

Neutron Radiation Identifier & Dosimeter – NRID

Phase II Sequential A002: Final Report

Issued: 13 JAN 2023



**Radiation Detection
Technologies, Inc.**



Reporting Period: Aug. 03, 2020 – Jan. 13, 2023

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USA CONTRACTING CMD-APG. - W911SR
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2.0 Program Overview

- **Contract:** W911SR-20-C-0039
- **Overall period of performance:** 03 Aug 2020 – 02 Aug 2022 [No-Cost-Extension (NCE) to 13 Jan 2023]
- **Team Contact Information:**

Primary Organization

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2.1. Project Scope:

The main objectives of the work herein was to develop a full-scale, commercially transitionable, portable neutron spectrometer. A Phase I demonstrated a proof-of-principle portable neutron spectrometer prototype. A Phase II added new capabilities to, expand some existing capabilities on, and increase the technology readiness of the proof-of-principle prototype solid state neutron spectrometer previously built by the proposing team: RDT and UMKC. Phase II sequential work was development and commercialization of an advanced portable neutron radiation identifier, imager, and human dose equivalent measurement device. The Neutron Radiation Identifier & Dosimeter (NRID) is a small, portable, cost effective, military-grade, neutron detection instrument for identification, localization, differentiation, and human dose equivalent measurement. The device is designed to detect neutron source emission spectrum to positively identify the source, e.g., Cf-252, AmLi, and AmBe sources.

2.2. Project Objective:

Neutron detection and identification is required to locate radiation sources and determine the threat and/or nature of radiation material, whether it presents immediate dangers to life and health, and to identify if it is a potential WMD or other type of radiation material (industrial, medical or other). This effort pursued more efficient methods for modifying this technology into a lightweight handheld and cost-effective configuration. This project was built on lessons learned during the Phase II effort (HDTRA1-C-16-002). The Phase II sequential prototype improved upon the Phase II prototype by optimizing the detector-moderator configuration, ruggedizing the detector packaging, redesigning the detector electronics, and refining the identification and directional localization algorithms.

The objective of this effort is to produce an instrument with average intrinsic neutron-detection efficiency from the thermal to the top-end of the neutron evaporation spectrum of $\geq 5\%$, while maintaining manageable instrument weight that is far less than the presently available alternatives; achieving neutron imaging with a directional resolution of $\leq 10^\circ$ with < 1000 counts¹; differentiating fission sources from alpha-n radiation sources; measuring neutron human-dose equivalent accurately with $< 20\%$ error; final testing of neutron radiation sensitivity; designing and building instrument packaging to meet rugged environmental and physical requirements; and, deploying an appropriately-sized instrument relative to customer need, weighing less than 20lbs. The contractor shall deliver one (1) complete operational neutron radiation identification devices per vendor technical proposal.

Anticipated applications of projects: provide a viable long-lifetime semiconductor-based neutron spectrometer for remote neutron detection, identification, and dosimetry CONOPS.

2.3. Project Deliverables:

Submit in electronic format in Microsoft Office (Word, Excel & PowerPoint) or in another format approved by the Government to: tierre.s.cobb.civ@mail.mil (SFAE-CBD-RND) and Melissa.a.bettinger.civ@mail.mil (CCAP-SCE).

Table 1: Project Deliverables - Contracts Data Requirements List (CDRL) Form 1423. (Updated JUL 2022 per signed Amendment P00004)

CDRL Number	Description	Due Date	Submitted Date
A001	Monthly Status Report	Due 15 th of each month	As necessary.
A002	Draft Final Report	07 DEC 2022	07 DEC 2022
A002	Final Report	13 JAN 2023	13 JAN 2023
A003	Draft Project Summary Report	07 DEC 2022	07 DEC 2022
A003	Project Summary Report	13 JAN 2023	13 JAN 2023

3.0 Project Summary

The NRID instrument detector-moderator configuration was optimized, the packaging was ruggedized, the detector electronics redesigned, and the identification and directional localization algorithms developed via AI/machine learning. The individual components for the NRID have

¹ Based on customer feedback during the Kickoff Meeting, we was consider imaging a low priority task and the focus of our efforts was be optimizing neutron source identification. Source directionality was still be performed to assist the operator in positioning the NRID correctly to accurately use the source ID feature.

been designed and manufactured. All parts have been assembled into the final prototype system. The NRID is splash proof, wipe-down-decontamination compatible, and has been designed for an IP66 rating. AI/ML algorithms have been developed, implemented, and have achieved approximately 75% success rate on source ID with 10,000 counts measured and about 87% success rate with 25,000 counts measured, while disregarding source location information (a worst-case scenario). These metrics are based on simulated data. More testing is needed to understand how well the simulated result translates to lab and field measurements. In future work we envision a hybrid approach to match the simulations to lab collected data (by tuning MCNP geometries and materials) and incorporate lab/field measured data into the AI/ML training algorithms will improve the ID accuracy. The digital infrastructure is now in place to allow for more rapid optimization and expansion of the source ID library.

Unfortunately, due to time constraints, the AI-enhanced neutron spectrum unfolding won't be ready for release by the end of this contract. RDT will seek opportunities that can allow us to continue development of high-accuracy neutron spectrum unfolding in the NRID. Full realization of spectrum unfolding provides a forward leap in state-of-the-art and provides (1) enhanced confirmation of source ID possibly including source enrichment levels, (2) extreme high accuracy area dose rate monitoring, and (3) a high-fidelity tool fitting into many neutron science applications. Neutron source measurements have been collected (AmBe & Cf with various moderators). As mentioned previously, we believe we can make massive improvements to the source ID accuracy by identifying and correcting errors in the simulations as well as using measured data to bolster the training algorithm set. Finally, the NRID showed good directionality response accuracy.

Table 2: Task accomplishment summary table.

Task	Task Description	Progress/ Accomplishments
1	Modified Modeling:	NRID V1 & Scorpion versions modeled in MCNP.
2	UI development	Inclusion of 5 operations screens for a variety of users.
3	Initial Product Integration	V1 NRID assembly has been completed and demonstrated.
4	Test & Validation	Troubleshooting of comms error resolved.
5	Revision and Modification based on Tasks 3 & 4	Complete redesign of V2 "Scorpion" case was made and re-ordered.
6	Re-test & Validation	NRID V2 electronics validated and implemented.
7	Build for Environmental/Physical Test	NRID V2 assembled.
8	Complete Build of Engineering Prototype	Full assembly NRID V2 prototype completed and tested for performance.
9	Field Testing-Demonstration	TBD demonstration

Status color code definitions: **R**= Task completion at risk, **Y**= Milestones/Deliverables at risk, **G**=Task proceeding as planned, **B**=Task Completed.

3.1. Task 1: Review, Refine and Finalize Design Requirements

The contractor shall develop a Detector Functional Design and shall model the NRID instrument to develop the instrument design and the identification algorithms.

3.1.1. Functional Design

The Team developed the functional design, which had the functional components or building blocks of the NRID detailed in a specifications document. Performance goals and design constraints were identified. CAD drawings were made to build a complete NRID system, starting with the neutrons sensors, PCBs, and HDPE moderator, and the handheld housing. Functional design components and decisions were documented and reported.

3.1.2. NRID Modeling

Rigorous geometry Monte Carlo N-Particle code (MCNP) modeling was developed to simulate the radiological performance of the NRID. Instrument design radiation transport modeling is a key element in the overall functional design of the NRID, a portable MSND-based neutron spectrometer. The design Team at RDT and UMKC conducted intensive simulations at the beginning of the phase II sequential effort to improve the detector-moderator configuration based on the phase II results; this included full-scale design approaches, support of the systems engineering tradeoff process, and provided RDT with an estimation of system performance based on those design concepts. The modeling provided RDT with the constraints and limitations for lightweight, handheld, designs and provide metrics for testing the commercially viable NRID instrument. During this initial redesign, the Team developed detailed requirements for the Portable NRID (detectors, detector-moderator configuration, digital signal processing/analysis, algorithms, and user-interface “UI”).

UMKC assisted RDT in the redesign and modeling of the optimal moderator and absorber type, geometry, thickness, and volume based on phase II NeuKopis instrument and the new NRID development requirements. The modeling enabled both the highest average intrinsic efficiency and provided the ability to identify and localize (triangulate) neutron emitting, or producing, sources. This intensive task required developing MCNP6 input decks that represent each moderator-MSND configuration considered in the NRID.

The key metrics for the NRID redesign was to provide a compact, ergonomic (lightweight) handheld system while retaining robust source ID capabilities. Aligning with previously developed operational procedures for source ID, the NRID requires the operator to point the front face of the detector at the source. To assist the operator in correct alignment, a directional “compass” was included in the UI to point the user to where the source is located (note this feature is not an image overlay on a 2D scene image). Once the detector is properly aligned, the source ID algorithms can predict the source/shielding type. In option year 2, the team explored performing source ID regardless of source position relative to the detector.

Initial MCNP models were performed to study the thermalization point of neutrons as function of neutron energy in a 10-cm thick HDPE moderator block (see Figure 1). The results of these simulations were used to inform the designs for optimization via MCNP simulation. Previously utilized operation parameters were used to measure the “goodness” of the new NRID designs. Namely, Pearson’s correlation coefficient, r , were used to quantify each design’s ability to

differentiate ^{252}Cf from AmBe. A r -value of 1 indicates that the NRID's response to ^{252}Cf and AmBe are identical (not ideal), and a r -value of 0 indicates no correlation between detector response for the two sources (ideal).

$$r_{Cf,AmBe} = \frac{1}{n} \sum_{i=1}^n \frac{N_{Cf}(z_i) - \overline{N_{Cf}(z)}}{\sigma_{N_{Cf}(z)}} \cdot \frac{N_{AmBe}(z_i) - \overline{N_{AmBe}(z)}}{\sigma_{N_{AmBe}(z)}}$$

$$N_{Cf} = [N_{Cf}(z_0), N_{Cf}(z_1), \dots, N_{Cf}(z_n)]^T$$

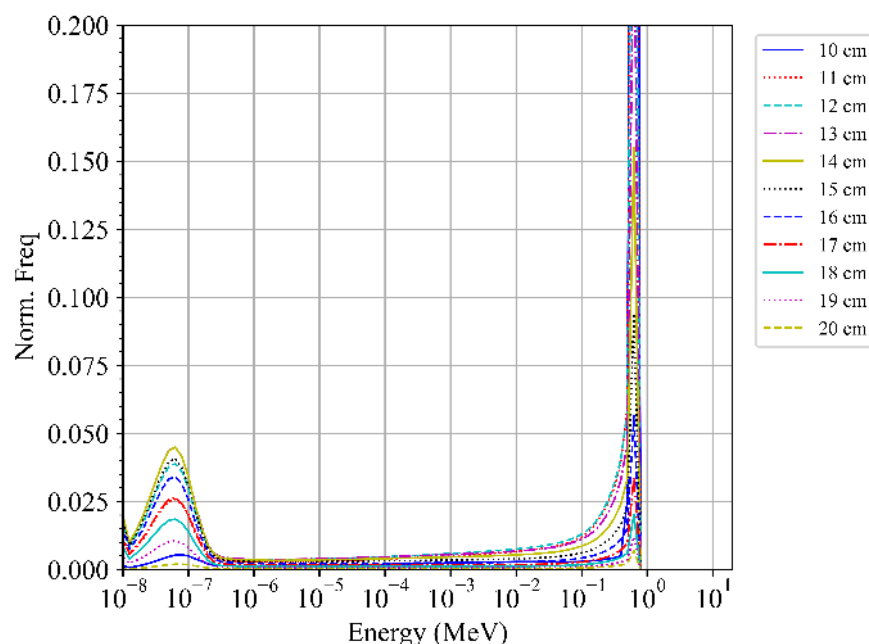


Figure 1: Results of MCNP simulation tallying energy dependent neutron flux for 1-cm spaced planes within a HDPE moderator cube. In the example shown, the moderator was irradiated by a beam of 630 keV neutrons. Peak thermalization occurred approximately 4-cm into the moderator.

The simulation design constraints for the initial new generation NRID were identified and are listed below.

NRID Design Constraints

Weight of Moderator, MSNDs, and Electronics = 8 lbs (3.63 kg)

Number of MSNDs = ~100 max, (fewer is better)

Electronics Board Material = FR4

Intrinsic Thermal Neutron Detection Efficiency of each MSND = 30% (normally incident, 0.025 eV)

MSND dimensions (active area and thickness) = 10 mm x 10 mm x 0.6 mm

Evenly Spaced/Equal thickness HDPE moderator

Evaluate on R^2 for Cf vs AmBe, then detection efficiency (goal is 5% intrinsic for Cf)

For the 4x4 MSND arrays

4-6 boards

FR4 Dimensions (min) = 57 mm x 66 mm x 1.7 mm

Mass (board + MSNDs + Electronics) = 37.1 g

Thickness of MSNDs + FR4 + Shielded Electronics = 7.13 mm

For the 3x3 MSND Arrays

6 – 11 boards

FR4 Dimensions (min) = 44 mm x 53 mm x 1.7 mm

Mass (board + MSNDs + Electronics) = 30 g

Thickness of MSNDs + FR4 + Shielded Electronics = 7.13 mm

The modeling/simulation effort was spent addressing two challenging, but surmountable objectives of the NRID project, specifically:

1. Differentiating fission sources from alpha-n radiation sources.
2. Average intrinsic neutron-detection efficiency from thermal to the top-end of the neutron evaporation spectrum of >5%.

These two objectives work in tandem, and sometimes against each other in moderating type neutron spectrometers, thus it is important to properly space detection elements throughout the moderating volume. The most common moderating material used in these types of spectrometers is high-density polyethylene (HDPE), Figure 2 shows the depth a neutron can penetrate into a volume of HDPE versus the energy of the neutron when entering the volume.

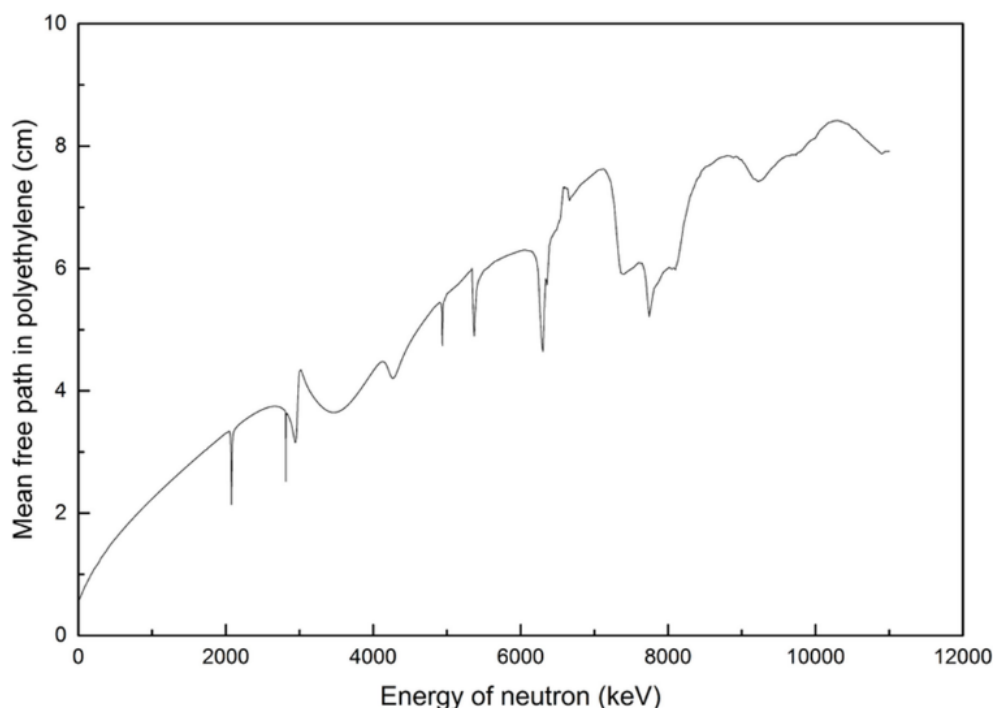


Figure 2: Mean free path for thermalization in polyethylene for different energies of incident neutrons.

Given the different distributions of energies for neutron sources, and the different mean free paths as a function of energy in moderating materials, the **trick to identifying one neutron emitting source to another is to sample at many different areas in a moderating volume**. A sphere moderating volume is the natural choice for most environments, where neutrons can scatter about the surrounding area. However, when weight must be minimized, while keeping as many “depth” sampling points as possible, a cylindrical moderating volume is advantageous. Figure 3 shows one simple potential detector-moderator geometry that consists of four 4x4 arrays of 1cm² neutron sensors, e.g., MSNDs, each array is spaced evenly through the long axis of the moderating volume. While many different energies can be detected at each axial array position, the geometry in Figure 3 effectively splits the incident neutron energy spectrum in 4 discrete (sometimes overlapping) energy bins; and increasing surface area at each axial position provides better detection efficiency of that energy bin. It is then possible to, by simulation or experiment, to create a library of various neutron source signatures or “templates” that the instrument compares to live neutron detections in the field.

3.1.2.1 Model Geometry Development

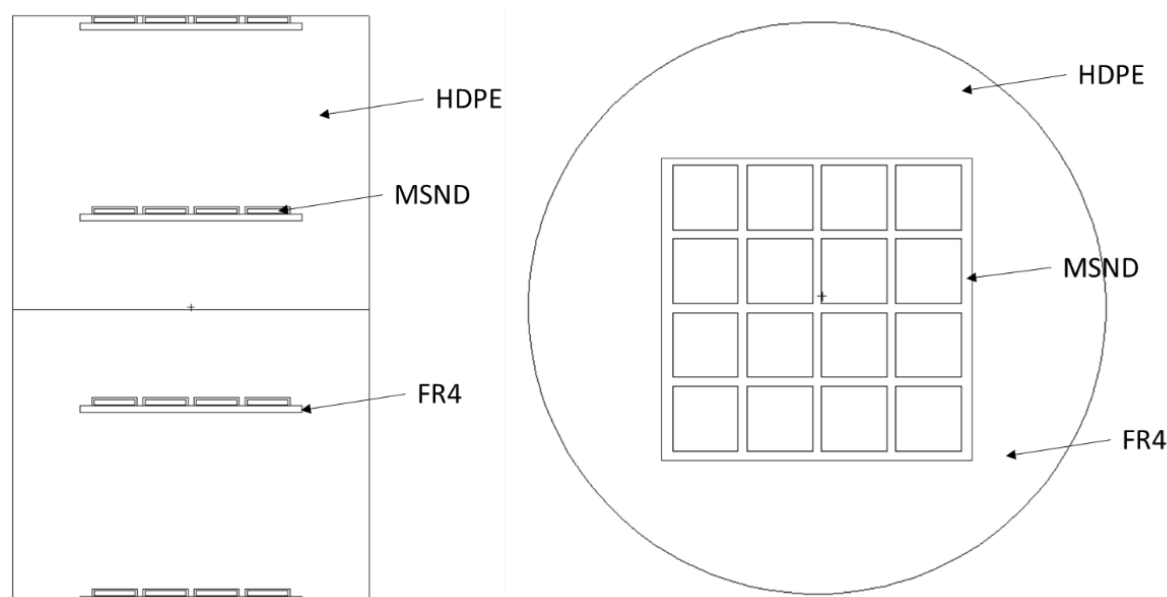


Figure 3: One potential (4x4x4) detector-moderator geometry.

To explore the surface area to axial sampling trade-offs a study was conducted using the Los Alamos National Laboratory software suite: MCNP. A fixed moderator volume was chosen and different distributions of detectors throughout the volume was studied. The moderator volume was set to a 4-inch diameter cylinder, 6-inches in length. This was to keep the final system weight to approximately ~5-10lbs, while still having enough moderator to interrogate a broad range of the neutron spectrum. To keep the end system cost down, the number of detectors in the system was limited to no more than one-hundred. Because of the decided detector limits, the individual axial array positions were kept to either 3x3 or 4x4, and additional axial positions were then evenly distributed through the moderator up to the detector limit. To rate the performance of objective one, each geometry was simulated against the two neutron emitting sources that tend to produce

the most similar templates (^{252}Cf “**Series 1**” and AmBe “**Series 2**”), then the axial distribution of detections was compared using the Pearson Correlation Coefficient; and in this case we desire dissimilarity, so lower scores are better.

Results of this study can be seen in Figure 4 through Figure 9, and Table 3. It appears that both versions of the 4x4 detector arrays outperform any of the 3x3 arrays, The radial spacing of the 3x3 elements was very tight in the center of the cylinder, by increasing the radial spacing detection efficiency could be increased. Lastly, there are other moderating materials that may have sufficient “moderating ability” for this application while providing other benefits such as weight reduction. These were all explored.

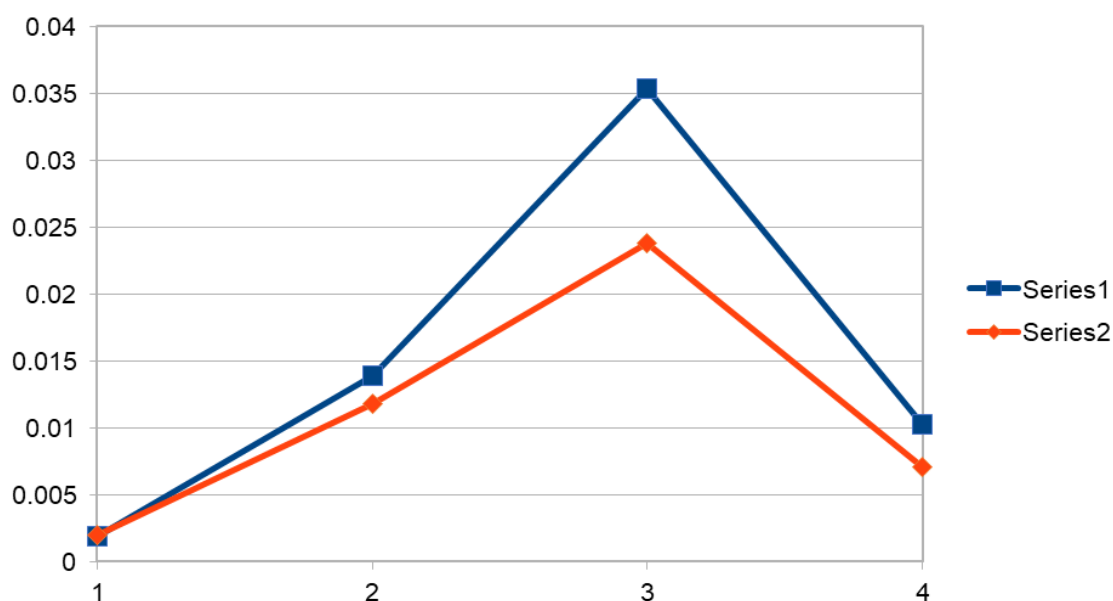


Figure 4: Axial view of a 4x4x4 Detector geometry. Neutrons Incident from the right side.

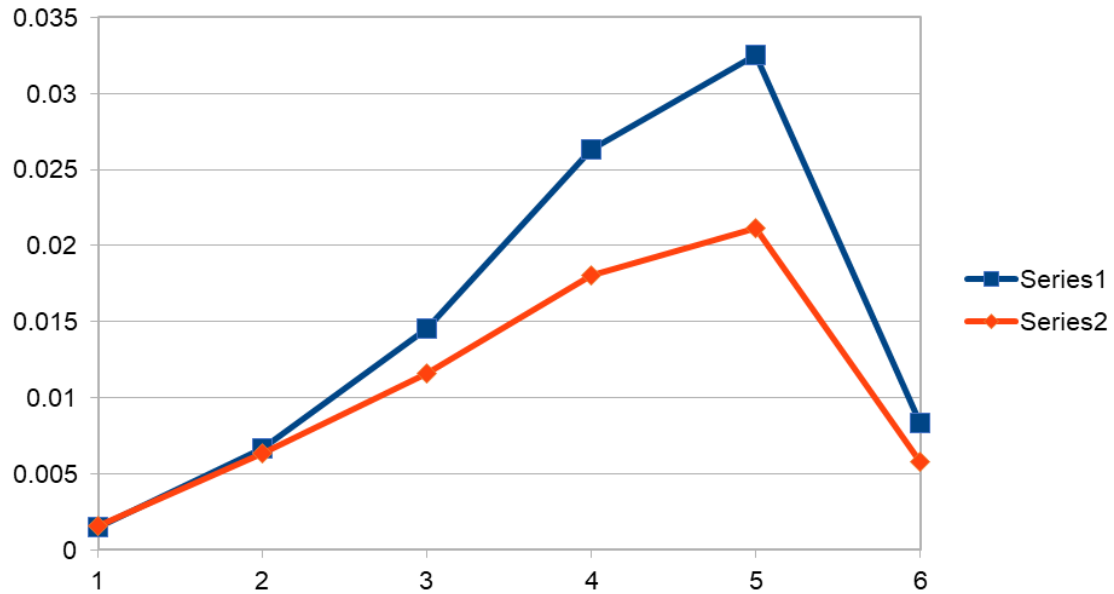


Figure 5: Axial view of a 4x4x6 Detector geometry. Neutrons Incident from the right side.

