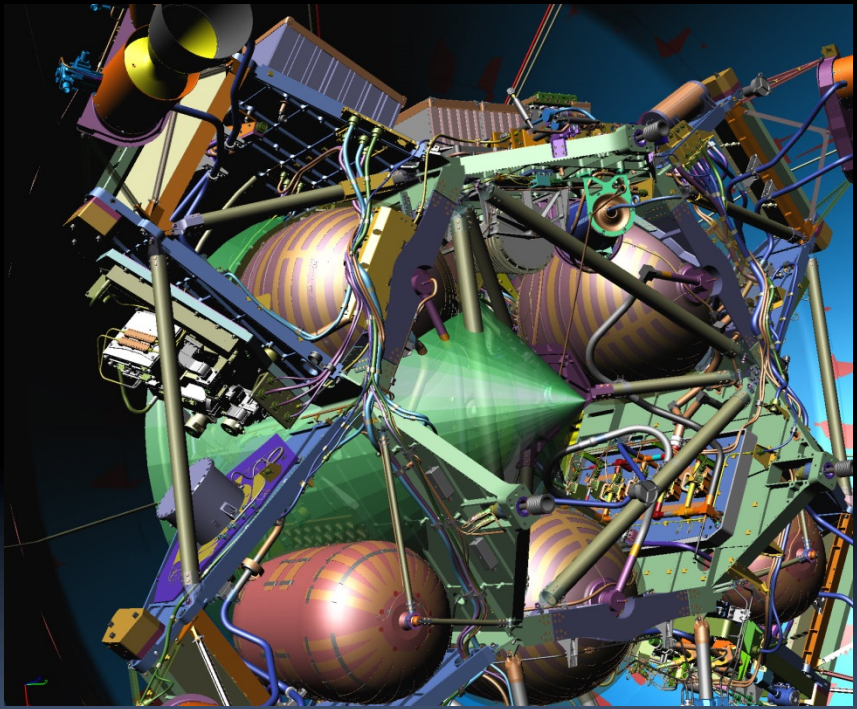
- Savannah River DoE (SRS) group measured RTG γ's.
- Vast majority of flux has E < 1 MeV.
- Both B and E see γ's, but:
  - B is small, detection efficiency is very low.
  - E detector threshold ~ 3 MeV.