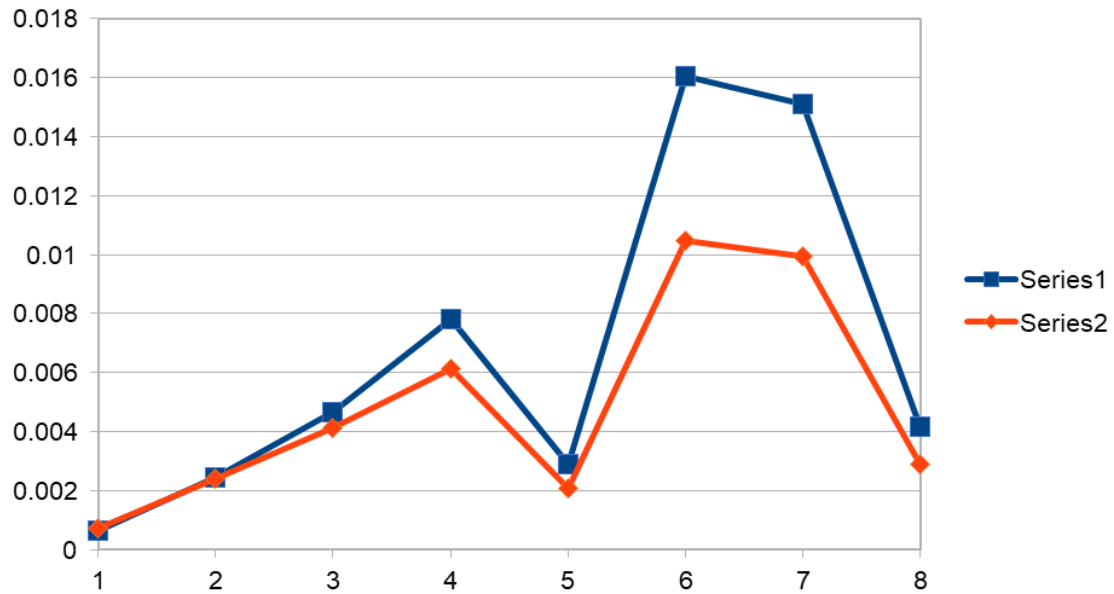


Figure 6: Axial view of a 3x3x8 Detector geometry. Neutrons Incident from the right side. Note there was a tally error in array 5.

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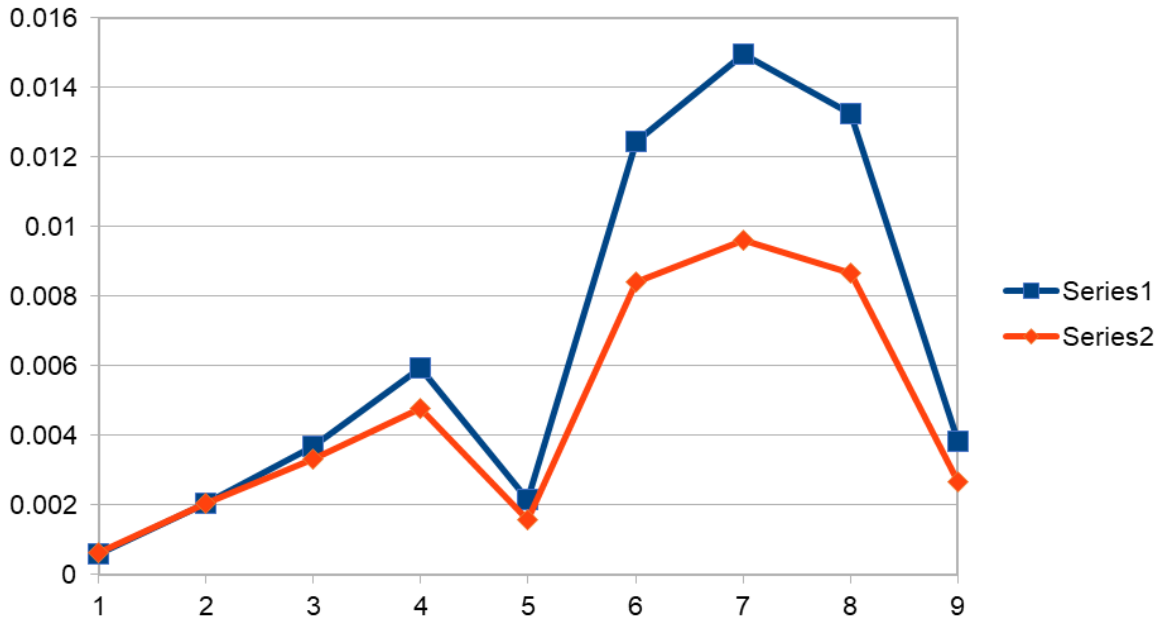


Figure 7: Axial view of a 3x3x9 Detector geometry. Neutrons Incident from the right side. Note there was a tally error in array 5.

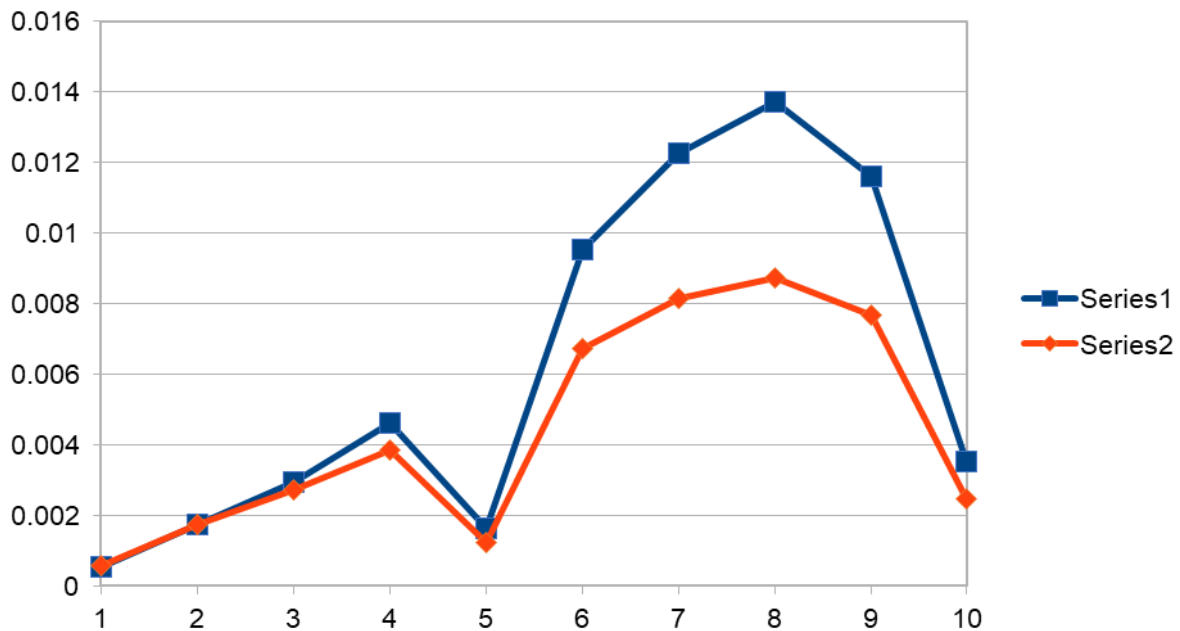


Figure 8: Axial view of a 3x3x10 Detector geometry. Neutrons Incident from the right side. Note there was a tally error in array 5.

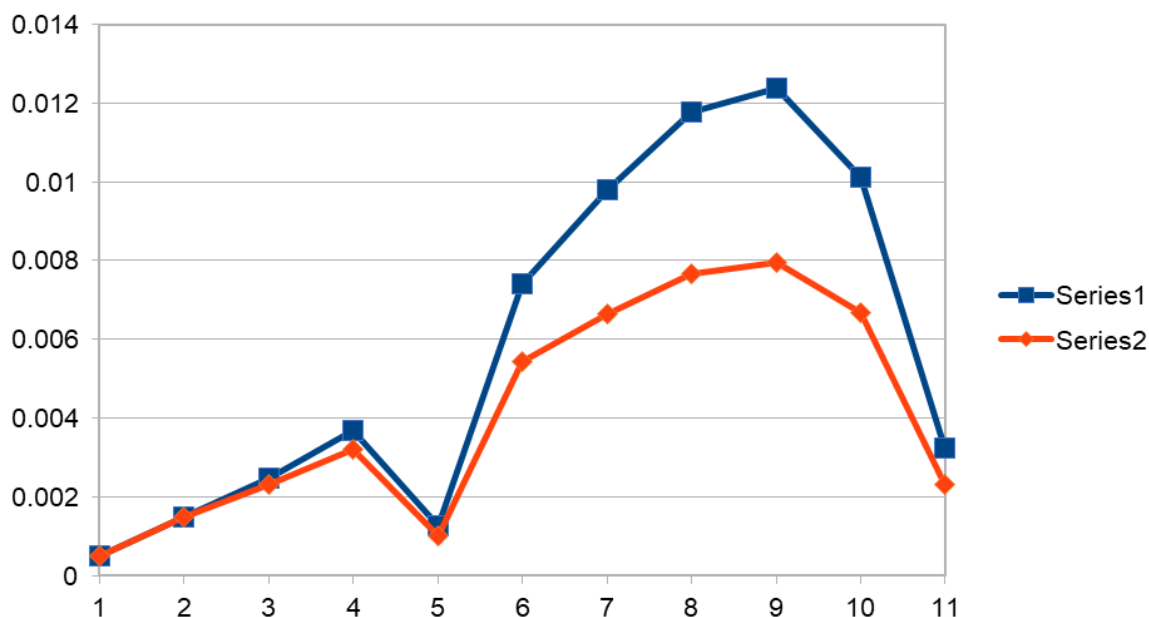


Figure 9: Axial view of a 3x3x11 Detector geometry. Neutrons Incident from the right side. Note there was a tally error in array 5.

Table 3: Geometry trade study results.

Detector Geometry	4x4x4	4x4x6	3x3x8	3x3x9	3x3x10	3x3x11
Cf-AmBe Similarity	0.986034	0.988091	0.987483	0.99	0.990772	0.991628
Cf Efficiency	0.061351	0.089803	0.053814	0.058858	0.062143	0.064147
AmBe Efficiency	0.044565	0.064444	0.038848	0.041777	0.043877	0.045254

The initial focus was ensuring the correctness of models. There was an issue with MCNP tallying reactions on the 5th detector board, this was corrected, but the investigation also revealed other geometry errors in the 3x3 simulations. Once all input, and geometry errors were corrected, simulations were re-ran using both HDPE and Delrin variant moderating materials.

Figure 10 (HDPE moderator) and Figure 11 (Delrin moderator) show the distribution of neutrons through a selected device geometry. In the case of an HDPE moderator, the peak positions of detection were located on the same axial position in the device. On the other hand, the Delrin moderator changed the peak detection location. Changing the peak detection location, increases the capability for differentiating sources with higher confidence; as can be seen in the last row of Table 4 through Table 7 (higher energy resolution). However, when comparing neutron detection efficiencies, there is almost an order of magnitude lost when switching from HDPE to Delrin, with the highest HDPE efficiency being ~9% and the highest Delrin efficiency being ~2%. The effect

on in-field operation of the device, with sources at a larger stand-off and/or smaller sources, would be more difficult to detect (trigger and alarm) and identify. The spectral differences between the HDPE configurations seemed minimal, and a high efficiency configuration is recommended, as the losses in sensitivity of the Delrin moderator seem too great. HDPE was the chosen moderator moving forward.

Important Objectives

- Explore moderator mixture of Delrin and HDPE to balance sensitivity and spectral capability.
- Explore radial spacing of 3x3 arrays.

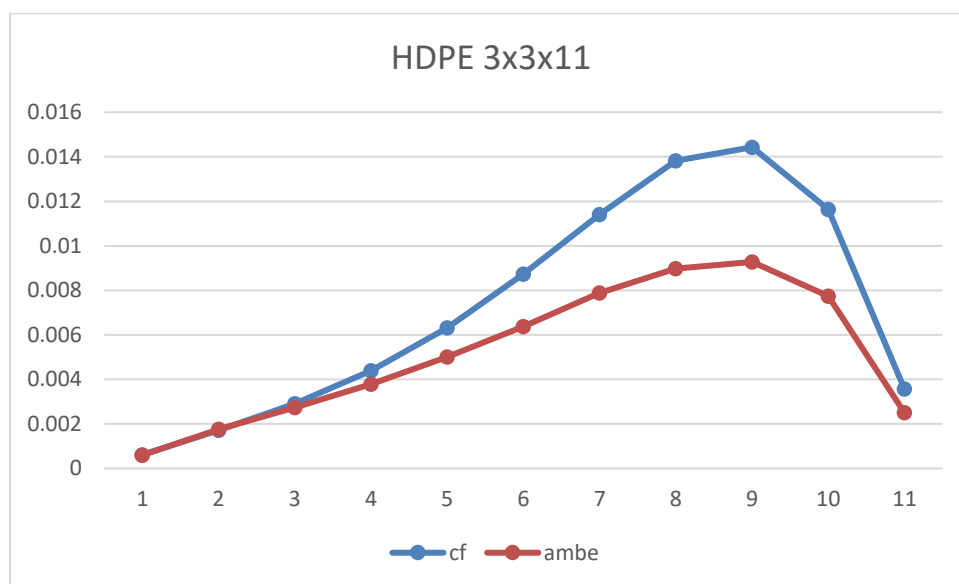


Figure 10: Axial view of a 3x3x11 Detector-HDPE geometry. Neutrons Incident from the right side (front of system).

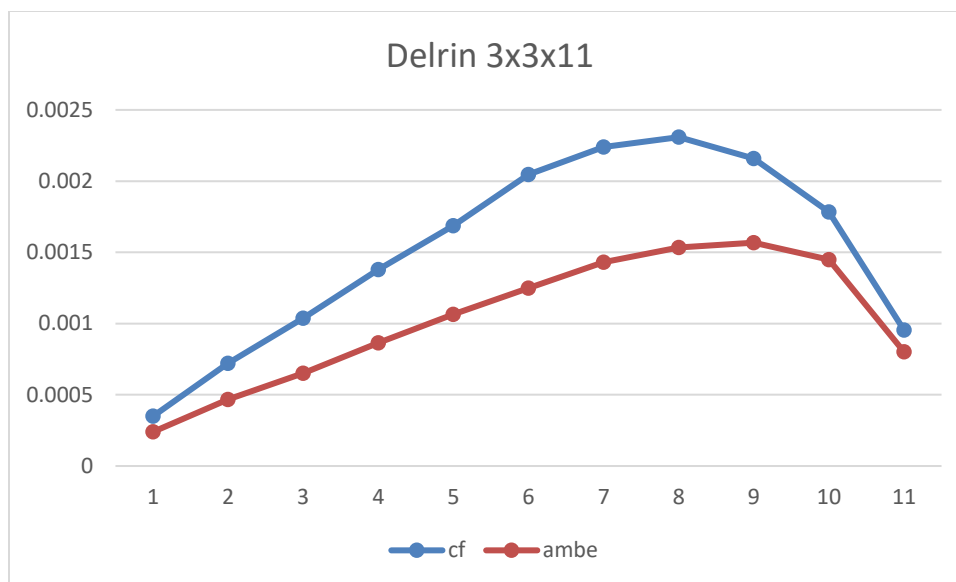


Figure 11: Axial view of a 3x3x11 Detector-Delrin geometry. Neutrons incident from the right side (front of system).

Table 4: Efficiency and Correlation results of 4x4 HDPE geometries

Geometry	4x4x4	4x4x5	4x4x6
²⁵² Cf Efficiency	0.0613513	0.0781378	0.08980301
AmBe Efficiency	0.04456546	0.05624736	0.06444409
Source Correlation	0.99299257	0.99340226	0.99402758

Table 5: Efficiency and Correlation results of 4x4 Delrin Geometries

Geometry	4x4x4	4x4x5	4x4x6
²⁵² Cf Efficiency	0.01335633	0.01616625	0.01825124
AmBe Efficiency	0.0090635	0.0109951	0.01240974
Source Correlation	0.99129881	0.98517716	0.98082639

Table 6: Efficiency and Correlation results of 3x3 HDPE geometries

Geometry	3x3x6	3x3x7	3x3x8	3x3x9	3x3x10	3x3x11
²⁵² Cf Efficiency	0.05615286	0.06143865	0.07224576	0.07551105	0.07788604	0.07953813
AmBe Efficiency	0.04043971	0.0440348	0.05181845	0.05407922	0.05587031	0.05664257
Source Correlation	0.99338057	0.99360939	0.99365884	0.99405274	0.99346444	0.99444587

Table 7: Efficiency and Correlation results of 4x4 Delrin Geometries.

Geometry	3x3x6	3x3x7	3x3x8	3x3x9	3x3x10	3x3x11
²⁵² Cf Efficiency	0.01146933	0.01246496	0.0146487	0.01545756	0.01617466	0.01666654
AmBe Efficiency	0.00774934	0.00852832	0.00996551	0.01049688	0.01093915	0.01131775
Source Correlation	0.98508619	0.97725626	0.97762606	0.97709549	0.97187461	0.96768221

One outstanding question explored early on was whether the radial spacing of detectors had a significant effect on the instrument's response. To that end, another set of 3x3xN simulations was run, this time with detectors spaced further apart on the PCB as can be seen in Figure 12. Results of these simulations can be seen in Table 8, and indicate that radial detector spacing (within reason) has no significant impact on instrument response. Qualitatively, we note that having additional radial moderator helps eliminate ambient or environmentally scattered neutrons, improving the directional response.

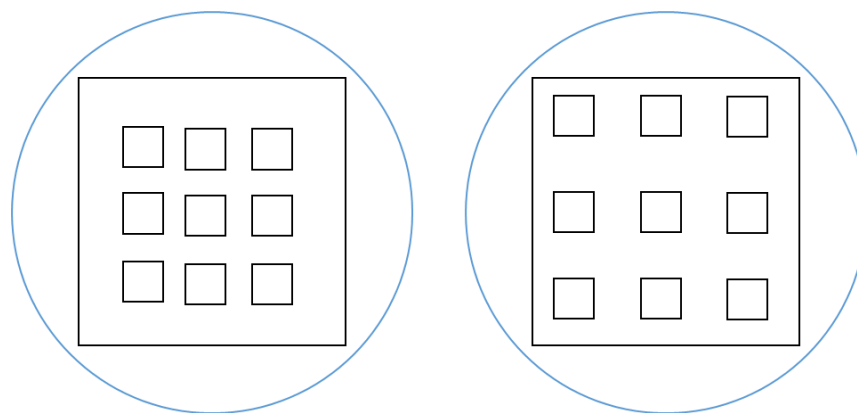
**Figure 12: Depiction of increased radial detector spacing in the 3x3xN simulations.**

Table 8: Results of radial spacing simulations

Geometry	Source	Spread Efficiency	Tight Efficiency
3x3x6	252Cf	0.05715058	0.05615286
3x3x6	AmBe	0.04102069	0.04043971
3x3x7	252Cf	0.06286886	0.06143865
3x3x7	AmBe	0.04511949	0.0440348
3x3x8	252Cf	0.06685582	0.07224576
3x3x8	AmBe	0.04785792	0.05181845
3x3x9	252Cf	0.0700167	0.07551105
3x3x9	AmBe	0.04998374	0.05407922
3x3x10	252Cf	0.07788604	0.07788604
3x3x10	AmBe	0.05587031	0.05587031
3x3x11	252Cf	0.07383898	0.07953813
3x3x11	AmBe	0.0522855	0.05664257

Several studies were devised to take advantage of the new insights about other potential moderating materials. The geometries of the proposed studies can be viewed in Figure 14. The team also considered “reflector” designs to balance detection efficiency and energy resolution. Previous work has shown that replacing the HDPE moderator entirely with a moderator that yields high-energy resolution significantly reduces the detection efficiency of the system [1]. Ideally, the “reflector” designs could allow us to retain high detection efficiency while improving the energy resolution; ultimately reducing the time-to-source-identification.

Reflector materials were chosen based on several factors including: C:H:O content (where higher C and O were preferred), cost/availability, and weight. These parameters narrowed the search space to common plastics and graphite (a common reflector used in nuclear reactors). The total neutron scattering cross section, C-scattering, and O-scattering components of the neutron cross section for the “reflectors” under consideration are shown in Figure 15.

In each of the configurations shown in Figure 14, four different “reflector” materials were tested. Namely: graphite, polycarbonate, Polymethyl methacrylate (PMMA), and Delrin.

- Graphite has the highest atomic density (atoms cm^{-3}) of carbon.
- Polycarbonate (PC) has the 2nd highest carbon atomic density, has some oxygen, and 4rd highest total cross section meaning it was still do some H-n moderation unlike graphite.
- Poly(methyl methacrylate) (PMMA) – Middle of the pack for C and O. 3rd highest total cross section. Also, PMMA is used in human-surrogate phantoms for dose measurements.
- Delrin – highest O atomic density, 2nd highest total cross section.

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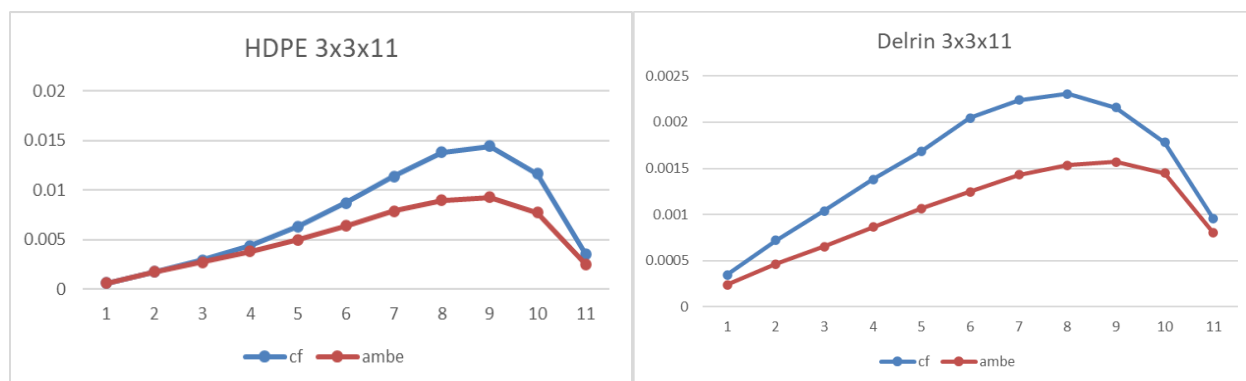


Figure 13: (right) HDPE and (left) Delrin moderator NRIDs. Axial view of a 3x3x11 Detector geometry. Neutrons Incident from the right side (front of system). The peak detection channel changes for AmBe in the Delrin system.

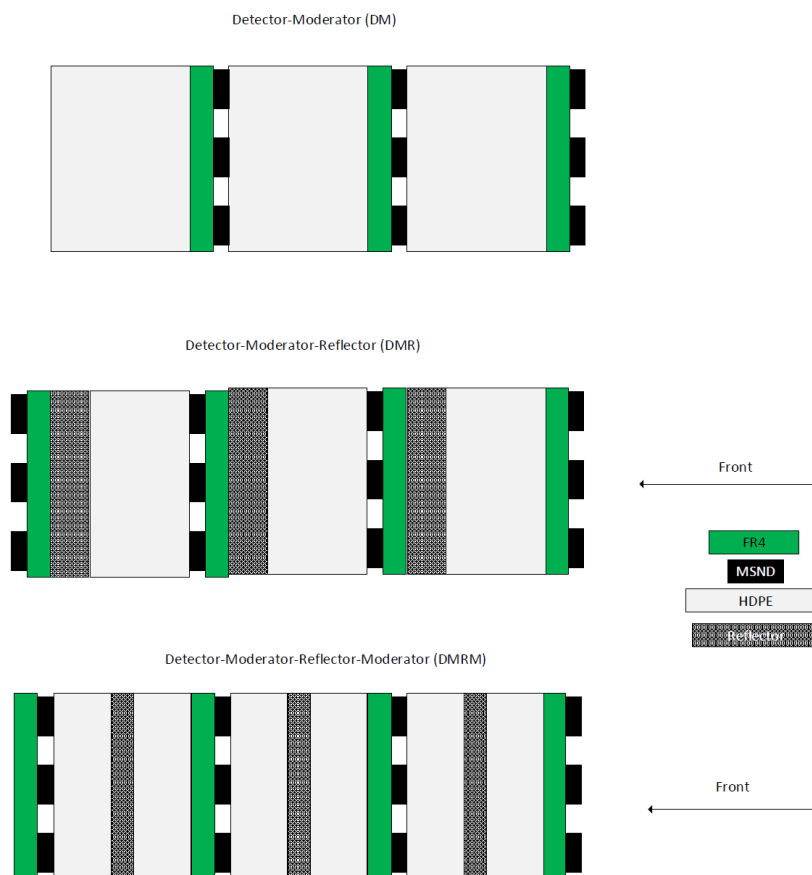


Figure 14: Three potential moderator/reflector configurations. Top: Typical Detector-Moderator (DM) configuration without reflector materials. Middle: Detector-Moderator-Reflector (DMR) configuration. Bottom: Detector-Moderator-Reflector-Moderator (DMRM) configuration.

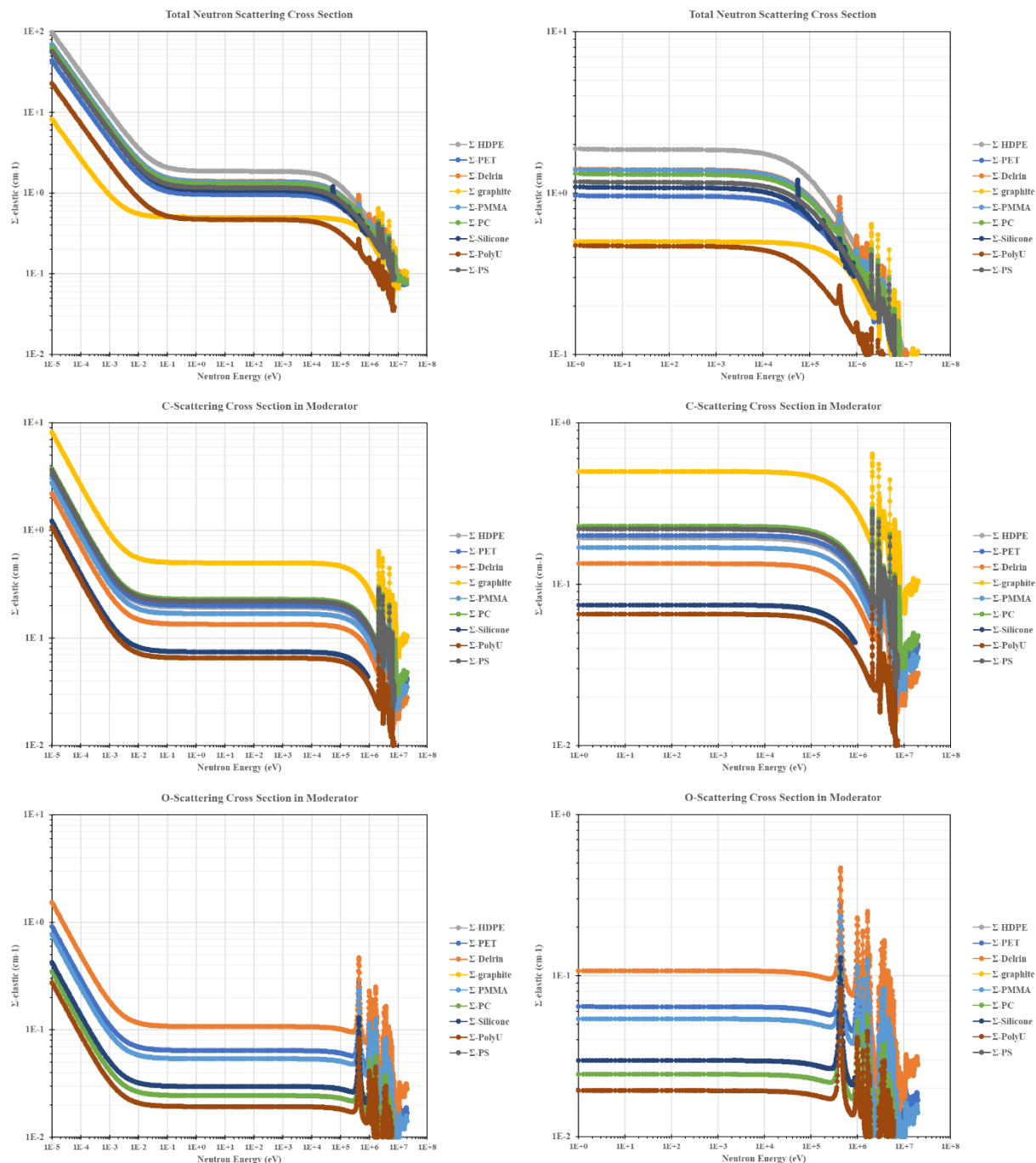


Figure 15. (Top) Total, (Middle) C-scattering, and (Bottom) O-scattering cross sections for neutron moderator and reflector materials.

The results of the “reflector” simulations are shown in Figure 16 and Table 9. Figure 16 shows that the reflector material and placement can have a large effect on the instrument’s response, however any change in response to ²⁵²Cf was followed by a similar change in response for AmBe. It should be noted that the y-axis in each of the plots in Figure 16 are the same, and a decrease in efficiency is seen for any reflector containing geometry when compared to the pure HDPE

geometry. Further, the correlation scores in Table 9 shows that the two sources were made to look more similar than without the reflector material. For the geometries and materials used, **it does not appear that there is anything to be gained from using reflecting material.**

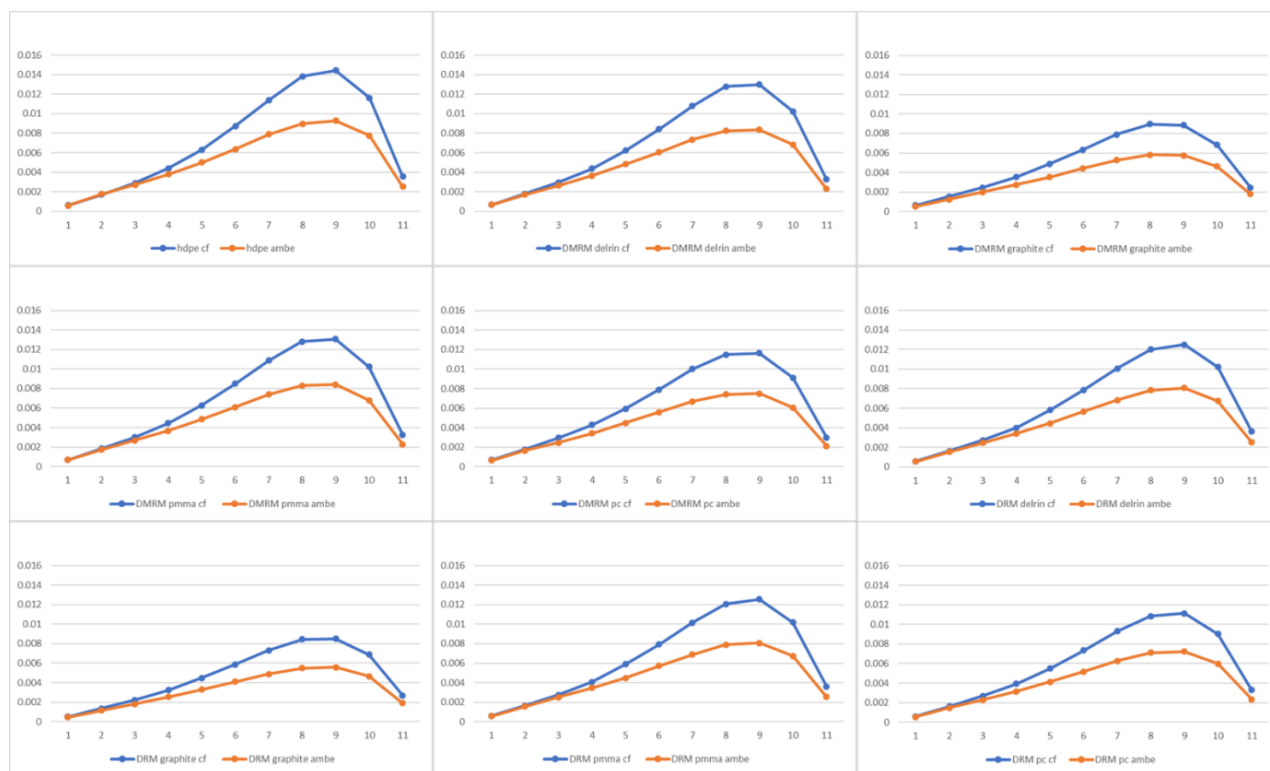


Figure 16: Results of the Reflector-Moderator geometry studies. (Top row, left to right) HDPE DM baseline, DMRM Delrin, DMRM Graphite. (Middle row, left to right) DMRM PMMA, DMRM PC, DRM Delrin. (Bottom Row left to right) DRM Graphite, DRM PMMA, DRM PC.

Table 9: Correlation scores of the Reflector-Moderator geometry studies.

Geometry	Cf-AmBe Correlation
HDPE	0.994445867
DMRM Delrin	0.995020251
DMRM Graphite	0.997603668
DMRM PMMA	0.995086293
DMRM PC	0.996193205
DRM Delrin	0.995366394
DRM Graphite	0.997725118
DRM PMMA	0.995482145
DRM PC	0.996988989

Up to this point, all simulations have been performed based on a segmented design where detector arrays divide the HPDE moderator into evenly spaced segments. This design is now referred to as NRID-S series (see Figure 17.) A new geometry was designed and is labeled the NRID-L series, because detector strips run along the length of the HDPE moderator. A channel in the L-series is defined as the detectors that share a cross-sectional plane parallel to the circular face of the NRID. For example, in the NRID-L5, shown in Figure 17, the front 5 MSNDs comprise the first (0)

detector channel. Ideally, the L-series of NRIDs improves the energy resolution of the NRID over the S-series, because the 1-cm² active-area MSNDs run along the length of the moderator, this arrangement was postulated to improve the NRID's ability to define the "peak thermalization" position.

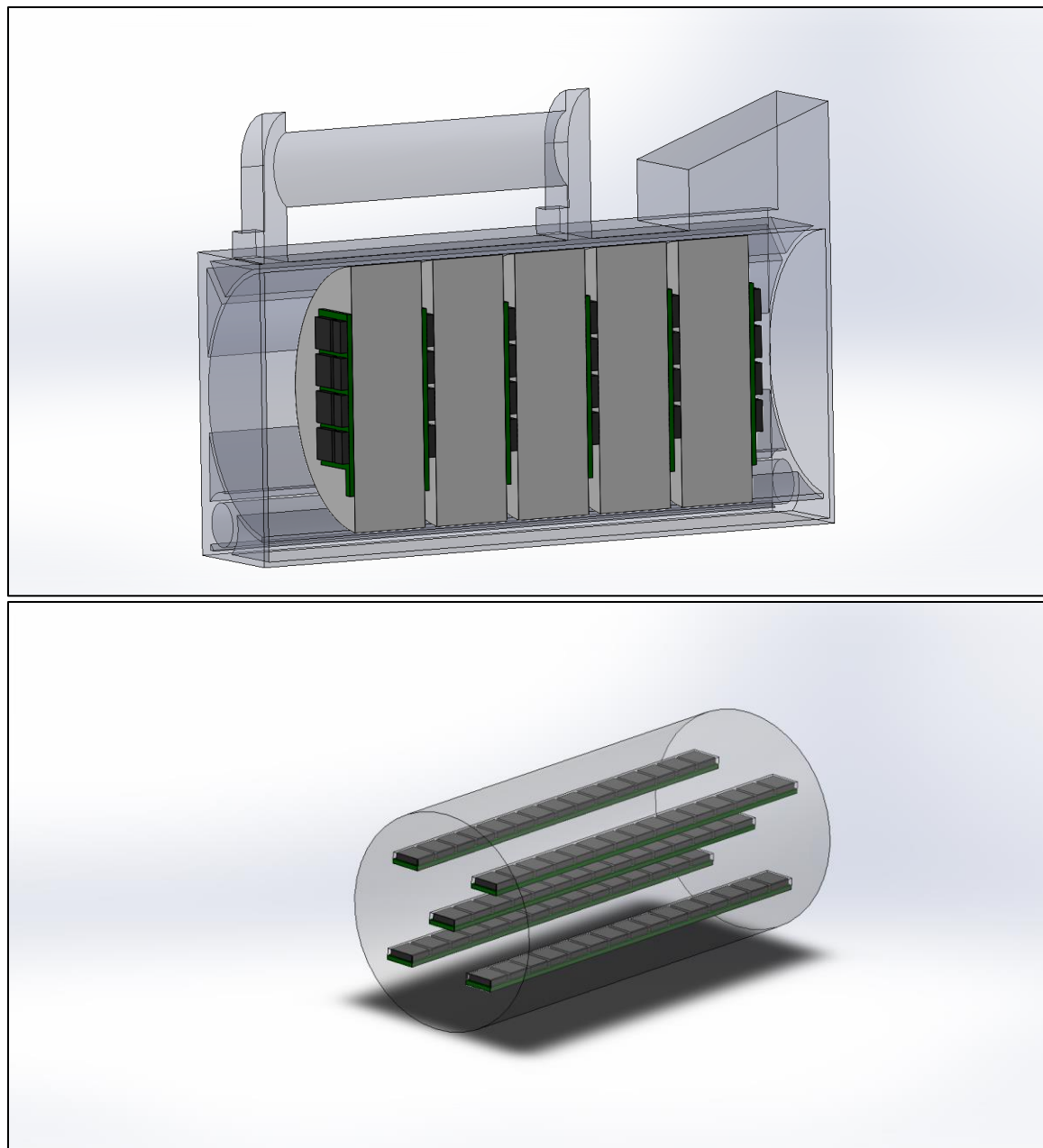


Figure 17: (Top) Example of NRID-S series. 4x4 MSND arrays were used in this example which would classify the design as a NRID-S16. (Bottom) Example of NRID-L series. Since each detector channel has 5 detectors, the example is an NRID-L9.

The detector system response to ²⁵²Cf and AmBe for NRID L5, L9, and L9-Offset designs were simulated. The L-5 detector had 5 detectors per channel. The L-9 design had 9 detectors per channel similar to the NRID-S9. In the L-9 design, 4 detectors from each channel were shifted

toward the back of the NRID by 0.5-cm, effectively doubling the number of channels for neutron energy resolution without increasing the number of detectors in the NRID. The L-5 had 20 channels (100 MSNDs), and the L9 and L9-Offset had 16 channels (144 MSNDs).

Figure 17 and Table 10 show the NRID responses and Pearson correlation coefficient for ^{252}Cf and AmBe, respectively. Moderator radii of 5, 7.5, and 10 cm were considered. For all L-configurations, as moderator radii increased, the neutron detection efficiency increased; but, the Pearson's correlation coefficient shifted towards 1, i.e., response shapes looked more similar (ID is performed on response shapes). Therefore, the 7.5 cm radii responses showed the best balanced detection efficiency and spectral resolution. The energy resolution of the NRID-L's appears to be better than the NRID-S, with initial calculations indicating the intrinsic neutron detection efficiency for ^{252}Cf is 2-3% for the L-series configurations.

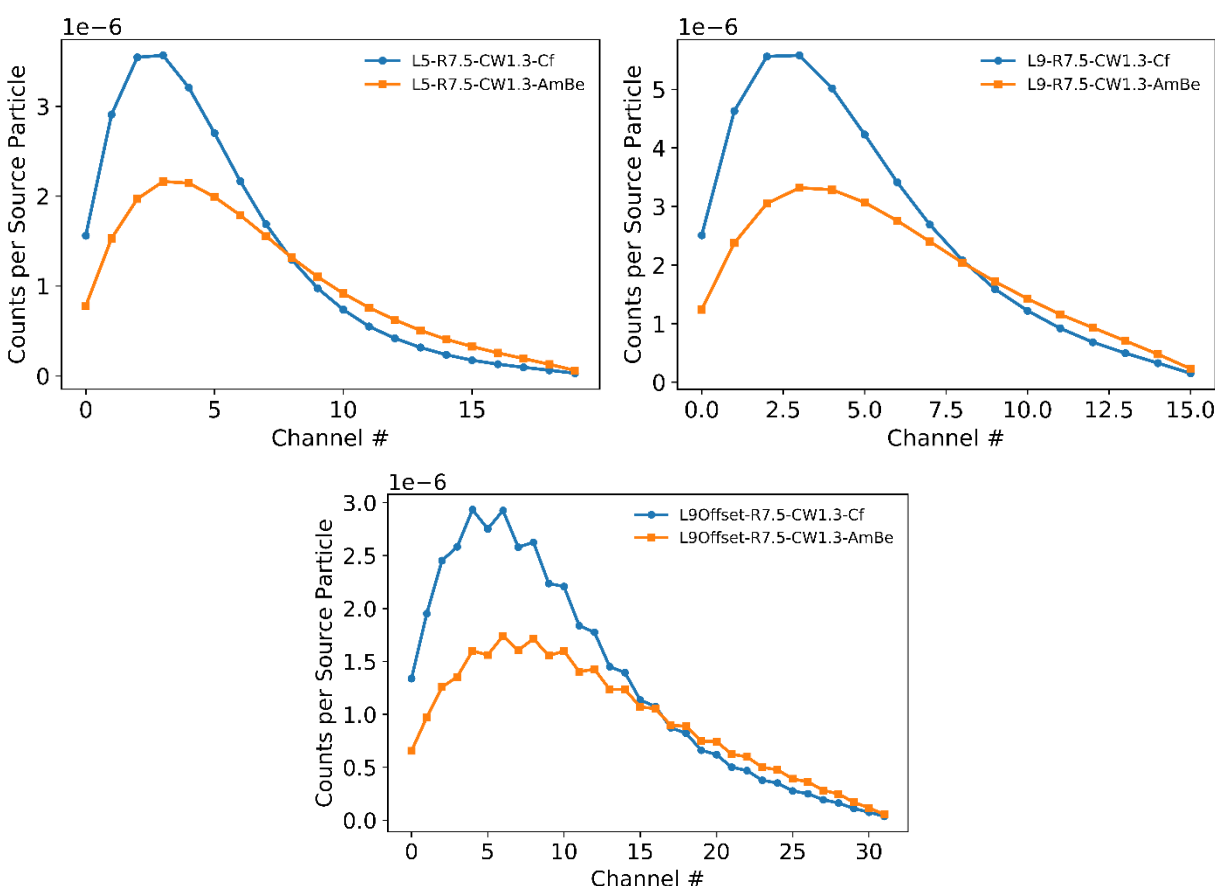


Figure 18: ^{252}Cf and AmBe response for NRID-L series detectors. (Top Left) L5, (Top Right) L9, (Bottom) L9-Offset.

Table 10: Pearson’s correlation coefficient for ^{252}Cf and AmBe responses for the NRID-L series designs (lower is better).

NRID-L Design	Correlation Score (Cf, AmBe)
L5	0.94984
L9	0.93967
L9-Offset	0.94059

In previous work simulations, UMKC uses an “MSND surrogate” composed of a homogeneous mixture of silicon and lithium-6 fluoride. This method of modeling is fast and is an efficient method to quickly simulate a wide variety of detector configurations to get a rough idea on how well the NRID can function as a source identifier. However, the “MSND surrogate” method cannot be used to accurately predict to true detection efficiency of the NRID, and will also lose some nuanced response characteristics from neutrons traversing LiF-filled trenches and silicon fins in the MSNDs. Therefore, the UMKC models were updated to include defined trenches and fins in the MSND, so that accurate comparisons could be made to the L-series MSND models.

3.1.3. L-Series NRID (NRID-L)

Three subcategories of NRID-L were modeled and evaluated based on detection efficiency and response shape (i.e., ability to differentiate Cf-252 from AmBe). A Watt distribution was used to model the spontaneous fission neutrons from Cf-252. Two AmBe source inputs were used. The first was generated by Sources-4c code and the second (AmBe-Jim) was based on the IAEA source compendium definition. It appeared that the IAEA-AmBe source definition included some background or room scatter, and has a larger thermal component than the Sources-4C generated AmBe source. The LR, LC, LCR versions of the NRID are shown in Figure 19. LR denoted a rectangular grid of array of MSNDs. NRID-LR5 and LR9 versions were modeled. The number denotes the number of MSNDs in each “layer”. LC signifies a circular array of MSNDs. LCR means circular array with HDPE reflector. In the LCR versions the inner moderating material was nylon, which has a lower neutron scattering cross section than HDPE. In the LCR versions, ideally the peak interaction location for neutrons with energies from 0.6 to 1.2 MeV (similar to ^{252}Cf) would spread out and differentiate in the NRID, making identification easier.

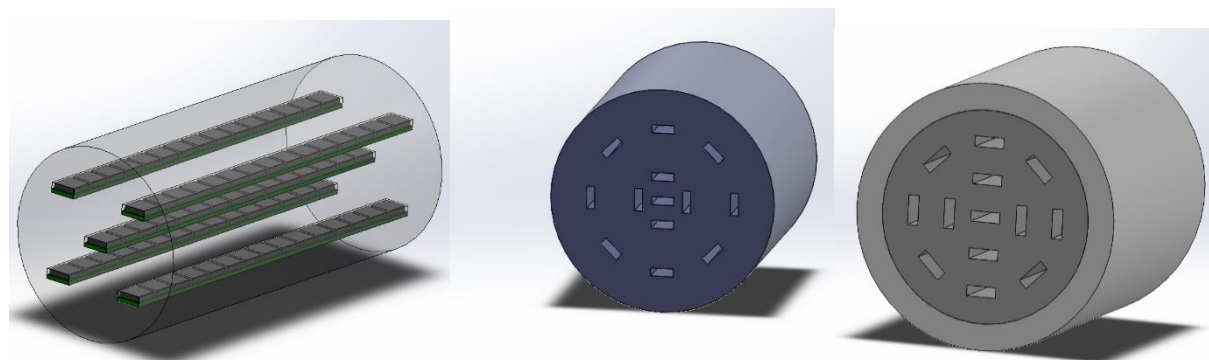


Figure 19. (left) LR5, (middle) LC13, and (right) LCR13 NRID designs. The number of MSNDs in each NRID was capped at 150 making the LR5 and LR9 longer than the LC13 and LCR13. The number following the geometry designation denotes the number of MSNDs in each “layer”.

Table 11 shows the selection of the results from the NRID-L simulations. Figure 20 shows NRID-L response to Cf-252 and the two AmBe sources for the best three NRID-L designs based on a balance of detection efficiency and differences in response for different sources. Note the sum-of-absolute-differences “SAD” algorithm was used to compare the differences in responses. The SAD algorithm is defined as

$$SAD = \sum_{i=0}^n |x_i - y_i|$$

where x_i is the measured normalized response of the i -th channel and y_i is the library normalized response of the i -th channel. A SAD score of 0 indicates a perfect match to the saved library spectrum. For simulation optimization, large SAD scores for different sources are desired. More discussion on SAD vs Pearson for library matching is reported in monthly reports.

At this point, the simulations indicate the NRID-L outperforms the NRID-S, and the LC and LCR versions are better than the LR version. The final test was to simulate the change in response for small angle offset (not perfectly aligned at 0°) for a given source. Since the horizontally aligned MSND strips could provide neutron free streaming paths for fast neutrons, the response function might change significantly as the free streaming paths close when the source is not perfectly centered on the front face of the detector. If the change is too large, source ID may be challenging. Therefore, a change in response for small angle misalignments (0°-10°) were modeled for both the NRID-L and NRID-S. If the change in response was acceptable in the NRID-L series, it was chosen as the preferred design.