Dose Estimates from SRS Data

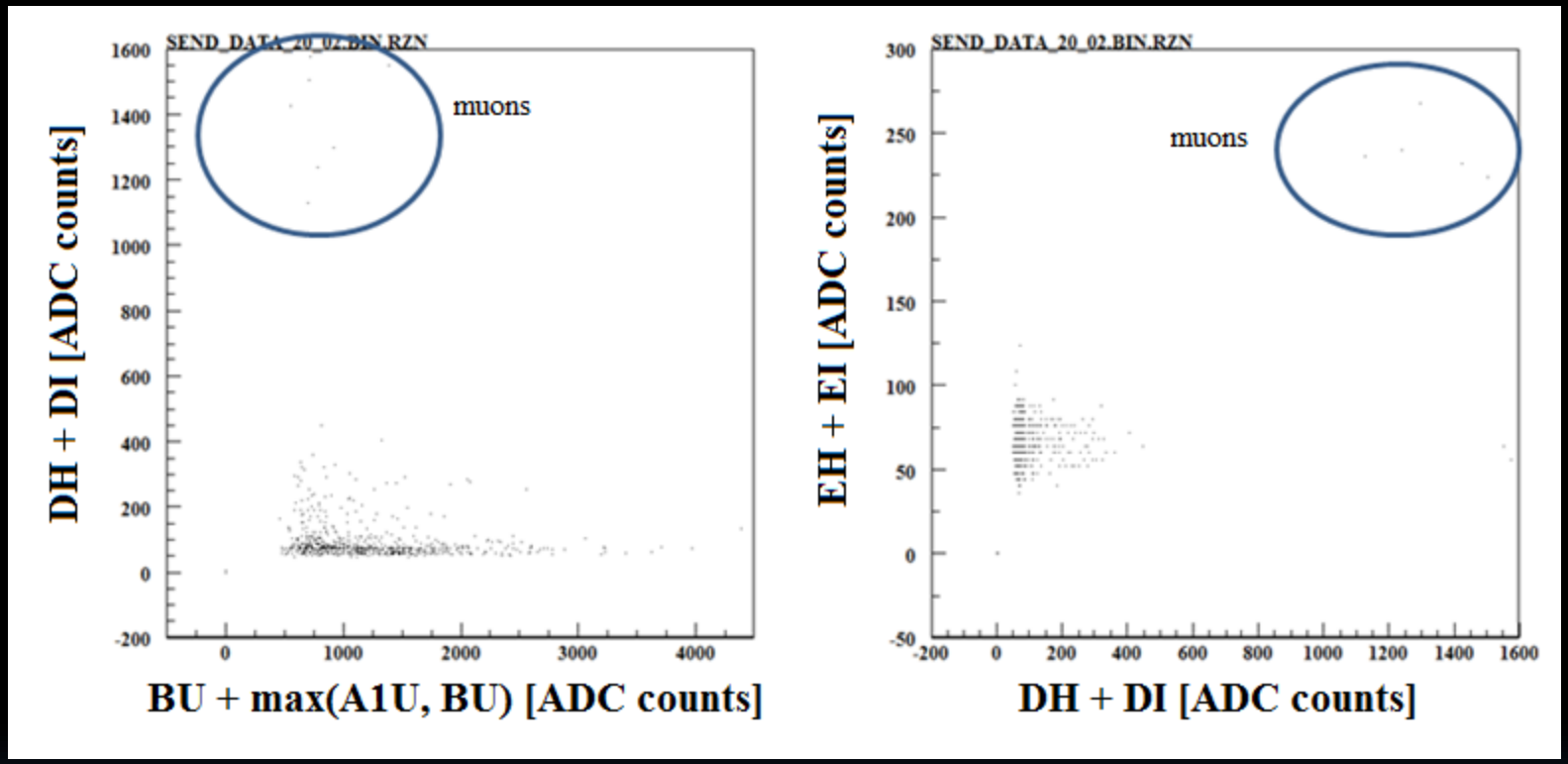
- Detector was 5.8 m from RTG, extrapolate to 1 m assuming $1/r^2$ dependence.
- Integrating measured spectrum → dose rate from γ's at RAD position ≈ 400 μGy/day.
- Convolve measured spectrum with attenuation lengths → upper limits:
  - B dose rate ~ 5.5 μGy/day.
  - E dose rate ~ 2.9 μGy/day (3 MeV threshold).
  - Both ~ negligible.

RAD Measurement of RTG Background

- RAD was turned on for 1 hour on the Cape after installation of RTG.
  - "Hour of Power."
- 85 μGy/day in B, ~ 0 in E.
- Descent Vehicle including fuel tanks, etc., just above RAD.

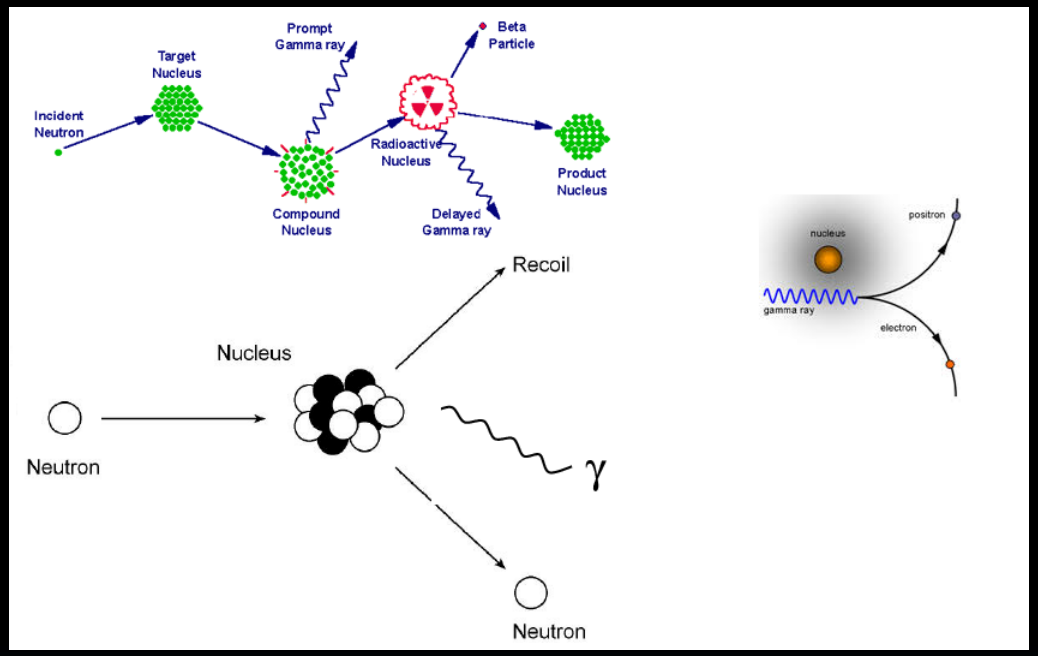


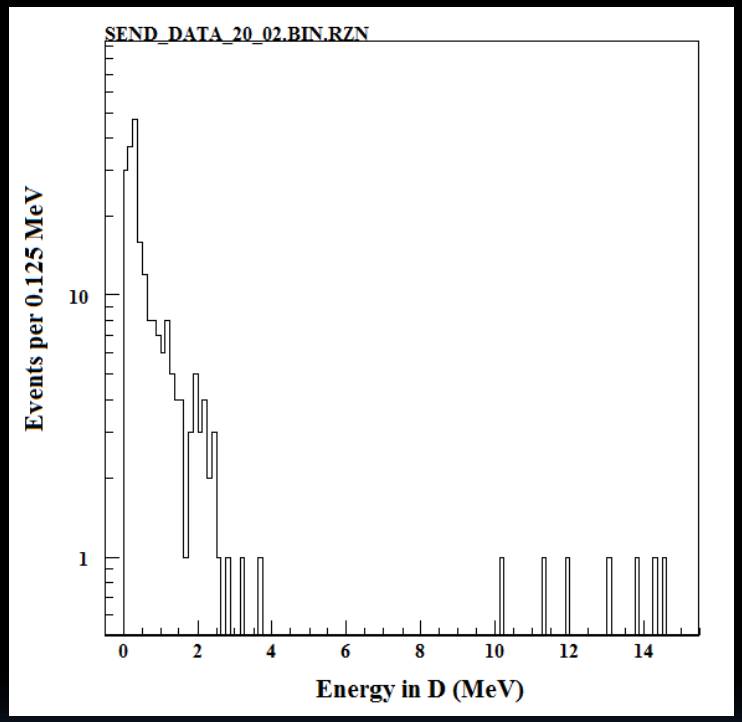
Hour of Power – Charged Particles



- In both D vs. (A+B) & E vs. D, see cosmic-ray muons, not surprising since RAD was vertical during test.
- Rest of particles look like mips in A+B but only ~ few MeV ΔE in D (<< muon ΔE) + nothing in E detector.
  - These can only be electrons.

RTG → Particles in RAD, Revisited





- Most of the RTG dose in B is due to electrons.