Table 11. Subsection of simulation results for NRID-L comparing detection efficiencies and efficacy for source ID. Not listed are SAD algorithm scores for other “Cf-like” sources.

	LC13x11	LC13x11	LC13x11	LC13x11	LC13x11	LC13x11	LC13x11	LC13x11	LR9x16	LR9x16_offse
E _{Cf,int}	2.991%	2.999%	2.368%	3.088%	2.529%	3.042%	3.132%	3.104%	2.934%	2.929%
E _{Cf,abs}	4.19E-05	4.20E-05	3.32E-05	3.01E-05	2.46E-05	2.96E-05	3.82E-05	4.35E-05	4.11E-05	4.10E-05
SAD _{Cf,AmBe,TRO}	0.19409	0.19907	0.19842	0.19215	0.19734	0.19693	0.19681	0.20252	0.25699	
SAD _{Cf,AmBe,jim}	0.09833	0.10359	0.11579	0.09592	0.10711	0.10453	0.10713	0.11704		
# Detectors	143	143	143	143	143	143	143	143	144	144
R _{hdpe}	7.5	7.5	7.5	6.25	6.25	6.25	7	7.5	7.5	7.5
R _{det}	0, 2, 3.5	0, 1.75, 3.5	0, 1.5, 2.5	0, 1.75, 3.5	0, 1.5, 2.5	0, 1.5, 4.5	0, 1.5, 4.5	0, 1.5, 4.5	3x3	3x3
Cw	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.3	1.3
R _{inner}	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
R _{outer}	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11
E _{Cf,int}	2.354%	2.229%	2.319%	2.206%	2.364%	2.238%		2.090%	2.084%	2.037%
E _{Cf,abs}	2.29E-05	2.17E-05	2.26E-05	2.15E-05	3.31E-05	3.13E-05		2.03E-05	2.54E-05	2.85E-05
SAD _{Cf,AmBe,TRO}	0.17552	0.25009	0.17900	0.25141	0.17208	0.25644			0.19013	0.18958
SAD _{Cf,AmBe,jim}	0.07145	0.13053	0.08680	0.12887	0.09001	0.13901				
# Detectors	143	143	143	143	143	143	143	143	143	143
R _{hdpe}	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
R _{det}	0, 2, 3.5	0, 2, 3.5	0, 1.75, 3.5	0, 1.75, 3.5	0, 1.75, 3.5	0, 1.75, 3.5	0, 1.75, 3.5	0, 1.5, 2.5	0, 1.5, 2.5	0, 1.5, 2.5
Cw	1.44		2	1.44	2	1.44	2	1.44	1.44	1.44
R _{inner}	5, nylon	5, nylon	5, nylon	5, nylon	5, nylon	5, nylon	5, nylon	3.75, nylon	3.75, nylon	3.75, nylon
R _{outer}	6.25	6.25	6.25	6.25	7.5	7.5	6.25	7	7	7.5

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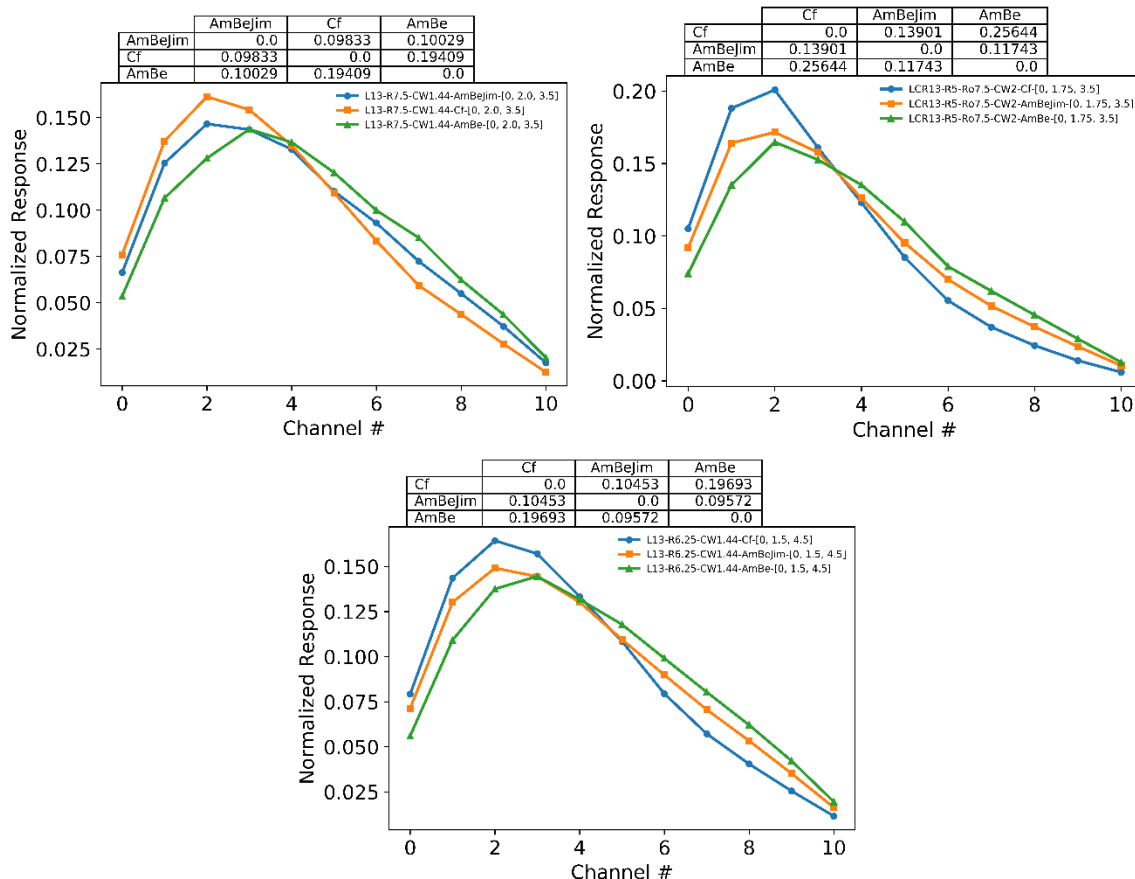


Figure 20: Normalized responses of LC-13 (left and right) and LCR-13 (middle) versions of NRID to Cf-252 and two AmBe sources. Also shown are their SAD algorithm scores.

Several iterations of radial detector spacing and “channel widths” or widths between adjacent MSNDs along the length of the spectrometers was modeled for each design. The best spectrometer design, was the spectrometer with the lowest cosine correlation (Equation 1) for ^{252}Cf and AmBe with an intrinsic neutron detection efficiency for ^{252}Cf greater than 5% while retaining relatively high absolute neutron detection efficiency i.e., we did not want to design a detector that was so small it would be impractical to use due to have too small of sensitive detector volume.

$$\text{Cosine Correlation} = \frac{\sum x_i y_i}{\sqrt{\sum x_i^2} \sqrt{\sum y_i^2}} \quad \text{Equation 1}$$

x_i – measured detector response in i^{th} channel
 y_i – simulated library detector response in i^{th} channel

Table 11 and Table 13 show a selection of the results from the NRID-L simulations. In general, the LC geometry outperformed the LCR geometry in detection efficiency and energy resolution (cosine correlation score). The higher performing LC-series NRID, which is the NRID that was

chosen to be fabricated and evaluated, which is the LC13x11 R7 CW2 [0, 2, 3.5] (see Figure 21). This design has 13 MSNDs per energy channel, 11 MSND channels throughout the length of the moderator, a 7-cm radius HDPE moderator cask, a channel width of 2 cm, and MSND array radial spacing of 0 cm, 2 cm, and 3.5 cm. Figure 22 shows the absolute response for the chosen NRID, as well as, the normalized response with corresponding cosine and SAD scores for ^{252}Cf , AmBe without room scattering (AmBe4c), and AmBe with room scatter (AmBeIAEA). The scores are adequate for source ID (low cosine scores, high SAD scores). Finally, the mono-energetic neutron response for each channel in the NRID was simulated and is plotted in Figure 23. Each channel has a unique energy response, which were beneficial to spectrum unfolding and neutron dose calculations.

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Table 12: Subsection of simulation results for NRID-LC series comparing detection efficiencies and efficacy for source ID. In the LC series, the MSND strips are arranged in a cylindrical patten within a cylindrical HDPE-moderator.

Efficiency	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x11	C13x1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Table 13: Subsection of simulation results for NRID-LCR series comparing detection efficiencies and efficacy for source ID. The LCR series has a nylon-moderator core and annular HDPE reflector.

Efficiency	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11	LCR13x11
$\epsilon_{cf,int}$	3.52%	3.93%	3.58%	3.79%	3.93%	4.53%	3.92%	4.31%	4.06%	4.77%	4.04%	4.80%	3.23%	3.55%	3.65%	4.16%	4.45%	4.45%	3.81%	4.51%
$\epsilon_{cf,abs}$	2.66E-05	2.96E-05	2.70E-05	2.86E-05	3.83E-05	4.41E-05	3.82E-05	4.19E-05	4.96E-05	5.83E-05	5.66E-05	6.72E-05	2.44E-05	2.68E-05	3.56E-05	4.05E-05	5.43E-05	5.43E-05	5.33E-05	6.31E-05
Correlation Scores																				
$\text{Cosine}_{cf,AmBe,TRO}$	0.98615	0.98452	0.97577	0.97545	0.98575	0.98386	0.97505	0.97418	0.98562	0.98351	0.98662	0.98344	0.98657	0.98540	0.98595	0.98513	0.98570	0.98375	0.98588	0.98462
$\text{Cosine}_{cf,AmBe,Jim}$	0.99833	0.99802	0.99559	0.99532	0.99779	0.99735	0.99450	0.99407	0.99727	0.99676	0.99704	0.99642	0.99864	0.99834	0.99805	0.99785	0.99763	0.99678	0.99738	0.99699
Configuration																				
R_hdpe																				
R_det	[0, 1.5, 2.5]	0, 1.75, 3.5	[0, 1.5, 2.5]	[0, 1.75, 3.5]	[0, 1.5, 2.5]	[0, 1.75, 3.5]	[0, 1.5, 2.5]	[0, 1.75, 3.5]	[0, 1.5, 2.5]	[0, 1.75, 3.5]	[0, 1.5, 2.5]	[0, 1.75, 3.5]	[0, 1.5, 2.5]	[0, 1.75, 3.5]	[0, 1.5, 2.5]	[0, 1.75, 3.5]	[0, 1.5, 2.5]	[0, 1.75, 3.5]	[0, 1.5, 2.5]	[0, 1.75, 3.5]
Cw	1.44	1.44	2	2	1.44	1.44	2	2	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44
R_inner	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5
R_outer	5.5	5.5	5.5	5.5	6.25	6.25	6.25	6.25	7	7	7.5	7.5	5.5	5.5	6.25	6.25	7	7	7.5	7.5

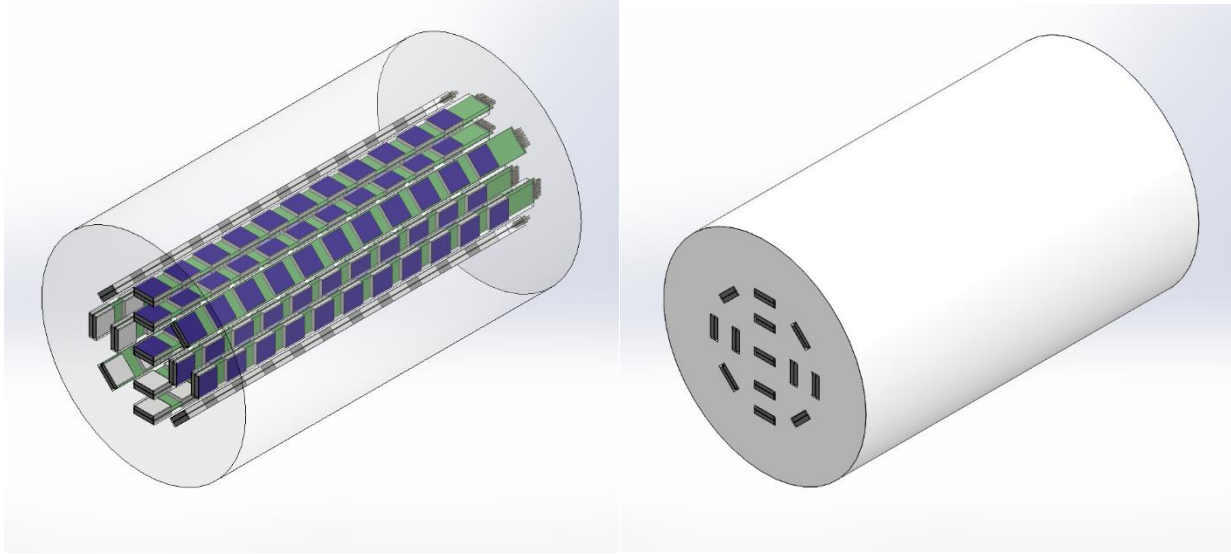


Figure 21: Final NRID moderator and MSND array design. LC13x11 R7 CW2 [0, 2, 3.5].

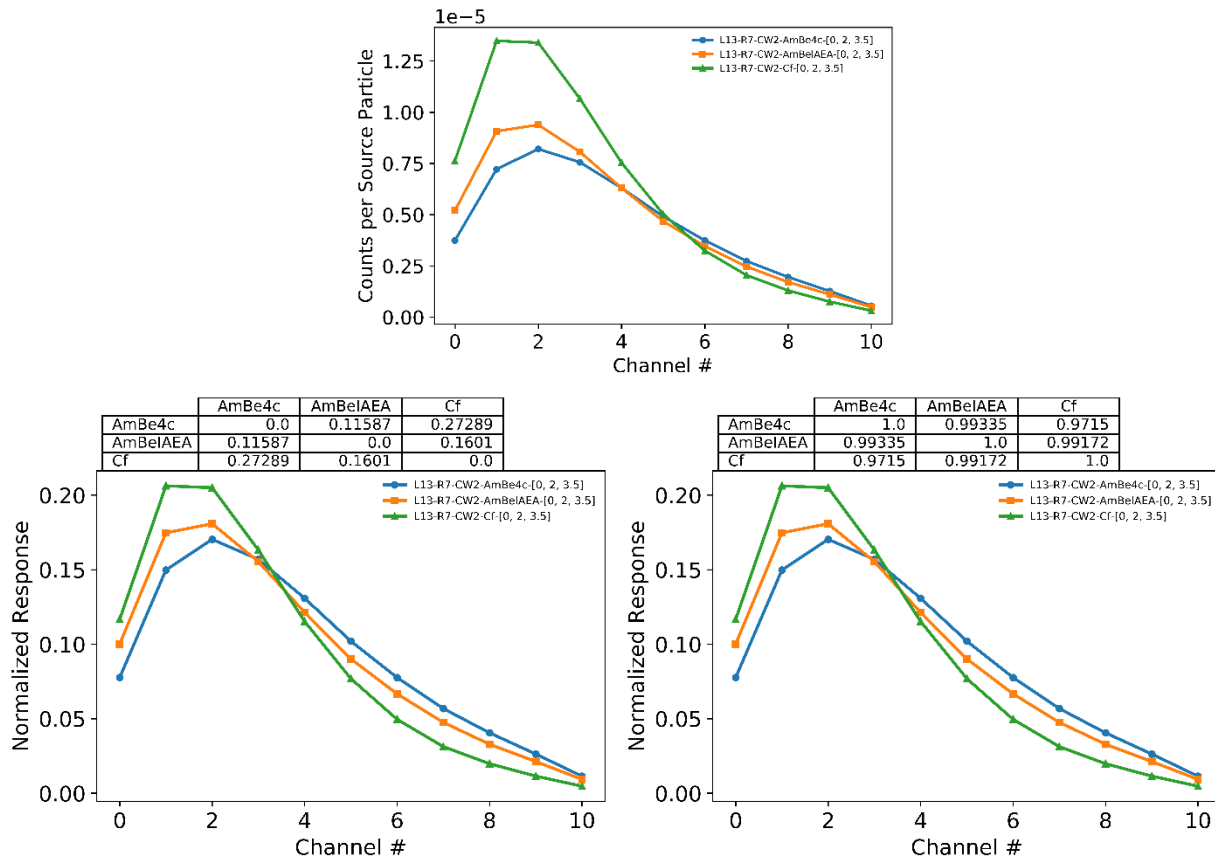


Figure 22: (top) Absolute NRID response, (bottom left) normalized NRID response with SAD score, and (bottom right) normalized NRID response with cosine score for the final NRID design for ^{252}Cf and AmBe with and without room scattering. All simulations were performed with the isotropic point source 1-meter in front of the NRID (0° angle orientation).

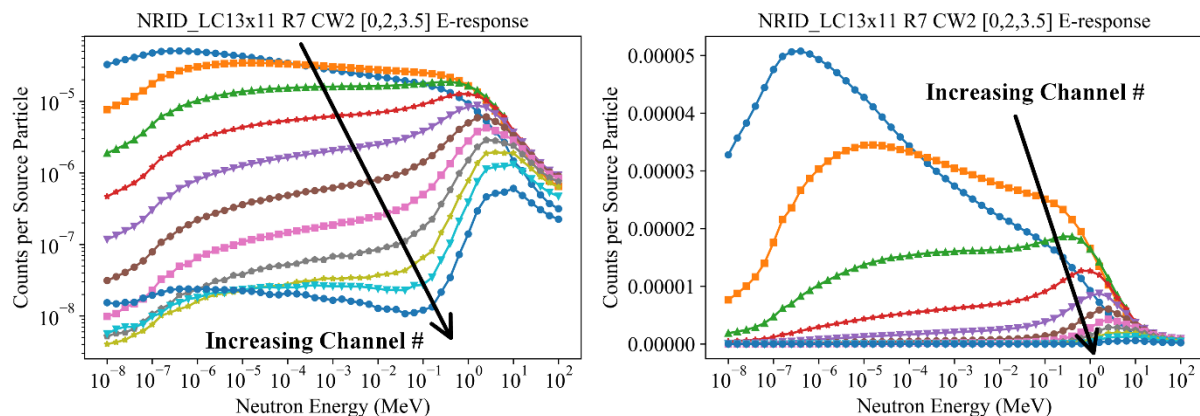


Figure 23: Monoenergetic neutron response for each channel in the NRID for a beam of neutron normal on the front face (Channel 0) of the spectrometer.

3.1.4. Additional Materials Considerations

NRIDs with FR4 (standard) and polyimide printed circuit boards (PCBs) were simulated. Certain elements in FR4 absorb thermal neutrons, which can't then be detected by the NRID, but FR4 traditionally has been significantly lower priced than polyimide (~100x). Preliminary results comparing FR4 and polyimide from the simulations are displayed in Figure 24 and Figure 25. Initial analysis indicates the detection efficiency could be up to 10% higher if polyimide PCBs are used instead of FR4 PCBs. Additionally, for more accurate unfolding and ID in isotropic neutron environments, the fast neutron sensitivity of the NRID may need to be improved. One method could be to replace one channel of MSNDs with hydrogens-material (e.g. wax) backfilled MSNDs that would utilize (n,p) reactions to detect fast neutrons.

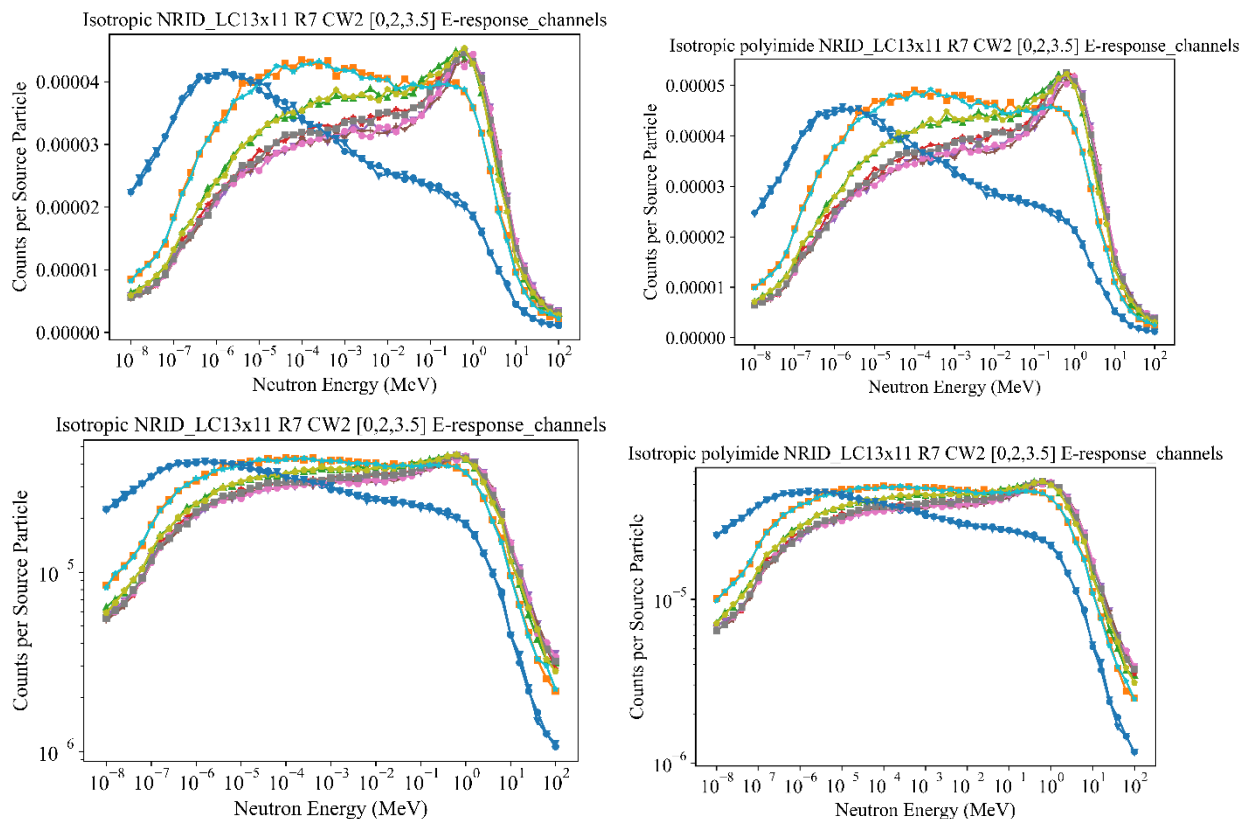


Figure 24: (Left) FR4 and (Right) Polyimide for NRID PCBs simulations results. The polyimide based NRID could have approximately 10% higher detection efficiency than the FR4 PCB NRID.

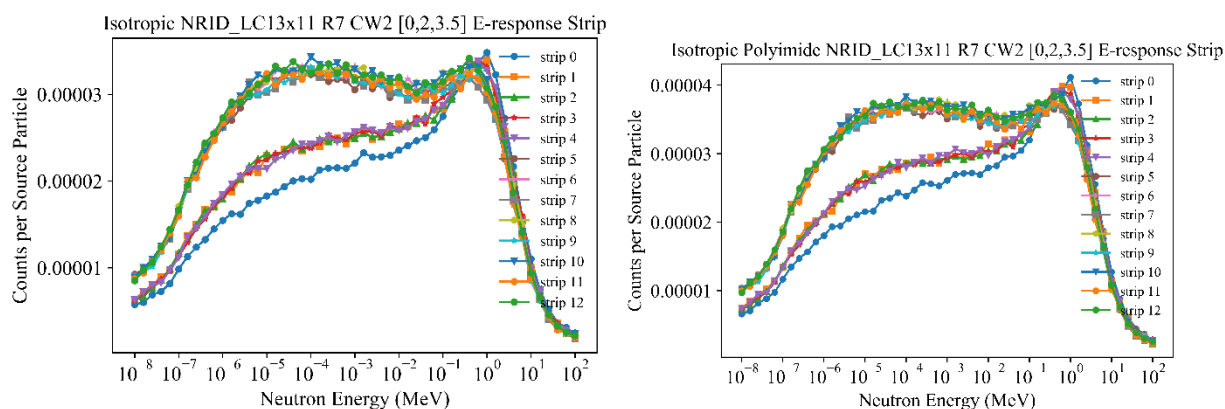


Figure 25: Isotropic source, response function for each axial strip in the NRID. (left) FR4 (right) polyimide.