- Therefore it's not surprising we don't see anything in E – it's shielded by D & F.

Hour of Power E Dose Rate

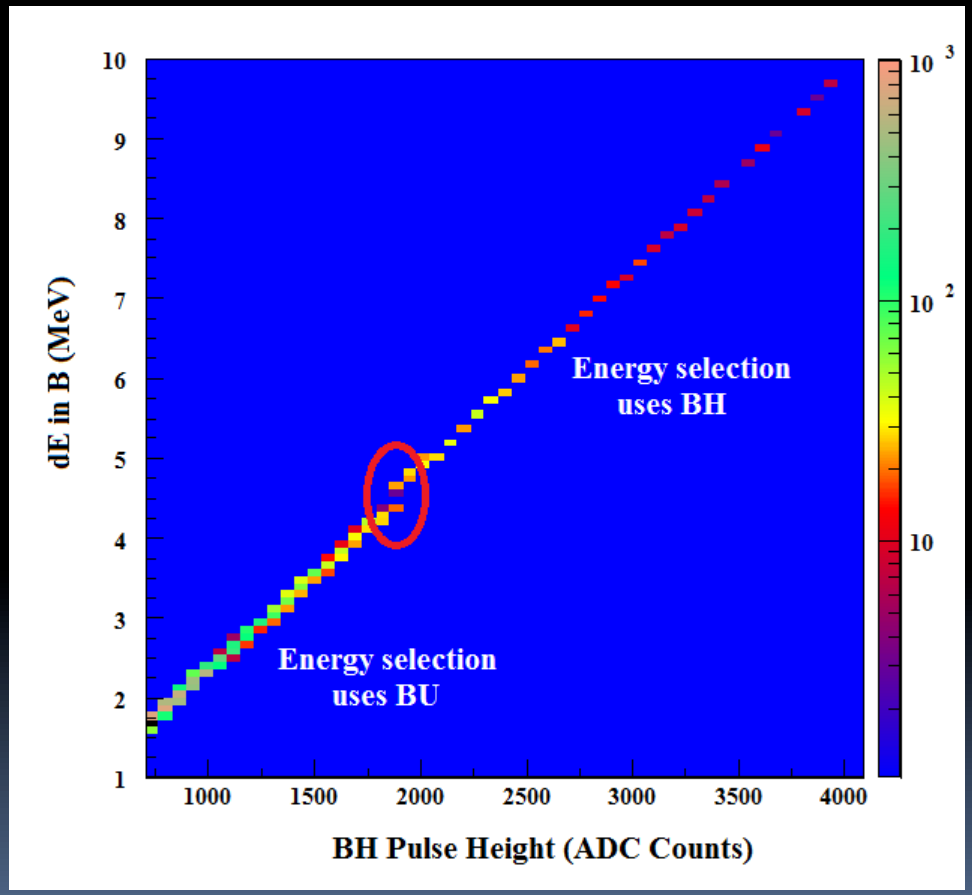
- E thresholds were lowered after Hour of Power, but if background is dominantly e^-, dose rate is still ~ 0.
  - Energy to penetrate minimum shielding around E (1.2 cm of plastic) is ~ 3 MeV + ΔE to get to threshold is ~ 3 MeV, so need > 6 MeV total.
  - Flux of e^- with E > 4 MeV was 0 in Hour of Power.

Onboard Histograms → Dose

- Dosimetry histograms record ΔE sum.
  - 2 B histograms, one for high-LET, one for low-LET.
    - Different throughput efficiency.
  - Corrected results are summed, divided by (acquisition time * detector mass).
- Mass of B is 0.134 g, E is 34.8 g (~ 250×).
- For B, subtract RTG background to get Si dose.
  - Multiply by "Si to tissue" factor.

Dosimetry Results Depend on Onboard Calibration Parameters

- Known issues:
  - Pedestal is approximated by noise peak, not completely accurate.
  - At points where the onboard calculation of ΔE switches from one gain to another, transitions are not perfectly smooth.
  - No quenching correction → E dose underestimated.

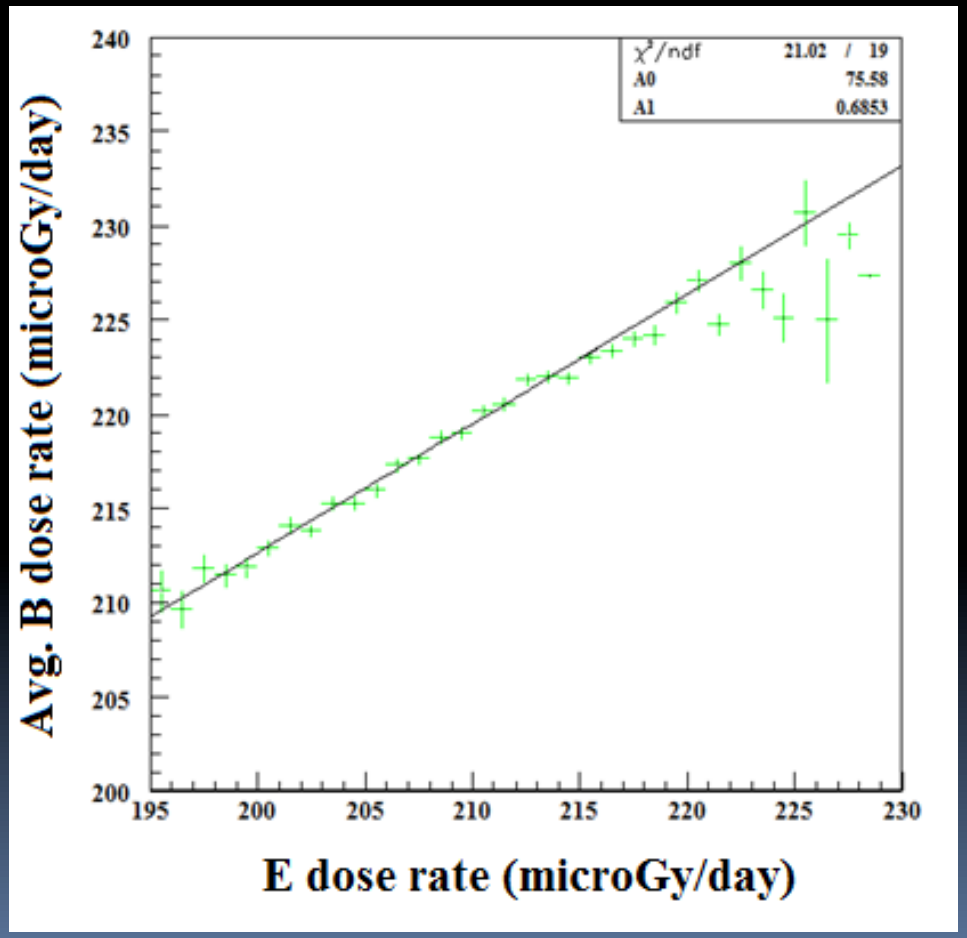


RTG Background in Surface Configuration

- No way to directly measure the effect of removing the mass that was above RAD.
  - Can't turn off RTG, can't turn off environment.
- Try to infer from data.

B-E Dose Rate Correlations in Surface Data

- With ~200 sols of data, find linear relation between B and E dose rates (pretty good χ^2).
- `B_dr = a0 + a1*E_dr`
- Associate `a0` with RTG dose rate in B, `a1` with Si-to-tissue conversion factor.
  - Can't use for cruise data – not enough variation.
  - Works in surface data because of diurnal variation (daily rise and fall of atmospheric pressure).



Interpreting B vs. E Fit

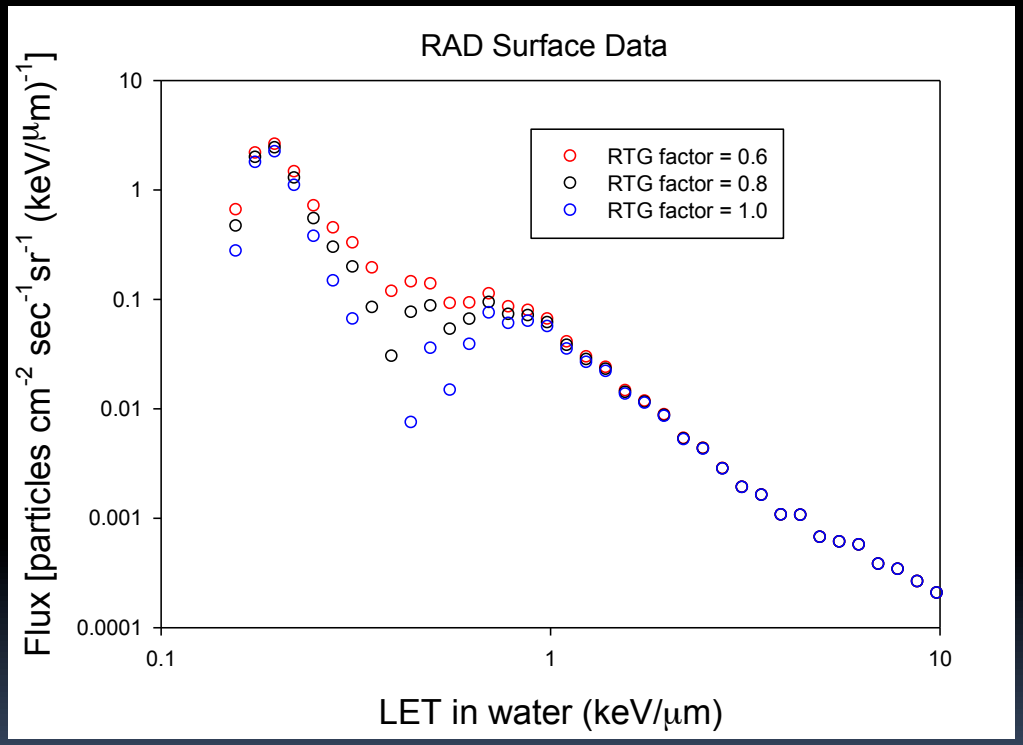
- a0 = 75.6 μGy/day
  - Was 85 μGy/day in Hour of Power.
- a1 = 0.6853, 1/a1 = conversion factor = 1.46.
- We used 1.45 in the *Science* paper (± 15%).
  - Factor of 1.2 commonly used.
- Fit depends on B and E calibration.
  - Subject to change.

Dose Equivalent Calculation

- LET spectrum – all uncertainties in play:
  - Use ΔE spectrum in B with onboard calibration.
  - Subtract RTG spectrum.
  - Convert ΔE in Si to H_2O.
- Determine errors using full error propagation including cross terms.
  - Scale errors in calibration tend to cancel in calculation of <Q>.
  - RTG subtraction differences also tend to cancel in calculation of H.