3.1.5. NRID 1 Advanced Models

The methods that allow moderating neutron detection systems to accurately detect, locate, and identify neutron emitting sources, requires accurate computational models to understand the

scattering properties the device is constructed with. While broad generalizations can be made with simple moderator-detector models, when in operation, it is important to incorporate as many materials as possible that might affect the neutron scattering properties of the device. Effort was spent constructing a more “detailed” model of the device including the housing for the moderating volume, and some electronics seen in Figure 26. MCNP needs only the atomic composition and density of a material, which is easily found for crystalline and atomic materials, however amorphous materials like carbon fiber pose some challenges. Carbon fiber materials have many manufacturers, manufacturing methods, and coating that can make the exact atomic make-up difficult to pin down, so a literature search was conducted to try and find the most all-encompassing atomic composition that might suit as a “good enough” material card for the MCNP simulations. Further refinement of these material cards could be done with additional manufacturer information. Work focused on generating various neutron source libraries, as well as the device’s response functions for neutron spectrum unfolding.

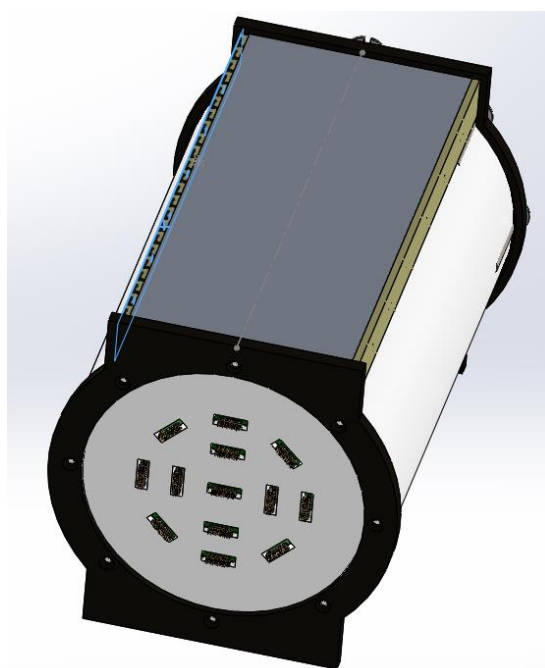


Figure 26: Model of the structural and detection components of the proposed NRID V1 system.

A mono-energetic isotropic neutron response was simulated for the NRID. Figure 23 shows the difference in response for front-on (e.g., source in front other detector) and the isotropic response (e.g., background, high scattering environments). For front-on irradiations, the channels in the back of the detector have peak sensitivities to fast neutrons, which improves ID and dose calculations. Recall that a channel is defined as the sum of 13 MSNDs at each axial length down the NRID and there are 11 channels in the system. In isotropic neutron environment, the response functions flatten in the epithermal neutron range, and the peak sensitivity occurs at approximately 1 MeV except for the two channels on the ends of the NRID. Fortunately, each MSND can be read out individually in the NRID, which allows us to select groups of detectors to use for the isotropic dose response. Figure 27 shows an example of detectors from only the center strip, which are used

along with a potential wax backfilled MSND. Ideally, the shape of the NRID response can be tailored to match the ICRP fluence to dose conversion coefficients, which would simplify the dose/dose rate calculations. Work continued to investigate the feasibility of producing fast-neutron sensitive MSNDs as well as further adjusting the moderator configuration with area-specific shielding or streaming paths to match the dose response function more closely throughout Y2 of the project. These modifications to the moderator and detectors would be implemented in the final NRID.

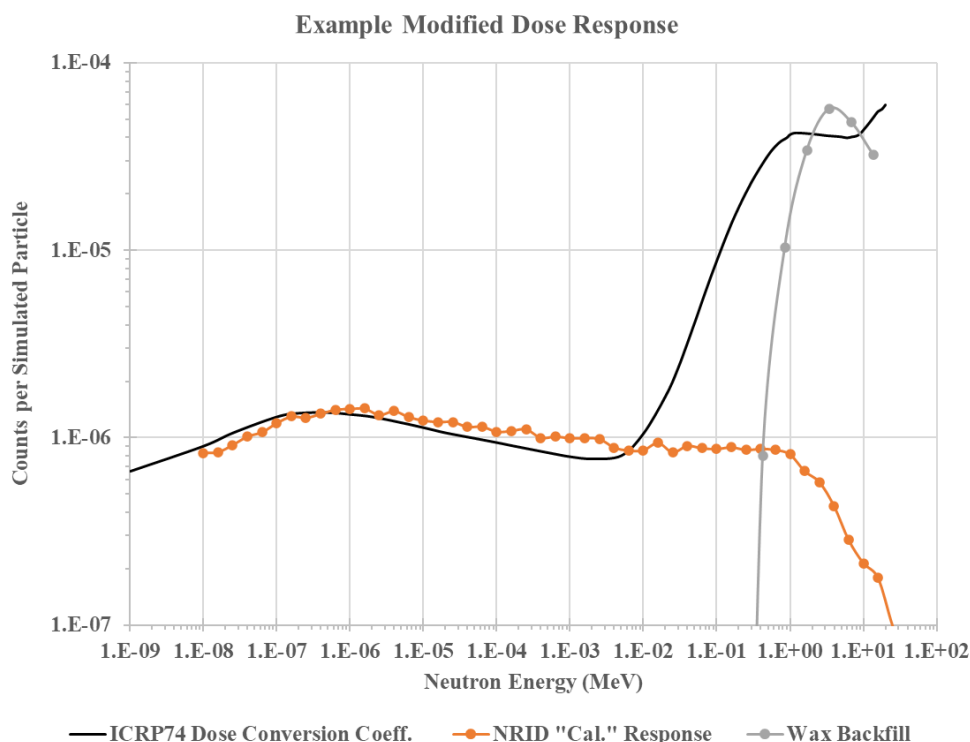


Figure 27: Example of tailoring the dose response of the NRID by using response of specific detectors in the array.

As the model refinement process produces significant changes, it is important to get an understanding of how some of the analysis algorithms might perform, where possible adjustments to those algorithms can be made. To that end, the response functions of a source incident on the front of the device were generated to make a qualitative assessment of their uniqueness for unfolding, as well as the angular signatures to a single spontaneous fission source. The response functions can be seen in Figure 28 and look like other proposed devices in that there is a broad range of detection possibility for many of the front detectors, and the back detectors have tighter peaks over the higher energies. The ideal case for unfolding is when each detector has a tight gaussian over a single energy; this is rarely the case for moderating type neutron detection systems. An additional metric for the unfolding problem is using the condition number of the response matrix. The condition number of a matrix can be used as a measure of error for the direct inversion of a matrix, the lower the condition number of a matrix the lower the error. In short, for the unfolding problem, the lower the condition number, the easier it is to determine the incident energy spectrum of a measurement. The ideal condition number is 1, and this device's condition number was calculated at 6.7E6, which is on the same order of magnitude to other proposed devices of this type; meaning Bayesian unfolding methods were necessary to unfold meaningful results.

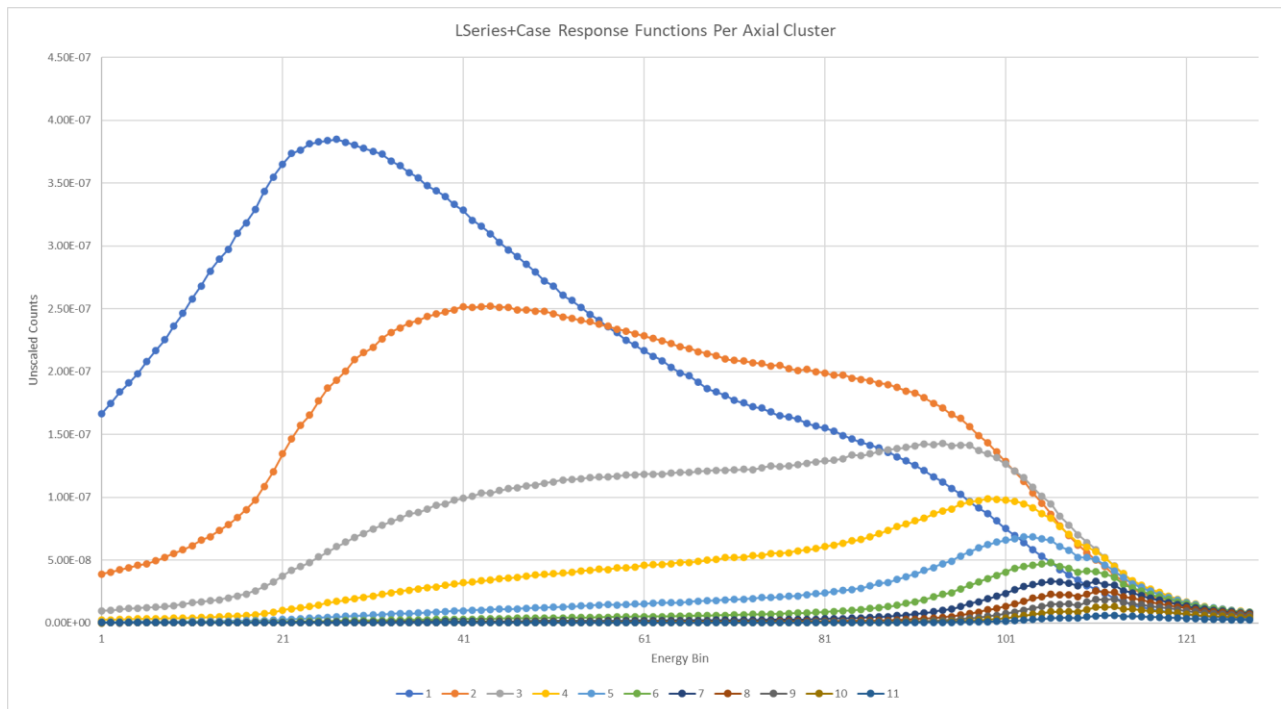


Figure 28: Response functions for the L-Series device with case materials.

The angular signatures were generated by rotating a simulated source around the device in both the horizontal and vertical planes. The source was kept at a constant distance and moved in 5-degree increments from 0 degrees (the front face) to 5 degrees off the back face at 175 degrees, the results are shown in Figure 29 and Figure 30. Qualitatively, the nearly perfect symmetry as the source rotates around the device, for example at 5 degrees the signature is almost identical to back side equivalent of 175 degrees. This is promising because the addition of the casing materials into the model doesn't seem to affect the angular response.

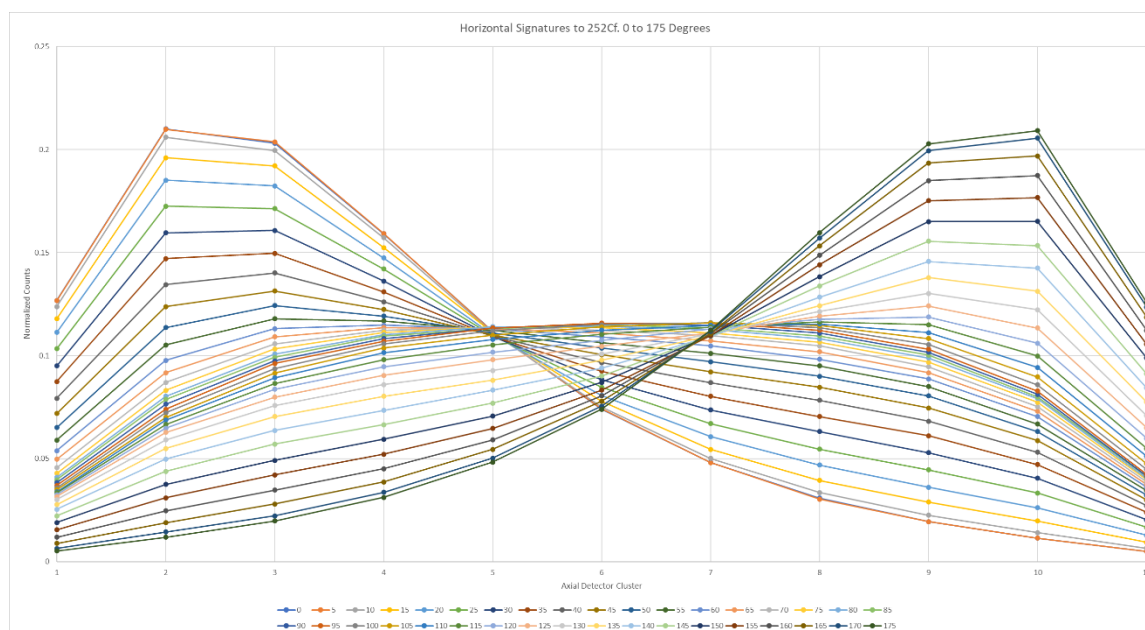


Figure 29: Horizontal plane signatures of ^{252}Cf from 0 to 175 degrees off the front face.

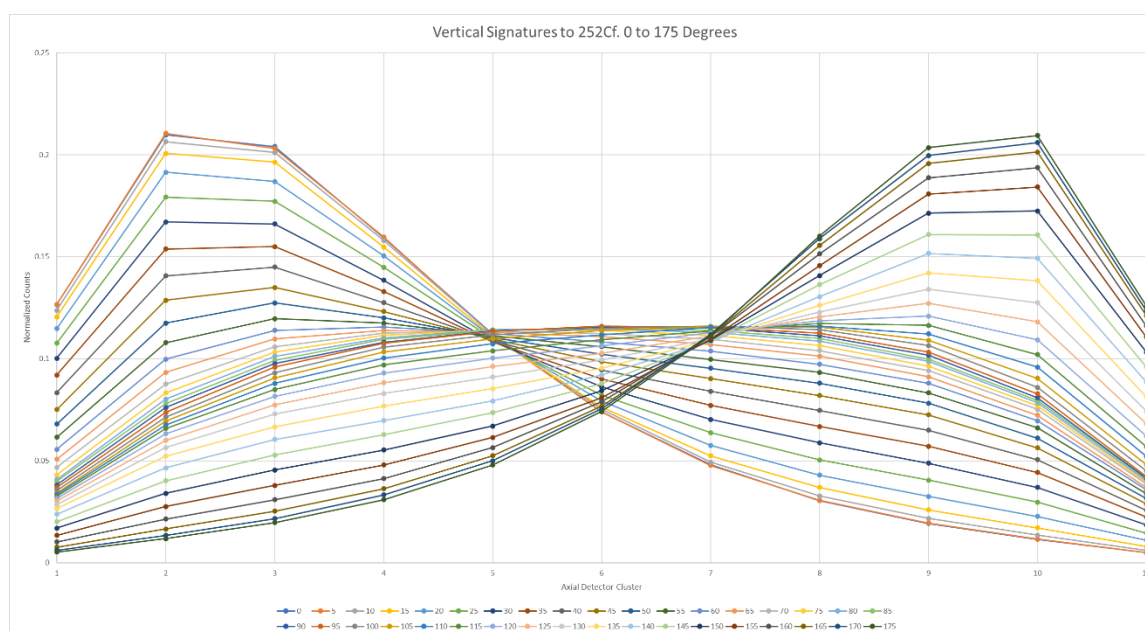


Figure 30: Vertical plane signatures of ^{252}Cf from 0 to 175 degrees off the front face.

3.1.6. [Algorithm and AI/ML Development](#)

3.1.6.1 Neutron Dose

There are two common methods used to estimate the operation neutron dose with a handheld or mounted neutron spectrometer. In the first method, the detector response is unfolded to determine the best guess at the incident neutron energy spectrum. Once the energy-dependent neutron spectrum is determined; the dose can be directly calculated using neutron fluence to dose rate conversion coefficients. Neutron unfolding is a challenging, computationally intensive, and often

requires a fairly accurate “first guess” at the energy-dependent neutron flux to converge on the correct solution. The second method for determining the neutron dose (or dose rate) is the design the detector/moderator configuration such that the detector response or adjusted sum of responses matches the shape of the fluence-to-dose conversion coefficient (see Figure 31). Simulations were performed to determine the proper methods to scale and match our detector response to the dose conversion coefficients for scenarios when a source is present and when the operator is in an isotropic background radiation field.

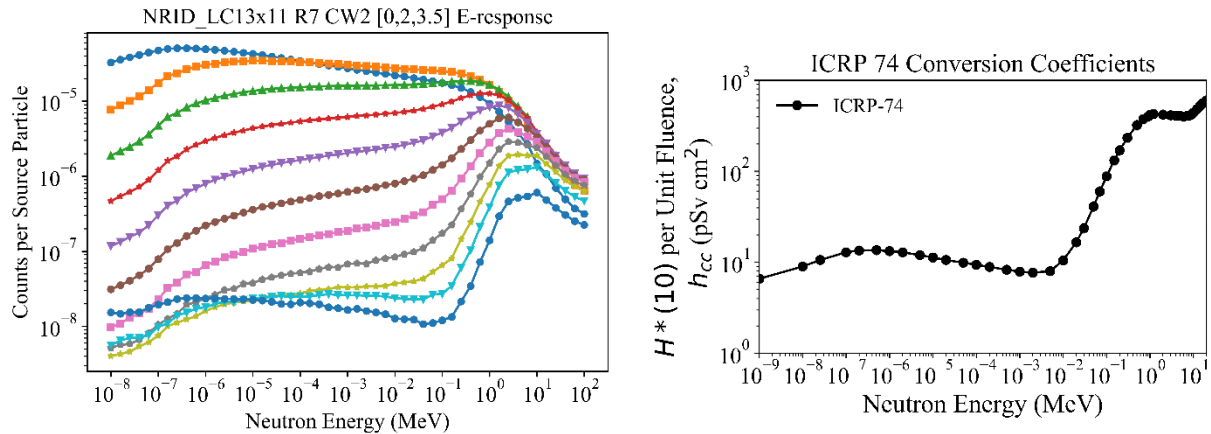


Figure 31: NRID response (Left) and fluence to dose conversion coefficients (right) for mono-energetic neutrons. The goal is to scale and combine the NRID response to closely match the shape of the ICRP-74 conversion coefficients.

3.1.6.2 Neutron Unfolding

The most accurate method for determining the human dose of incident neutron radiation is given by a method called “Unfolding.” Unfolding is the process of using a detection system’s known response to neutrons as a function of energy, called response function(s), and the results of some measurement with that device in order to determine the neutron emission spectrum from some neutron radiation source. In general, the neutron detection problem with a multi-detector element instrument can be modeled by the following matrix expression.

$$N = R\Phi \quad (1)$$

Where N is a vector representing the counts on each detection element. R is a matrix of response functions for each detection element, with dimensions [Detectors x Energy bin]. Φ is a vector that represents the intensity of emitted neutrons per energy bin of a neutron source. R is known a priori through simulation, and N is obtained by a physical measurement, and by inverting the response function matrix one can solve for the incident energy spectrum Φ , as show below.

$$\Phi = NR^{-1} \quad (2)$$

However, in practice the inversion of the response matrix is not always possible. Typically, the neutron response matrix is not “diagonalizable,” meaning the response functions that make up the total response have very similar characteristics. Because of this lack in “unique information” the

usual linear least squares inversion of the response matrix has poor solution stability, and as a result Φ has infinitely many solutions for equation (2). To obtain the incident neutron flux for dose calculations alternative methods have to be employed, the most common for measurement systems of this type is that of the Maximum Entropy Method (MEM).

The MEM method is derived from information theory, which simply says that the most unbiased, and likely solution for any optimization problem is one that maximizes the information entropy of the system. To do this, it is important to utilize all a priori information known about the system. For our problem the information entropy is given by the following expression.

$$Z = -\sum_i \Phi_i^G \exp(-\sum_k \lambda_k R_{ki}) - [\chi^2 \sum_k (\lambda_k \sigma_k)^2]^{1/2} - \sum_k N_k \lambda_k \quad (3)$$

Where Z is the information entropy. Φ here is an initial guess spectrum. λ is a set of coefficients to be optimized; N and R are the measurement and response functions, respectively. From the processes of iteratively maximizing Z with response to λ , the incident spectrum can be reconstructed using the following expression.

$$\Phi_i = \Phi_i^G \exp(-\sum_k \lambda_k R_{ki}) \quad (4)$$

The first step in utilizing any unfolding method is obtaining the discrete response functions for each detection element in a device, for a desired energy range and binning structure. For the following design investigation, 128 logarithmically spaced energy bins were used in the range of 1E-9 MeV to 70 MeV. This binning structure was chosen because of successful use with previous detection systems of similar detector geometries and moderating volume. It is important to encompass as much of the detectable range as possible into each response function because you want the probability distributions to be as complete as possible. That is, if a detector could detect an energy region from A MeV to B MeV, and only the range A MeV to C MeV (where C MeV = 0.5*B MeV) were accounted for in the response function, then neutrons in the range of C MeV to B MeV, would be inappropriately binned in the A to C MeV range.

For each energy bin, an equal number of neutrons for each energy bin (totaling in 1E10 neutrons) were incident on the front face of the device, and detection events were tallied as a function of their initial energy from the source. The response functions can be seen below in Figure 32.

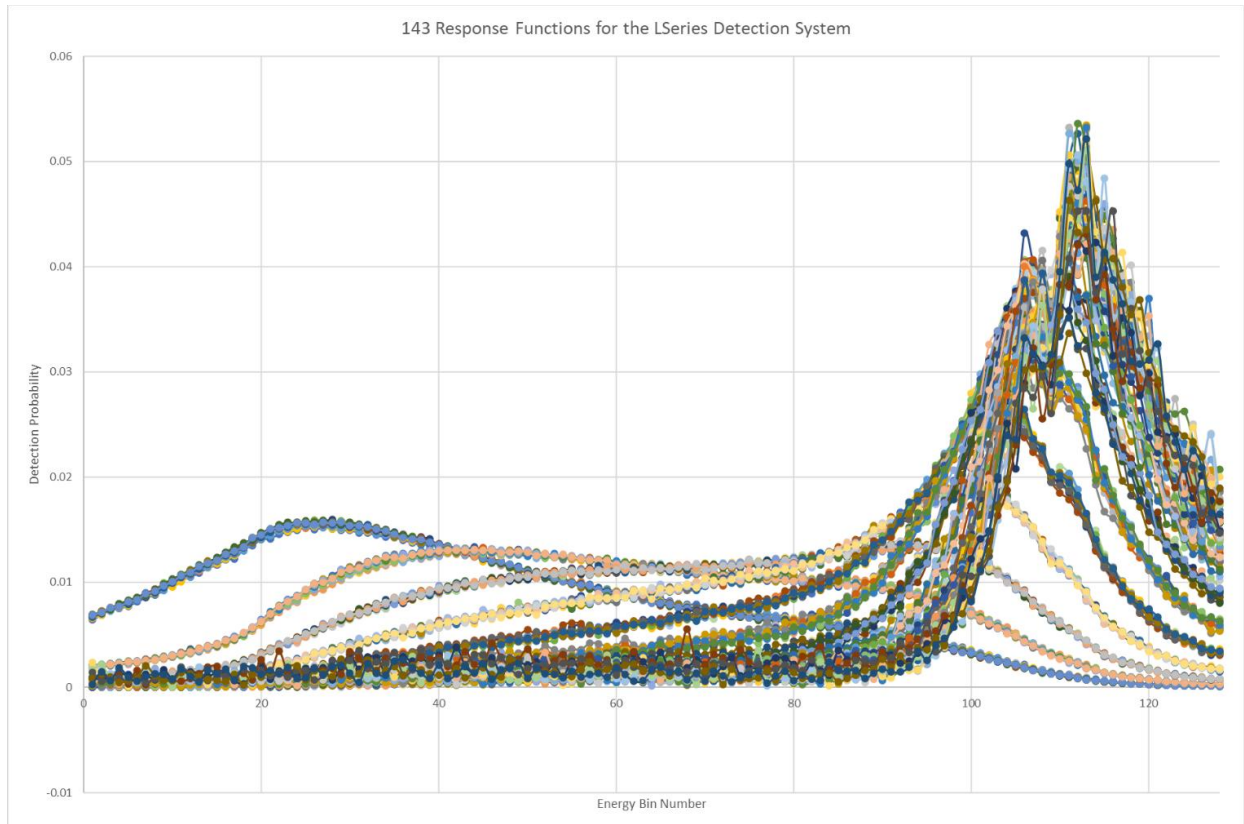


Figure 32: 143 Response Functions corresponding one for each detector in the L-Series Neutron Detection System. The y-axis represents the detection probability for a particular energy bin. X-axis does not contain actual energies but represent the bins logarithmically from smallest energy (left) to highest energy(right).

While Figure 32 is messy because of the number of chart elements, distinct groups of response functions can be made out easily on the low energy end of the figure representing groups of detectors toward the front of the device, while detectors in the back of the device have their peak detection energy probabilities shifted toward the higher energy end. The higher energy peaks in the 100 to 120 bin regions correspond to 1MeV and 20MeV respectively, and the overall shapes of these response functions are typical (not identical) for moderating type spectrometers of this type. The ideal, but nearly impossible to achieve shape of the response functions is for each detector to cover a tight gaussian region over one of the energy ranges. This would allow for a more conditioned response matrix that would allow for direct inversion as in expression 2.

Figure 33 and Figure 34 illustrate the idea of solution instability. Because the response matrix in this example is 128 energy bins x 143 detectors, the response matrix was inverted using a pseudo-inverse method, since the least squares method requires a perfectly square matrix. If the energy bins were resampled into 143 bins, this would provide a square matrix. However, this approach has been applied to other spectrometers and because of the broad nature of many of the response functions, adding additional bins into already smoothly sampled regions does not provide much new unique information. That is, many of the response functions will still contribute to the same regions almost equally, therefore not providing the desired tight gaussian regions as mentioned above. Figure 33 shows the result of the matrix inversion, the noisy appearance further displays

the non-unique contribution of information to the detection system. Further, this one of a nearly infinite solutions of the inversion, as seen in both Figure 33 and Figure 34 suggest that negative values of fluence are possible, implying that a mathematically possible solution is for the detection system itself to emit neutrons at fluences that are not physical.

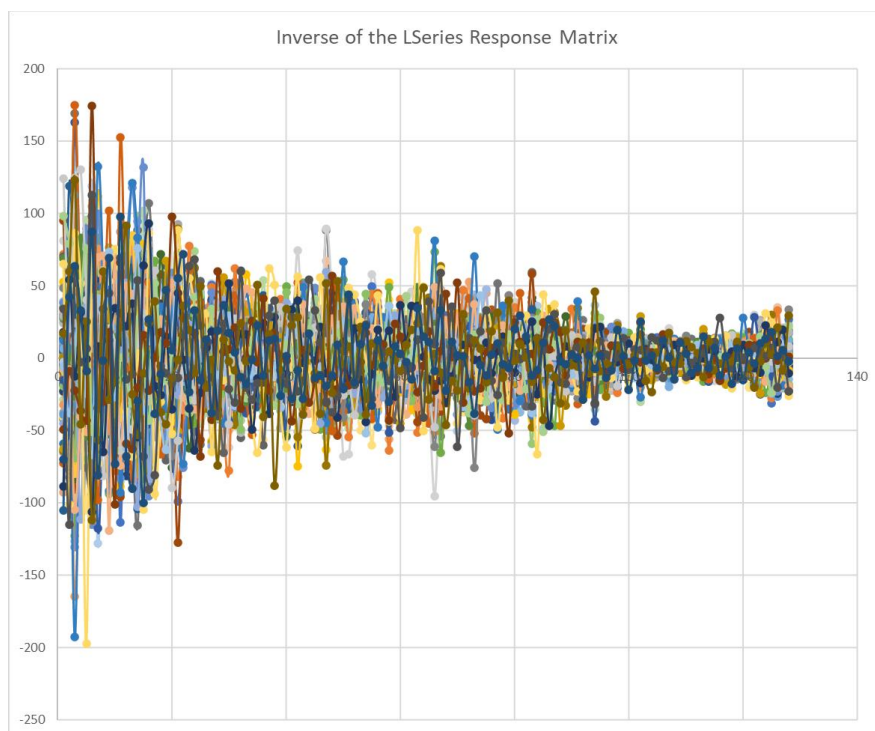


Figure 33: Pseudo inverse of the response matrix.

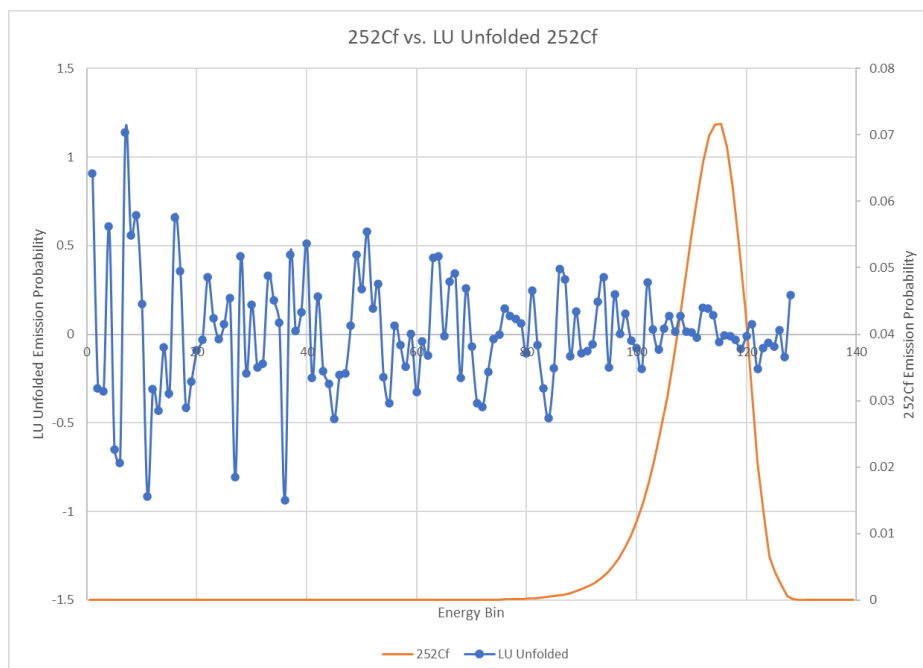


Figure 34: (Blue) Result of the direct inversion calculation of the ^{252}Cf fluence on the spectrometer.

Figure 35 as mentioned above, to apply MEM to this set of problems a guess spectrum or “Default” is required to help steer the algorithm in the right direction. Applying apriori information is common practice for very ill-conditioned systems, and can be made available by other detection characteristics such as library identification. In Figure 35 we have attempted to unfold a single ^{252}Cf measurement (simulated) using 3 different default spectra. In blue, a tight gaussian over 1MeV region, red using the actual ^{252}Cf spectrum the counts were generated with, and in grey the AmBe IAEA spectrum as a default. Note that red is not visible, because the MEM method could not find any solution better than the default method, so the maximum entropy solution is the apriori information itself, which we expect as it is the exact solution. The yellow line moves slightly off the blue, suggesting that there might be some place better in the solution space, but the algorithm was not fed with sufficient hyperparameters to find itself to far away from a good local maximum. The green line moves more significantly towards the correct solution, but similarly gets stuck in a local maximum.

Further illustration of the difficulty of this issue can be seen in Figure 36 and Table 14. If the proposed unfolded spectra are then “folded” back into the response matrix, to produce a new count vector, we see they all look very similar, while simultaneously the 3 proposed unfolded spectra look very different to the human eye in Figure 35. This does not mean the problem is insurmountable, as there is still much tuning to be done with the model itself, as well as the correct application of optimization algorithms in the MEM process. This only suggests that on previous detection systems, the conventions and “Art” of unfolding on that particular device do not apply to this new device, and more investigation is needed.

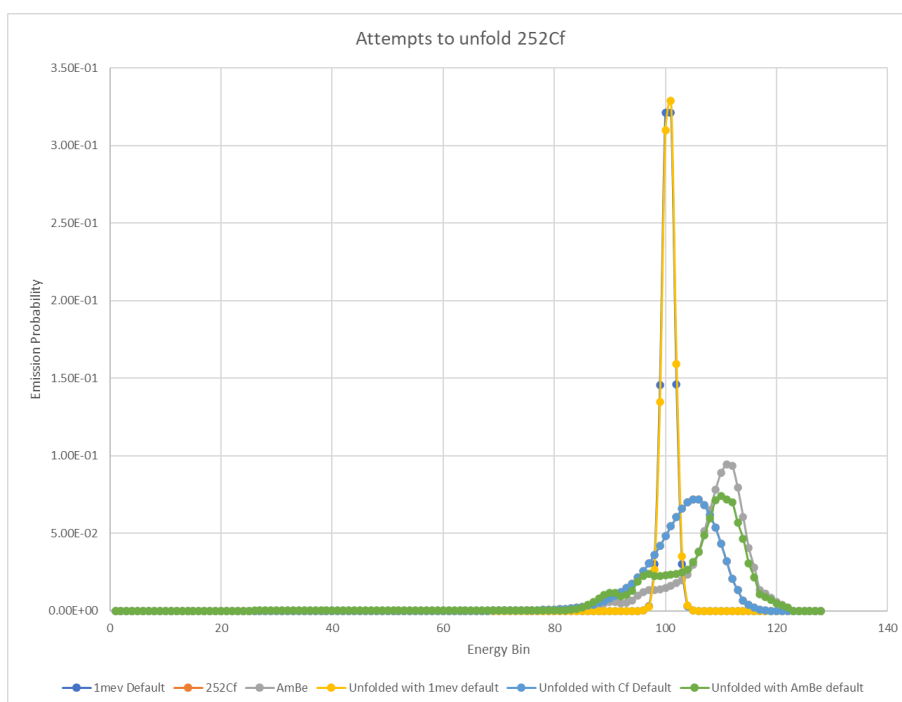


Figure 35: Three unfolded spectra next to the 3 default spectra.

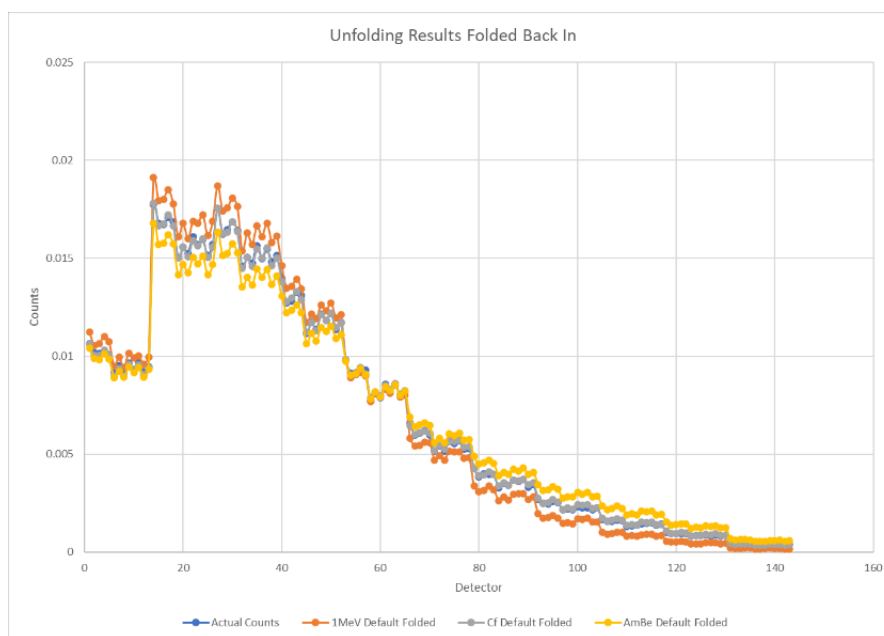


Figure 36: Comparison of what the unfolded spectrum’s count signatures (libraries) would look like on the detection system.

Table 14: Correlation matrix between count signatures in Figure 36.

	Actual Counts	1MeV Default Folded	Cf Default Folded	AmBe Default Folded
Actual Counts	1	0.998872944	0.999906842	0.998982461
1MeV Default Folded	0.998872944	1	0.998792516	0.996229069
Cf Default Folded	0.999906842	0.998792516	1	0.999155659
AmBe Default Folded	0.998982461	0.996229069	0.999155659	1

In addition to MEM for neutron spectrum unfolding, the team considered Machine Learning as a means to offers a computational efficient method for source ID, localization, and dose calculations. We are currently performing feasibility studies to determine if higher order algorithms (i.e. 3D data vs 1D and 2D) are better suited to ML/AI.

3.1.6.3 AI/ML

RDT developed a partnership with INL to do preliminary analysis of INL’s artificial intelligence/machine learning (AI/ML) algorithms on RDT’s NRID response for isotope identification. To complete this initial feasibility study, RDT performed additional basic MCNP simulations for different neutron sources (and varying neutron energies) incident on the NRID. The simulation results were used to train the AI/ML algorithm, which was then tested against additional simulated responses. RDT requested INL to be added as a subcontractor/consultant to the project and a larger training data set was comprised for additional sources, source locations, and environmental conditions. The AI/ML algorithms may allow for more accurate and faster ID than current template matching schemes.

Algorithm training data was generated using MCNP with a model of the RDT NRID V1. This data was generated for sources placed in front of the detector and were used as a quick feasibility/sanity check on the current AI/ML algorithm’s ability to distinguish different neutron sources based on NRID response. After feasibility was proven, the simulation space was expanded to include off-

normally-incident irradiations and the ability to backout dose rate information. To fully integrate a first generation of the state-of-the-art algorithms, approval was required for an extension of the PoP with a the requested for no cost extension. The AI/ML milestones included Preliminary analysis, AI/ML directionality and room scatter considerations implementation, AI/ML spectrum unfolding, and Full integration by end of PoP.

Intricate MCNP modeling of the NRID was performed to build training and evaluation data sets for the AI/ML algorithm development, which were used primarily for high-accuracy neutron-source identification with limited number of counts (~5000 or less). Secondary goals include (2a) source directionality and tracking, (2b) on-the-fly neutron spectrum unfolding, and (2c) neutron dose calculations. RDT worked with INL and leveraged their Spectral Observation Convolution neural network (SPOCK) system for isotope identification. A simplified NRID was modeled and bare and moderated, AmBe, ^{252}Cf , and ^{240}Pu sources irradiated the front face of the NRID. The ML/AI algorithm was trained and tested on the MCNP-generated data. The ID algorithm was able to correctly identify the incident radiation source at a rate **greater than 87%** (See Figure 37). We believe these results justified further development and tailoring of the AI/ML algorithms with INL for NRID.

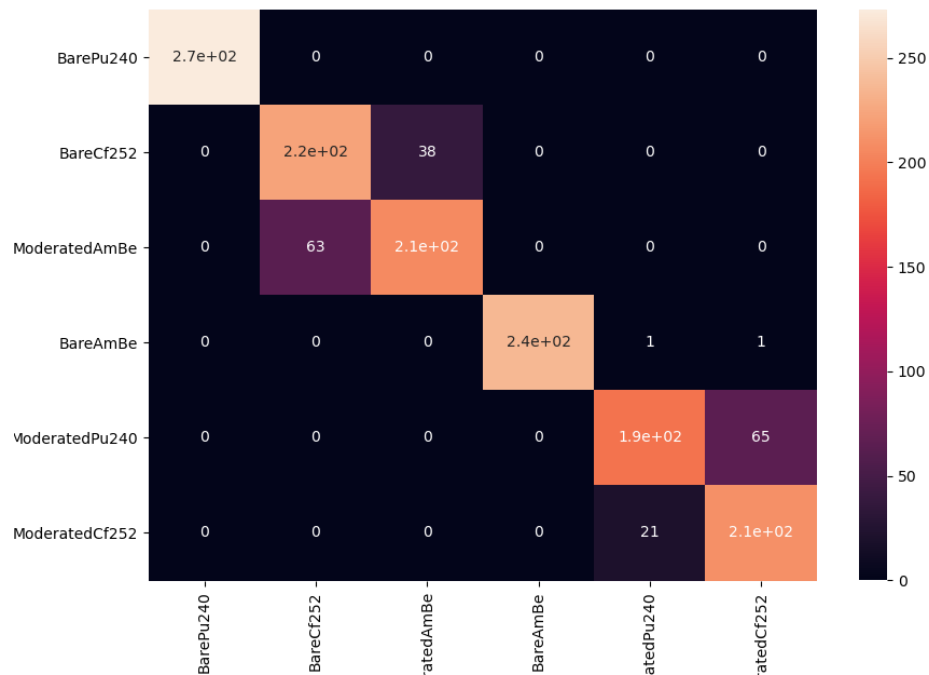


Figure 37: Confusion plot for SPOCK source ID with NRID on initial simulated data set. Numbers on the diagonal are correct identifications and off-diagonal numbers are incorrect.

Highly detailed models of NRID were (and are still being) developed and refined that accounts for internal scattering properties of the case, electronics, and ground (Figure 38). In the next step for algorithm training, the sources were incident on different angles relative to the front face of the detector to not only train source ID but also source direction.

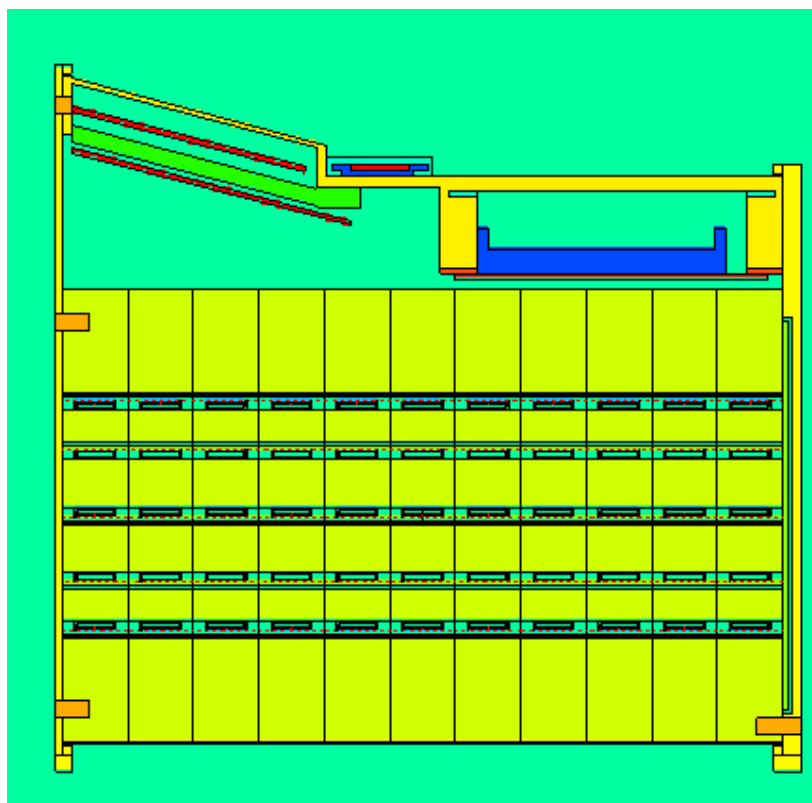


Figure 38: Detailed model of RDT's NRID for neutron transport simulations.

In the next set of simulations, the horizontal (theta) irradiation space was encompassed by 360° in 10° increments and the vertical space (phi) between 0° and 90° in 15° increments. Additionally, more neutron emitting sources were modeled. Bare and ANSI moderated (spherical, 0.5-cm lead, 1-cm steel, 4-cm HPDE) version of each source were used. To reduce simulation time, the sources were modeled separately to determine their neutron energy spectrum, and the results of those simulations were used as the source input in the NRID simulations.

Approximately 1000 simulations, were required for each irradiation angle for each source to train the ML/AI algorithm. Therefore, for each source (~225,000) ID required, there needs to be generated enough data for all sources, so 1.5-2.5 million simulations were performed. In the initial 10,000 simulations, the neutron source emission was isotropic, so that the floor and sky shine albedo could be very accurately modeled. However, it took over one week to get through the first 500 simulations making this method unreasonably slow to develop the ML/AI algorithms. Therefore, the next round of simulations were biased such that neutrons are emitted in a cone towards the detector. The cone was large enough so that interactions with the floor and air in a 6-m diameter circle around the detector was simulated. This method balances the required number histories for each simulation (i.e., speed), while still retaining the neutron albedo effects. Finally, the simulations were performed as if the operator were to set down the NRID and vacate the area during the ID measurements. This eliminates the need to model different sized operators to account for different neutron moderating characteristics of various sizes and body types of users.

Following the initial success of AI/ML training and algorithm development to perform neutron source identification on NRID, effort continued to generate additional training data. Recall that the

initial study was performed with only the moderator cylinder and detectors modeled with the source directly in front of the NRID at various distances, with no room scatter. To ensure that the AI/ML algorithms translate well from simulation world to operational environments, the model was updated to include the NRID case, ancillary support electronics, batteries, buttons, and screens. Additionally, a concrete floor was added 1-m beneath the detector so that ground scatter effects can be included in the simulations, heading off an issue in previous NRID versions that skewed directionality and ID algorithms requiring ad hoc corrections.

Our goal was to have the AI/ML trained such that for a given incident neutron flux, the algorithm can report the most likely source, direction relative to the NRID, and dose rate. To train the AI/ML more than a thousand detector responses (with various ranges of precision) are required for each source configuration at each angle of incidence. The initial approach to generate that training data was brute forced in that a thousand separate simulations were going to be performed for each irradiation angle. With a source library of only 12 sources, over 1 million simulations were going to be required possibly generating over 100TB of data. A data reduction solution was found that limited the output file sizes and then only required ~6TB of data. Unfortunately, another problem arose, where even though the simulations were performed on 250 cores on a supercomputing cluster, more than 3 months of wall time would be required to cover the first pass at the simulation space. To solve this problem, a new training data generation method was developed to cover the simulation space with 1000-2000 simulations, and then through statistical sampling of those results, the Team was able to generate the required 1-2 million training and evaluation data sets.

Neutron transport modeling of the NRID response to bare and moderated neutrons sources, both benign and special, is ongoing, requiring further refinement in a future effort. In this work, the results of the simulations were used to train the AI/ML algorithms, which in turn was provide estimates for 3D source location and ID. The simulations are including ground scatter considerations and the effects of the neutron energy spectrum softening when the source-to-detector distance increases. The AI/ML training algorithms were trained on 12 different neutron sources at locations encompassing 2π steradians around and above the NRID. Initial neutron dose tallies were also performed in the simulations so that we can understand if the AI/ML algorithm can also report accumulated and real-time dose rate; if those calculations needed to be analytical algorithms

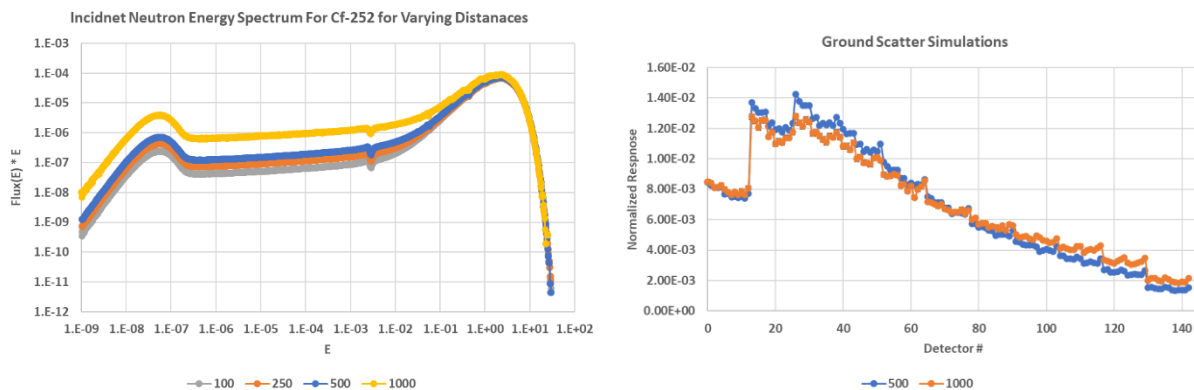


Figure 39: (Left) Plot showing change in neutron energy spectrum as a function of source-to-detector distance. Ground and air albedo shift the neutron energy spectrum lower. (Right)

Change in normalized detector response for different radii of ground scatter effects included in the simulation.