RTG Effect on LET Spectrum

- LET spectrum below about 1 keV/μm affected by RTG.
- <Q> varies with RTG scale factor, but not much:
- 0.6 → <Q> = 2.82
- 0.8 → <Q> = 3.05
- 1.0 → <Q> = 3.31
- Dose also varies but in opposite direction, i.e., smaller RTG scale factor → higher dose.
- H = D * <Q> so variation is relatively small.



Conclusions

- This work is just starting – all sources of systematic error need more study.
- B calibration: Assumed ± 7%, this included consideration of the gain switching.
  - Room for improvement.
- E calibration error was taken to be ± 20% largely due to concerns about (lack of) quenching correction.
- B vs. E dose rate on surface gives us a bit more confidence in the Si-to-tissue factor.
  - Dominant uncertainty when using B.

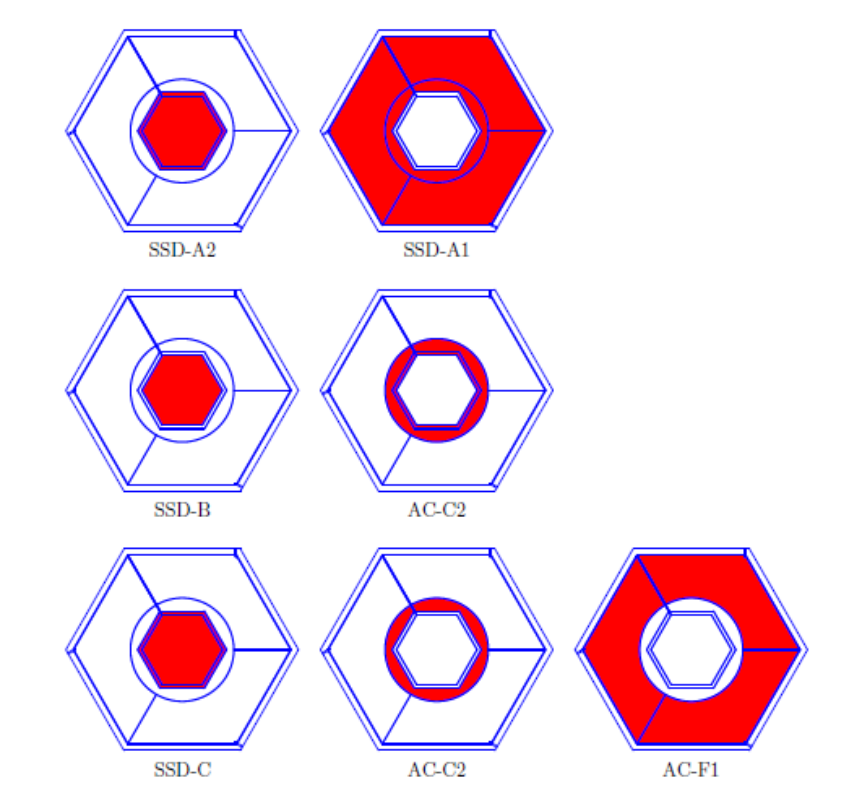
Backup Material

Readout Electronics

- Sensor head has low-noise preamps & shaping amps.
  - A1, A2, B, and C preamp outputs are split into two shapers (→ 8 signals out of sensor head).
  - D and E each have 3 diodes for readout, each produces 1 signal (→ 6 signals).
  - F1, F2, and C2 have 1 output apiece → 3
  - 17 total.
- On "analog board," each shaped signal from sensor head is input to 2 separate channels of the VIRENA ASIC → 34 of 36 channels used.
- VIRENA has additional amplification available, typically in a redundant pair of channels, one gets x8, the other x1.

Segmentation of A, B, C

- Inner A segments = A2.
- Outer A = A1.
- "C2" anticoincidence channel includes segments on B and C.
- Outer C segments collect light from F1 scintillator.
- Each detector has 4 readouts with differing gains: U, H, M, L.



Triggers

- RAD allows up to 16 coincidence conditions to be defined as individual triggers. Examples:
  - A1U*BU fires on low-LET charged particles in the telescope, outer A segment.
  - A2M*BM fires on high-LET charged particles in the telescope, inner A segment.
  - BU alone = "B dosimetry," fires on any hit above threshold in B.
  - EH*EI = "E dosimetry," fires on any hit above threshold in two E diodes with high gain.
  - EH*EI*!F1*!F2*!C2*!CU*!BU = E neutral, like E dosimetry but also require nothing in anticoincidence.