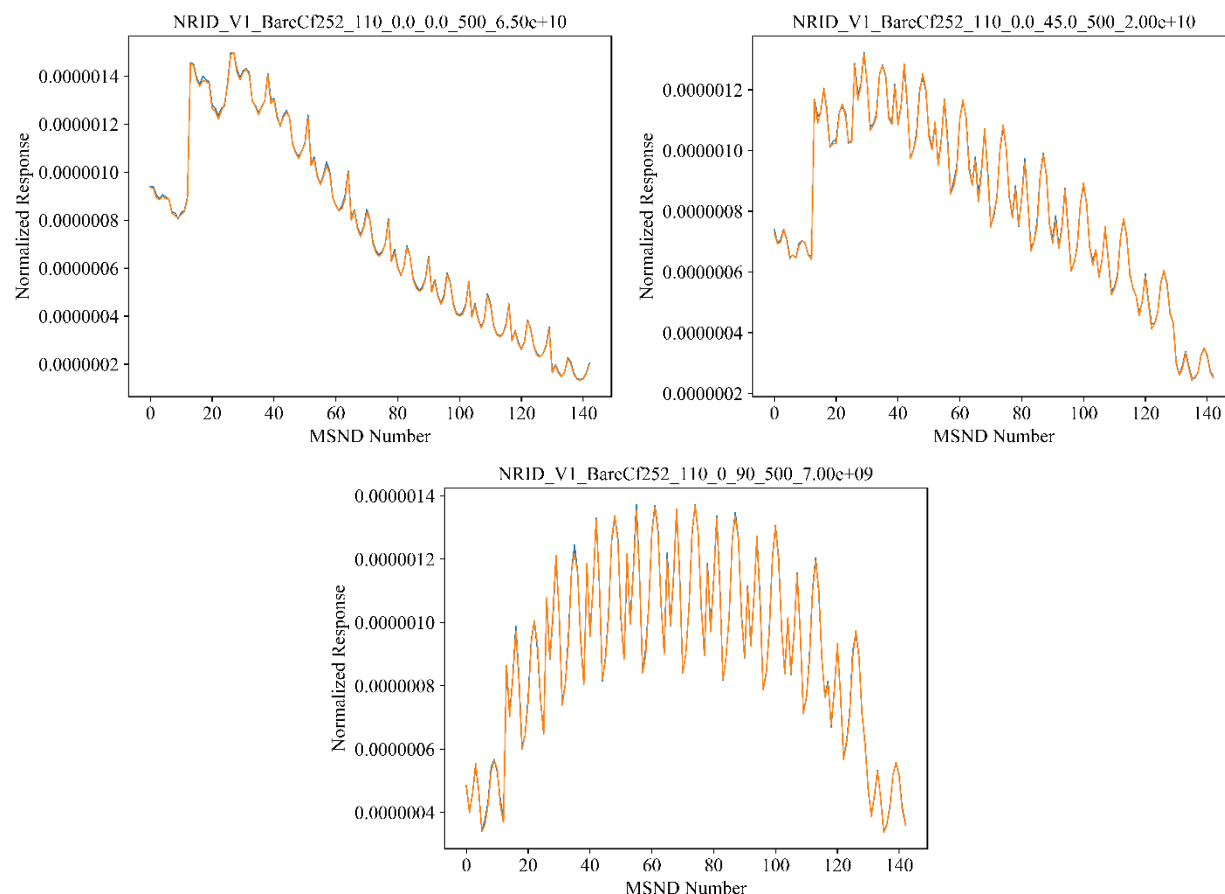


Figure 40: Simulated NRID responses for a bare ^{252}Cf source in plane, 45°, and directly above the NRID. The orange and blue lines were to check consistency between optimized versions of the simulation which further reduced the required simulation time by a factor of two.

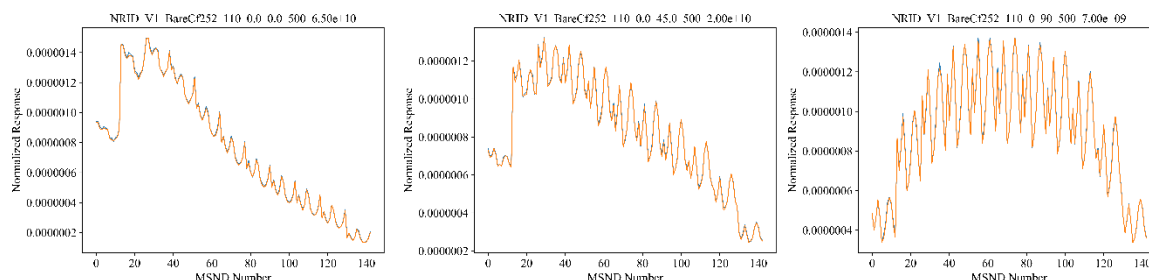


Figure 41: Simulated NRID responses for a bare ^{252}Cf source in plane, 45°, and directly above the NRID.

The AI/ML team has been hard at work developing methods to handle the very large training data sets. The initial trial to train on the 78 million spectra available crashed the system. A smaller data set, 20k spectra, was able to be pushed through, and the results were evaluated. Full training on the 78 million spectra data set was performed. After this training was completed, the NRID V1

was considered completely trained. An updated MCNP model of the NRID V2 was developed. This new model allowed for the generation of the training data set for the NRID V2. The second round of data generation and training was much faster than the first round, due to the protocols put in place to handle the larger data sets. This data set was composed of 12 sources (6 bare and 6 moderated) with source locations spanning the entire hemisphere above the NRID with distances varying between 1 and 5 meters. The number of counts in each NRID response spectrum varied between 1000 and 10,000 counts. Approximately 90% of the 26 million spectra were used to train the ID algorithm, and the remaining 10% of files were used to test the algorithm accuracy. In this round of training the source was position was randomly selected from any source location and the algorithm attempted to ID without knowing the source location. This represents a worst-case scenario. Overall of the sources tested, the average success rate for correct source ID was approximately 75%. Additional detailed information can be provided to US government parties in Non-Distribution A documentation.

The algorithm was retrained to first determine source location and then feed that information into the source ID algorithm to improve accuracy. Finally, we expect the best Source ID accuracy to occur when the source is directly in front of the NRID. A separate ID algorithm was developed specifically for this scenario. For field operations, if the operator wants the best accuracy, the operator can use the directionality compass to properly orientate the NRID and then begin the Source ID measurement. Additionally, the ID accuracy as a function of the number of counts measured in the NRID were determined. The NRID can then use that information to provide time-to-positive-ID metrics.

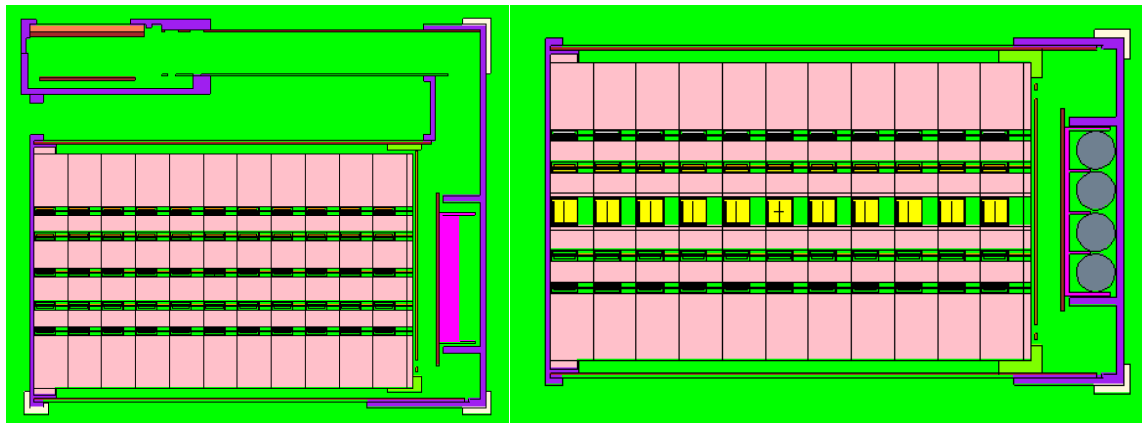


Figure 42: Updated model of NRID V2 with the Scorpion case.

3.1.7. Modeling Overview/Conclusions

Rigorous geometry modeling to simulate the radiological performance of the NRID was performed utilizing MCNP. The key metrics for the NRID redesign was providing a compact, ergonomic (lightweight) handheld system, while retaining robust source ID capabilities. The optimized NRID geometry is shown in Figure 21. The NRID is composed of 143 MSND distributed on 13 strips. One-dimensional spectrum unfolding, dose monitoring, and source ID can be performed for radiation sources and beams by separating the NRID into 11 energy channels along the axial length

of the system. Higher order unfolding algorithms, where the response of individual detectors is used for dose calculations and ID, are still being investigated and are likely required for isotropic neutron fields (e.g., background, highly neutron scatter/clutter environments). The NRID was simulated in an isotropic neutron field with monoenergetic neutrons ranging in energy from 1e-8 to 100 MeV and ML/AI was used to create ID algorithms.

3.2. Task 2: MSND & Electronics System Refinement Development

The contractor shall develop an overall system architecture, which was include: MSND design, Moderator Configuration, Electronics, Unfolding-Algorithms and UI Software, and Housing/Packaging.

RDT developed the overall system architecture with subcontractor UMKC. This improved the overall system architecture, based on the phase II PoP prototype, which represented the functional decomposition of the NRID instrument. The development defined the internal interfaces among the system's components, and the interface between the MSND and analog pulse readout electronics, the detector digital pulse acquisition, summing, the moderator stacking and identification/imaging algorithms, and finally, the display electronics and user interface (UI). The system has five functional areas: MSNDs, moderator configuration, electronics, unfolding-algorithms and UI software, and instrument housing/packaging.

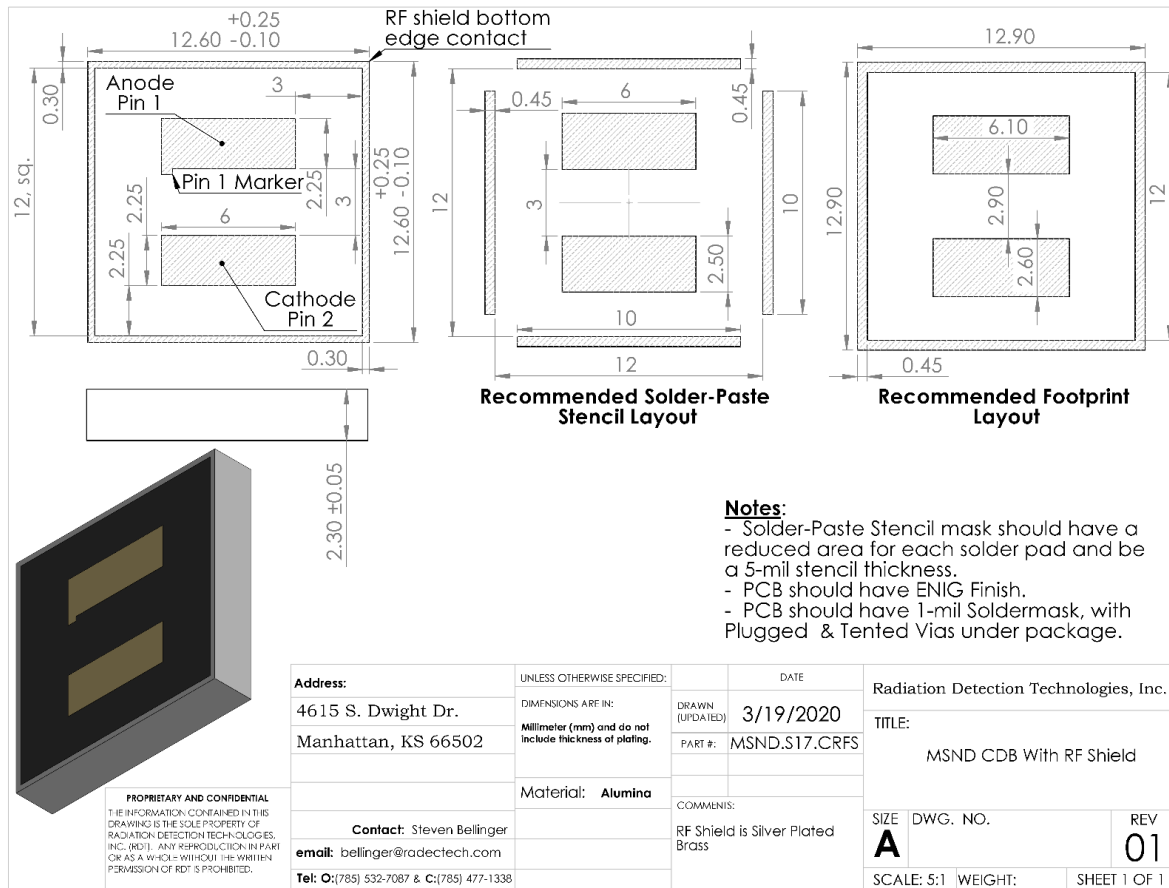
3.2.1. MSND Design

RDT developed a detailed redesign for the MSND sensor and packaging of the sensor. Detector improvements in size and power specifications integrated over the phase II prior design. Work was focused on the MSND sensors meeting requirements for electrical power, portability/mass, reliability/ruggedness, neutron sensitivity, and cost realism envisioned by the program milestones. The MSND were a single sided 30% th. n. det. eff. device packaged in a surface mount two-pad ceramic package; a picture shown in Figure 43.

RDT has manufactured and calibrated 1000 MSNDs for use in the NRID prototypes, assuming extras were needed to account for spares and assembly problems. The intrinsic neutron detection efficiency for each MSNDs was measured against a calibrated MSNDs. These efficiencies were used to efficiency correct the measured NRID response function. The MSNDs are standard to RDT's manufacturing line for MSND tiles and Dominos which have been well characterized and shown good field performance (TRL 9).



Figure 43: (left) Top and bottom picture of the two-pad ceramic case and metal lid the MSND sensor is packaged in, a.k.a. MSND Tile, for PCB surface mounting. (right) Illustration of the physics of how the MSND detection neutrons.



3.2.2. Moderator Configuration

RDT and UMKC worked together to develop the moderator-stack design. The moderator design was focused on maximizing sensitivity, source-identification accuracy, and source localization/imaging accuracy for a system that could meet the overall NRID performance requirements, at the specified size and weight constraints, e.g., less than 20lbs. Moderator size and geometry were based on modeled design optimization of Task 1. The moderator was chosen to be high-density polyethylene (HDPE). The final moderator dimensions for the NRID V1 build was a cylinder with 7-cm radius and 23-cm length. The moderator was fabricated by water-jet cutting the holes for the MSND detector arrays in HDPE disks, and then, aligning and attaching the HDPE disks to each other using either very-high bond (VHB) 3-M tape or HDPE-specific structural adhesive. The MSND arrays were inserted through the moderator and solder connected to a PCB plate on the back of the NRID. The PCB was then be connected to CPU and power conditioning electronics boards.

RDT has purchased a CNC router to manufacture the specialized HDPE moderator geometry and Carbon Fiber housing. Permabond TA4611 was used to glue the moderator disks together to form the larger moderator cylinder. This epoxy is HDPE-specific and has shown good adhesion on

HDPE scraps. Bulk carbon fiber sheets were used to perform neutron attenuation/moderator measurements and machine the end pieces of the NRID.

The final moderator dimensions for the NRID V1 build were cylinder with 7-cm radius and 22-cm length and accommodate 13 MSND strips (see Figure 44). The moderator was fabricated by waterjet cutting nine 1-in. thick HDPE moderate disks (the last disk was milled down to meet the final moderator length dimension). The disks were then aligned and epoxied together with TA4611 (or similar) polyethylene epoxy. Three-eighths inch diameter HDPE alignment rods run the length of the moderator block to ensure all the disks are properly align and to provide another surface for the structural adhesive further improving the NRID ruggedness. The MSND strips and backplate were installed into the moderator. Potting epoxy secured the MSND strips in the moderator and fasteners secured the backplate to the moderator. The tolerances around the MSND slots have been tightened (Figure 45). The goal was to maximize the volume of HDPE surrounding the MSND strips, to maximize the performance of the NRID.

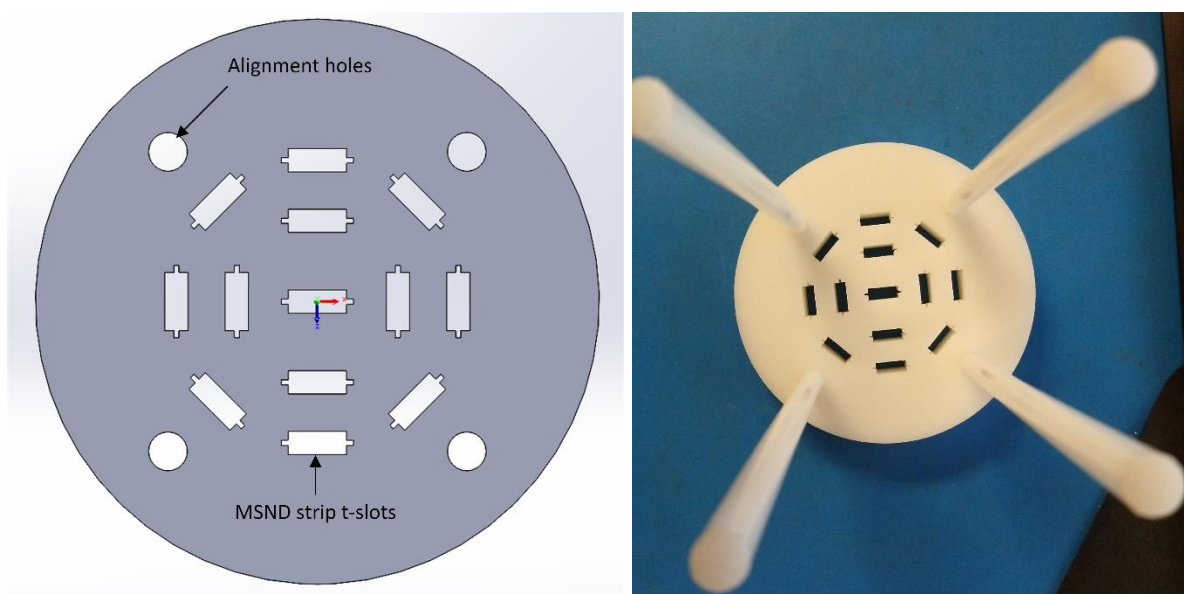


Figure 44: Moderator disk drawing and prototype. Nine disks were machined, aligned, and epoxide together to form the neutron moderating volume of the NRID.

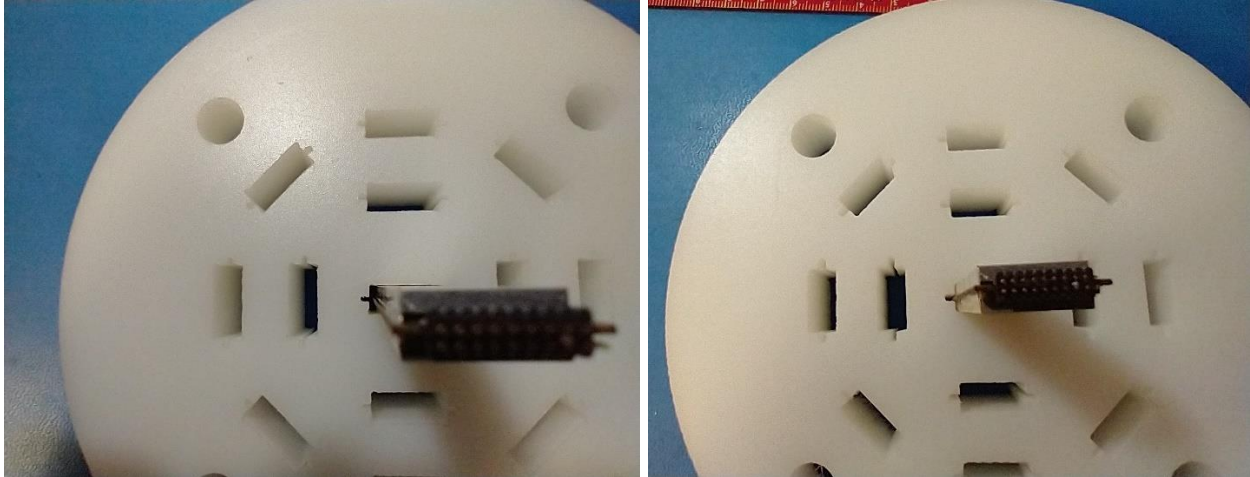


Figure 45: Improving MSND slot tolerance in the HDPE moderator to maximize HDPE volume near MSNDs.

All the HDPE disks have been water jet cut from 1-inch-thick HDPE. The slots for the MSND strips were deburred to ensure a snug fit. RDT CNC milled approximately 1.5-cm off one of the disks to achieve the final desired length of moderator (22-cm). After machining the final disk, the moderator stacks were epoxied together, see Figure 46.

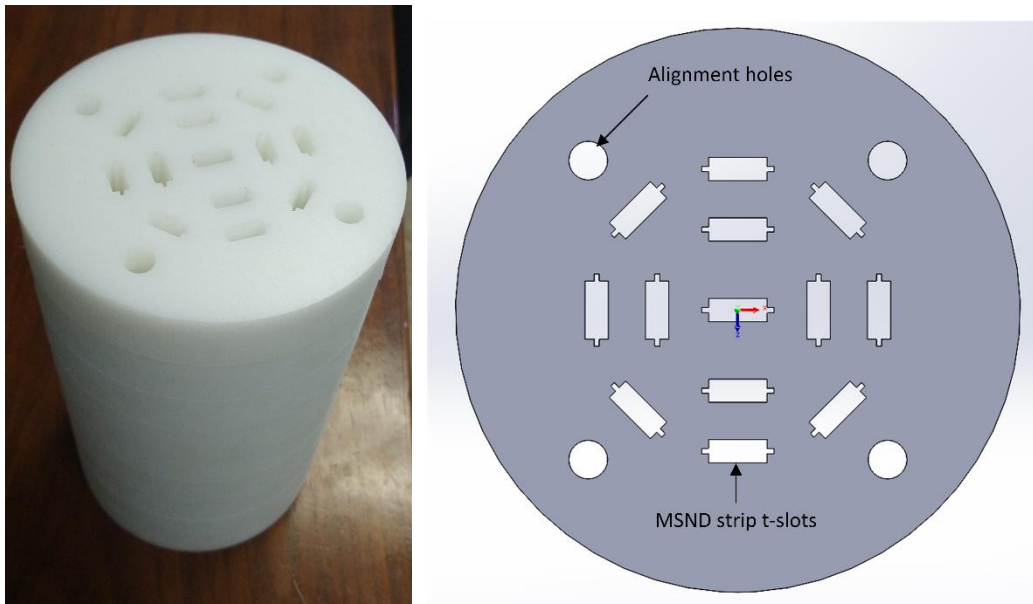


Figure 46: Moderator disks fabricated and assembled for the NRID.

3.2.3. Electronics

The Team defined the electrical system and allocated those functions to the redesign packages necessary to achieve the NRID instrument requirements. The NRID firmware, including detector pulse acquisition, summing, and user display electronics were designed and built. The detectors and the circuitry needed to be packaged and protected from impact, moisture, and EMI. Once the designs were completed, test development boards were manufactured to evaluate individual component performance before integrating the MSND readout electronics, communication

electronics, FPGA/computer electronics, power electronics, and display electronics into compact unified circuit board configurations.

Design and layout considerations and component selection for the array of electronics necessary for reading out the arrays of MSND tiles in the NRID instrument was completed. The readout electronics were based on prior designs, but re-routed to fit the required array layout of the MSND tiles for individual detector readout capability, see Figure 47.

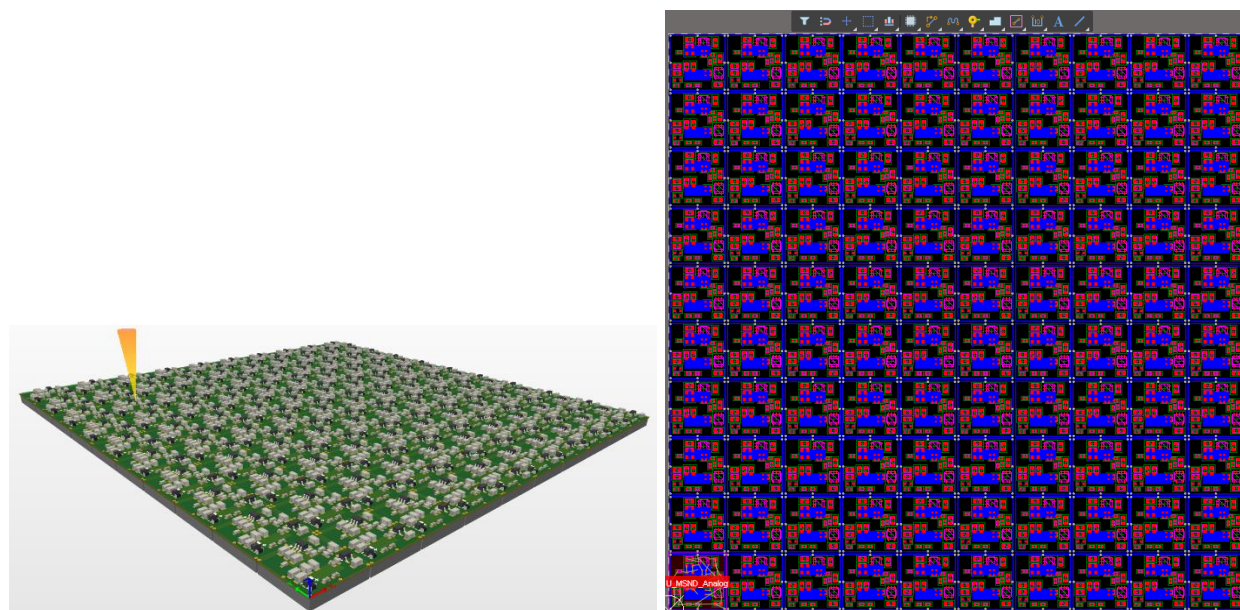


Figure 47: CAD picture of an array of MSND readout electronics that the NRID array were based on.

3.2.3.1.1 Schematic Hierarchy

To take advantage of repetitive circuitry and avoid cluttering the workspace, a hierarchal approach was selected for the NRID design. Figure 48 shows that the upper-level schematic separates the board into two components: Analog and Digital circuits. The Analog circuit was then split into multiple identical subcircuits, each sharing the base electronic schematic. This makes it easier to expand or decrease the total amount of MSND circuits without large design changes.

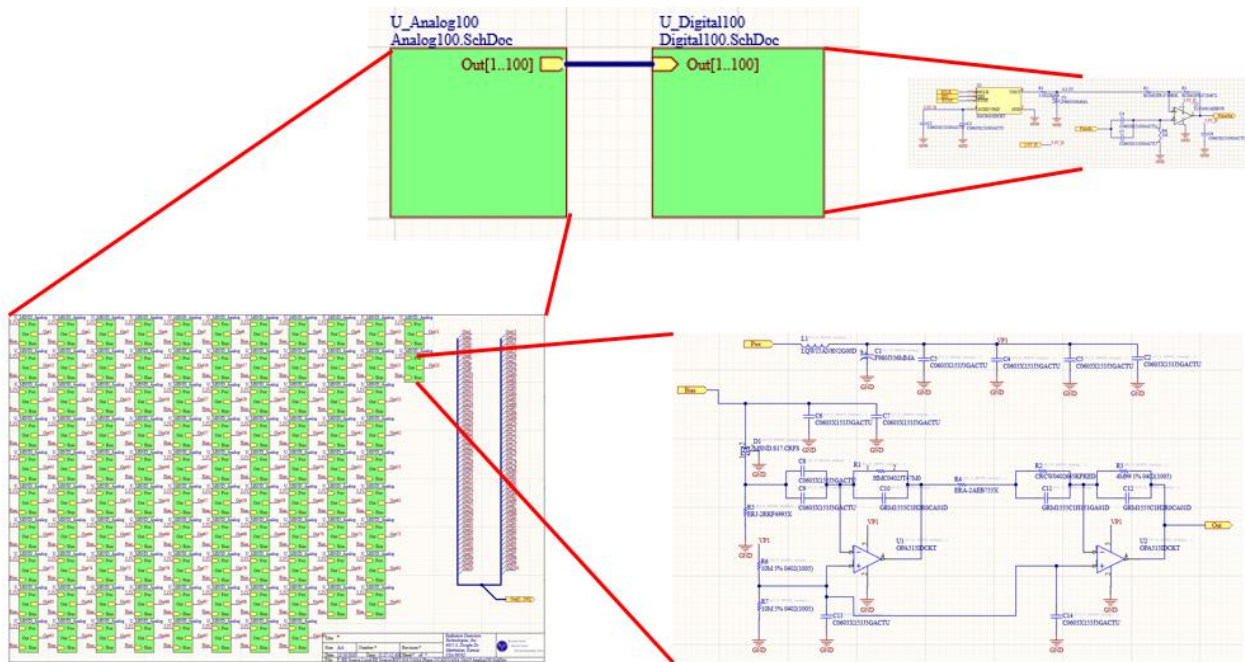


Figure 48: Hierarchical Schematic Design.

3.2.3.1.2 Layout and Routing

For layout of the actual PCB, keeping all the analog electronics behind the footprint of an MSND allowed for expansion without the cost of space. Figure 49 shows the layout for a single MSND, where the red is the copper for the discrete components, the dark blue is the MSND on the backside, and the light blue is the internal routing layer for the analog outputs. The location of the outputs on the lower half of the analog circuit maximizes spacing from the sensitive front end. Along with spacing, a dual ground plane is used to shield both the MSND and the analog components from the output pulses routed internally. Figure 50 shows the orientation of the internal layers, where the innermost layers are used for output routing and power. Both bias and power are coupled and filtered to help reduce noise as well.

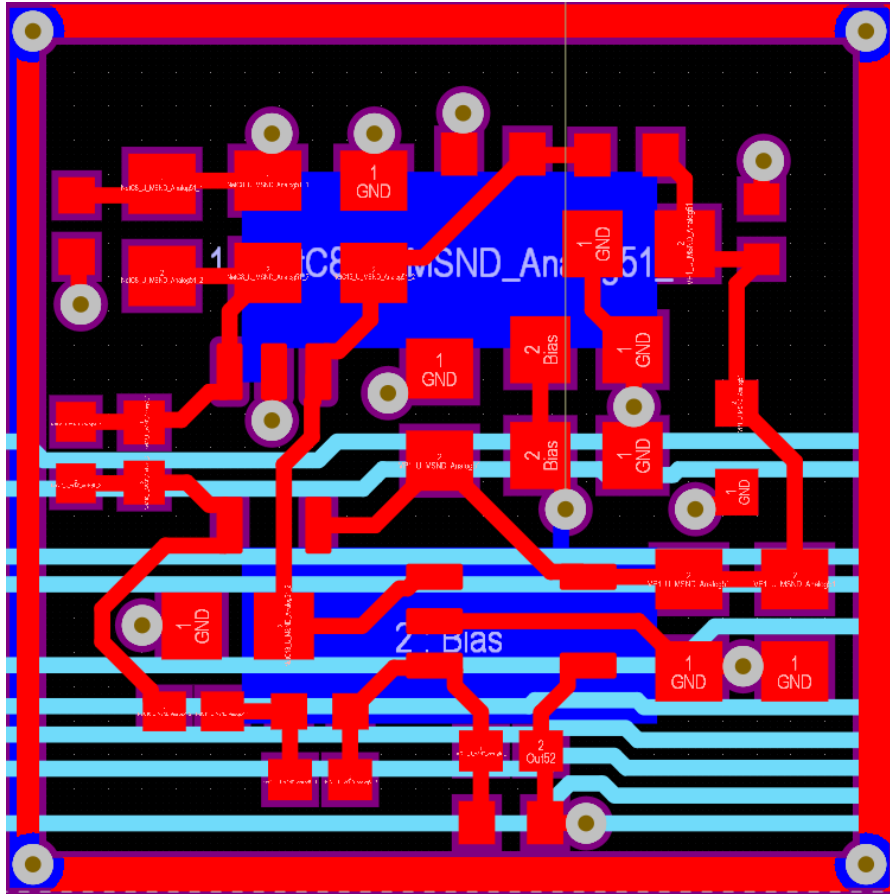


Figure 49: Single MSND Analog Layout.

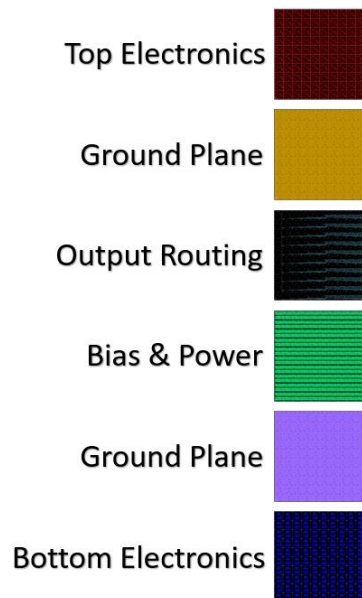


Figure 50: Circuit board layers illustration.

3.2.3.1.3 *Display and processing hardware*

The Raspberry Pi 4 was selected over the Nvidia Jetson.

Computer, Display, and Power Boards

The Raspberry Pi 4 was selected as the processing computer, which has a max active power need of under 4.5W, with an average around 3W. The Pi was a viable, more power efficient alternative, with the ability to have nearly the same operating systems on both boards, additional development time was needed to port the current software from the Nano to Pi. By evaluation, the NVIDIA Jetson NANO required too much power (5-10W) to operate and would require a large, heavier battery configuration to support an 8-hour mission. Therefore, the Team decided to move to the Raspberry Pi4 platform for our central processing unit responsible for source localization, ID, and dose calculations as well as UI display. Since, real-time source image overlay was not specified as a high priority for the users interview the removal of the GPUs by switching to the Pi4 with minimal impact on performance. The Pi4 has only 1.8W power consumption as well as a smaller footprint than the Jetson NANO. The power draw of the Raspberry Pi4 for low power (search mode) and high power (onboard unfolding) was studied.

As previously reported, there were low and high-power modes of operation. In low power mode, the NRID were able to perform the relatively computationally inexpensive tasks like search, localization, template matching source ID, and simplified dose rate calculations. In high-power mode, the on-board processor of the NRID was perform spectral unfolding/AI/Machine learning to back out in incident neutron energy spectrum for higher precision source ID and dose rate calculations.

The results from these measurements determined the number of 18650 batteries required for continuous 8+ hour mission operation. The 18650s were rechargeable in-system and field replaceable. The NRID has 4, 18650 rechargeable batteries, which provides greater than 8 hours of operation on a single charge. A dedicated power distribution board was fabricated and housed in the electronics housing of the NRID (Figure 60). This board was interface with the two sets 18650 battery holders and provide regulated power to the MSNDs, backplate/FPGA, and Raspberry Pi4 (which in-turn powers the display). Additionally, a charging port were installed in the electronics case and connected to the power distribution board so that the 18650 batteries can be recharged instead of replaced, if desired. Finally, a data port (likely USB-C) was installed in the cases that interfaces with the Raspberry Pi for data offloading.

The batteries and battery clips were acquired for the NRID (Figure 51). Effort was focused developing a PCB that was coupled to the battery pack that regulates power to the system (CPU, display, FGPA, detectors) and provides battery charging and overcurrent/short protection for the 18650s. The batteries were rechargeable in system, or they can be swapped out by the operator. The NRID has two IP67 rated USB ports on the side of the top plate for data transfer and fast charging.

The display screen for the NRID V1 is the Waveshare 4.3" DSI, see Figure 51. This screen directly interfaces with the Raspberry Pi4 that can be mounted directly behind the screen. The reaming four mounting points was secure the screen and Pi inside the detector housing. The user controls the NRID though a set of IP67-rated buttons that were mounted to the housing beneath the screen.

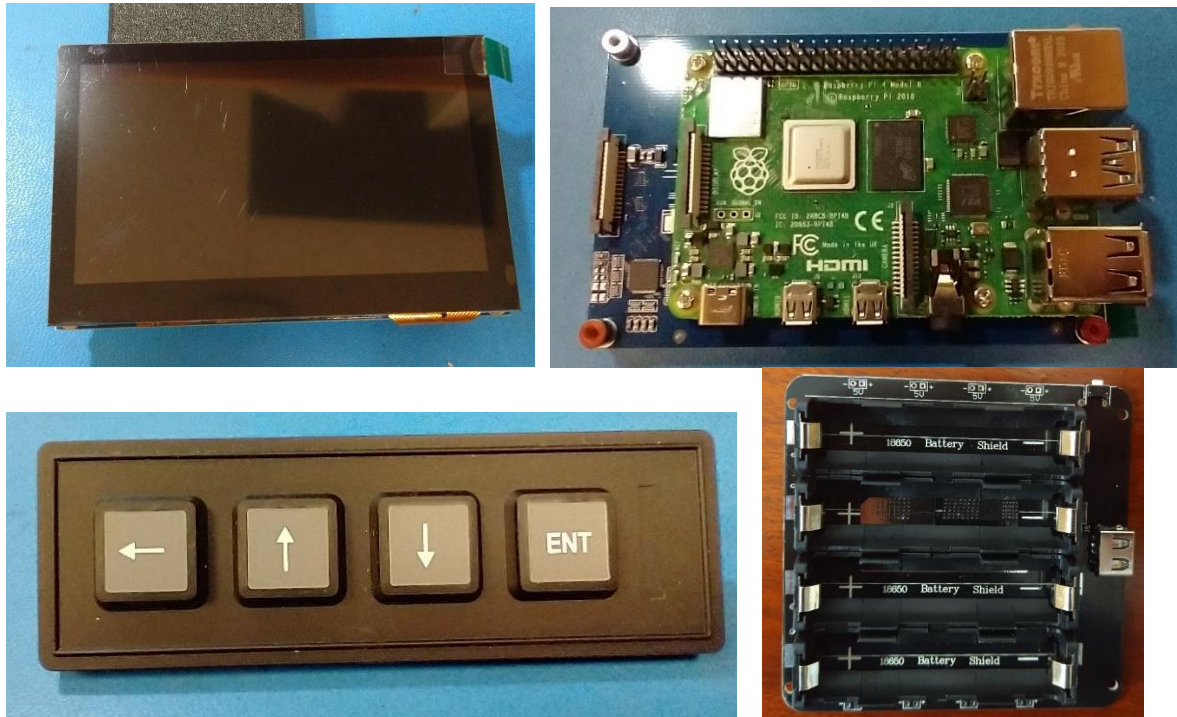


Figure 51. (Top left) 4.3" display. (top right) Raspberry Pi4 mounted on backside of display. (bottom left) IP67 rated buttons for NRID control. (bottom right) 18650 COTS battery board with fast charging and circuit protection.

MSND Signal Processing Electronics

A design for bias, amplifying, discriminating, and digital pulse generating for the MSND strips in the NRID was developed (see Figure 52). The RF-sensitive analog components were placed directly behind each MSND and have dedicated RF shields. The digital electronics were placed between MSNDs. Digital-pulse-carrying traces were run on the edges of the board extended past the edge of the MSNDs and onto counters located on the motherboard.

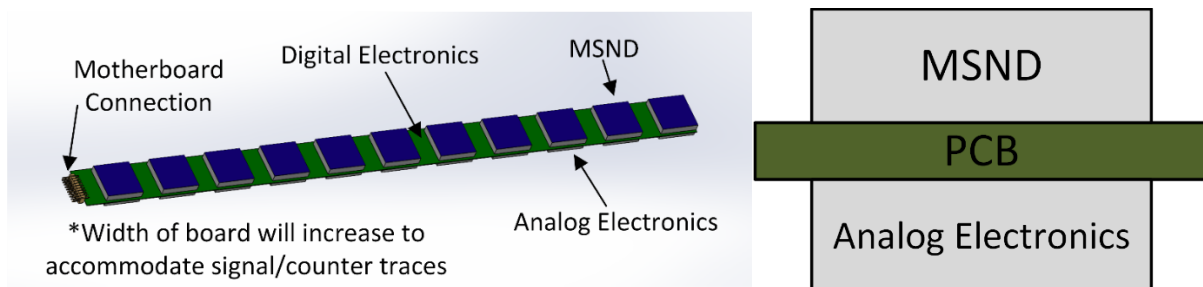


Figure 52: (Left) MSND strip (1x11) electronics overview. (Right) Cross sectional view of MSND Strip. The digital traces are routed outside the RF shields to prevent cross talk between MSND detectors.

The MSND strips are connected (soldered) to a polyimide PCB backplate which routes all the signal pulses to an on-board FPGA (see Figure 53). The FPGA handles all communications to the detector (e.g., setting discriminator threshold, setting bias). Additionally, the FPGA reads out the

pulses from each MSND, formats the data, and outputs the data to the CPU for algorithm processing (directionality, ID, unfolding). The MSND strip spacing on the backplate has been confirmed as viable and the FPGA selected. Since the FPGA is programmed at the factory, the firmware must be developed in conjunction with board/trace layout. There was a slight delay involving a licensing issue with the IDE, which was required to program FGPA.

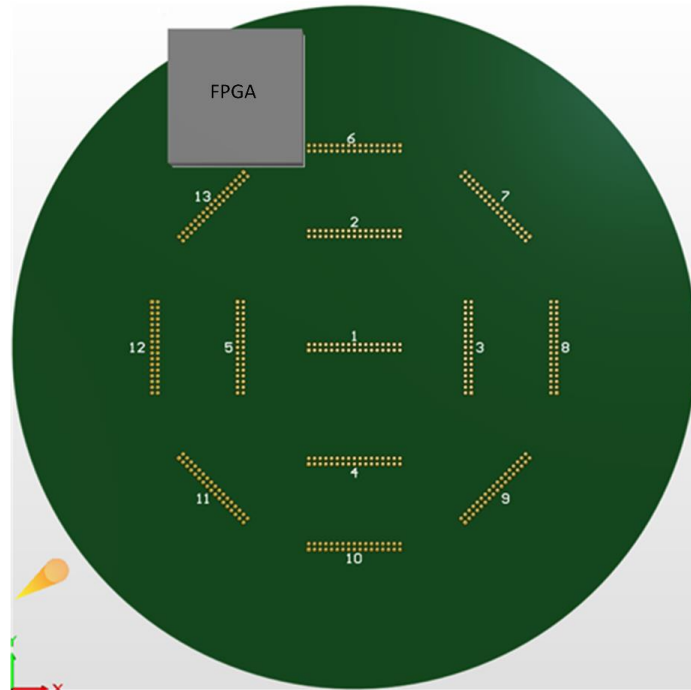


Figure 53: Backplate layout. MSND strips are soldered to the backplate, and the detector signals are processed, organized, and streamed to the CPU. Recall each MSND is readout individual to maximize directionality, ID, and unfolding algorithms.

The Gen 1. MSND strips were fabricated and populated with MSNDs Figure 54. Component shortages initially delayed PCB manufacturing, however RDT was able to supply the backordered components from our inventory to allow the PCB fabrication to proceed. Each strips holds 11 MSNDs and 13 strips were inserted into the moderator cask. The analog and digital signal processing electronics for each MSNDs are also located on the strips, and the strips connect to the NRID backplate (Figure 55). The output for each strip is routed to an FPGA on the backplate which handles communication between the detectors and the NRID CPU for algorithm calculations.



Figure 54: MSND strips populated with detectors.

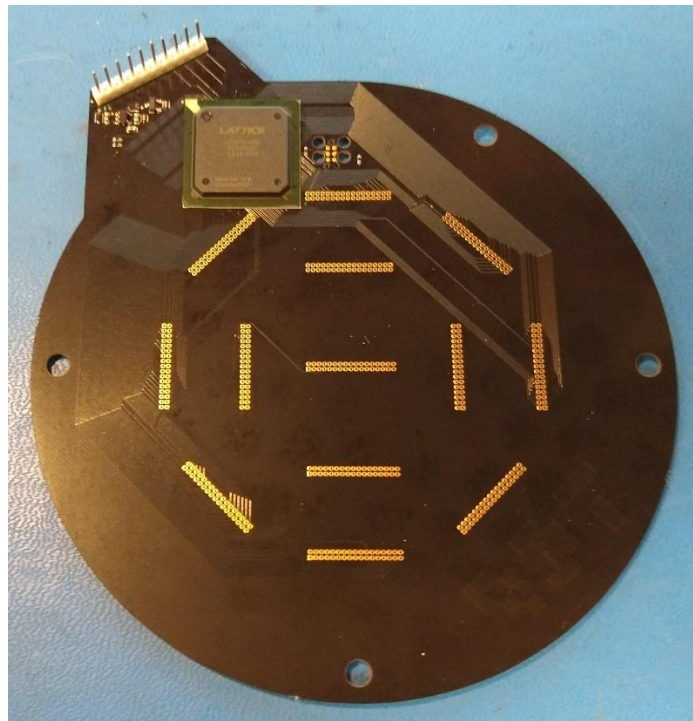


Figure 55: NRID backplate. The MSND strips are soldered to the backplate, and outputs are routed to the FPGA. The backplate communicates with the CPU and receives and routes power from the battery board.

The NRID firmware, including detector pulse acquisition, summing, and user display electronics were constructed. The detectors and the circuitry were packaged and protected from impact, moisture, and EMI. The functionality of the backplate was confirmed. Then, each strip was tested and installed on the backplate before being mounted into the moderator assembly.

Several minor modifications to the Raspberry Pi and battery control board were identified. The ethernet port was removed and is not needed. The GPIO header was removed and wires from the backplate were soldered directly to the Pi board. Finally, the USB-A ports were replaced with vertical ports to better fit inside the NRID case. On the battery board, the USB-A port and button were relocated so that the battery clips fit into the battery cavity in the NRID case.

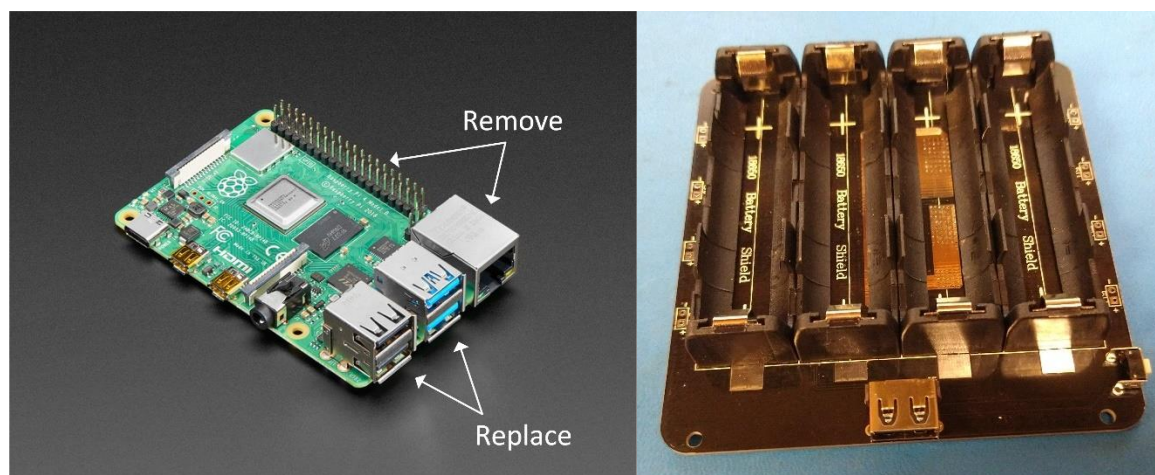


Figure 56: Raspberry Pi and battery board prior to modifications

3.2.4. Unfolding-Algorithms and UI Software

RDT and UMKC worked on the foundation of the prior algorithms and considered ways to reconstruct the libraries required to enable source localization and identification. The algorithms were based on the moderator and MSND geometry; hence, any change to the stack configuration was affect the algorithm accuracy. The UI software was developed at an administration level to modify instrument configuration, e.g., detector sensitivity levels, data storage/collection protocols, etc., and a user level which was display the neutron count/dose rate, neutron source ID, and localization of the neutron source at the front of the NRID instrument.

The required software was consist of 5 major sections, two of which were to interface with external hardware. Upon program start from the section Main(), the MSNDGrids() and Comms() sections initialize themselves. Comms() was then be solely responsible for setting up the initial connection to the MSND Arrays and all subsequent transmission. MSNDGrids() compiles the information to be sent and what is received into a format that Main() can distribute between IsotopeID() and Dosimetry() for computation and UI() for presentation of the data. While dosimetry was wholly calculate, the dose rate internally, IsotopeID() was compared to the live measured data with a stored template libraries. UI() section handles all input from the user. Figure 57 shows an overview of the main software functions that were developed.

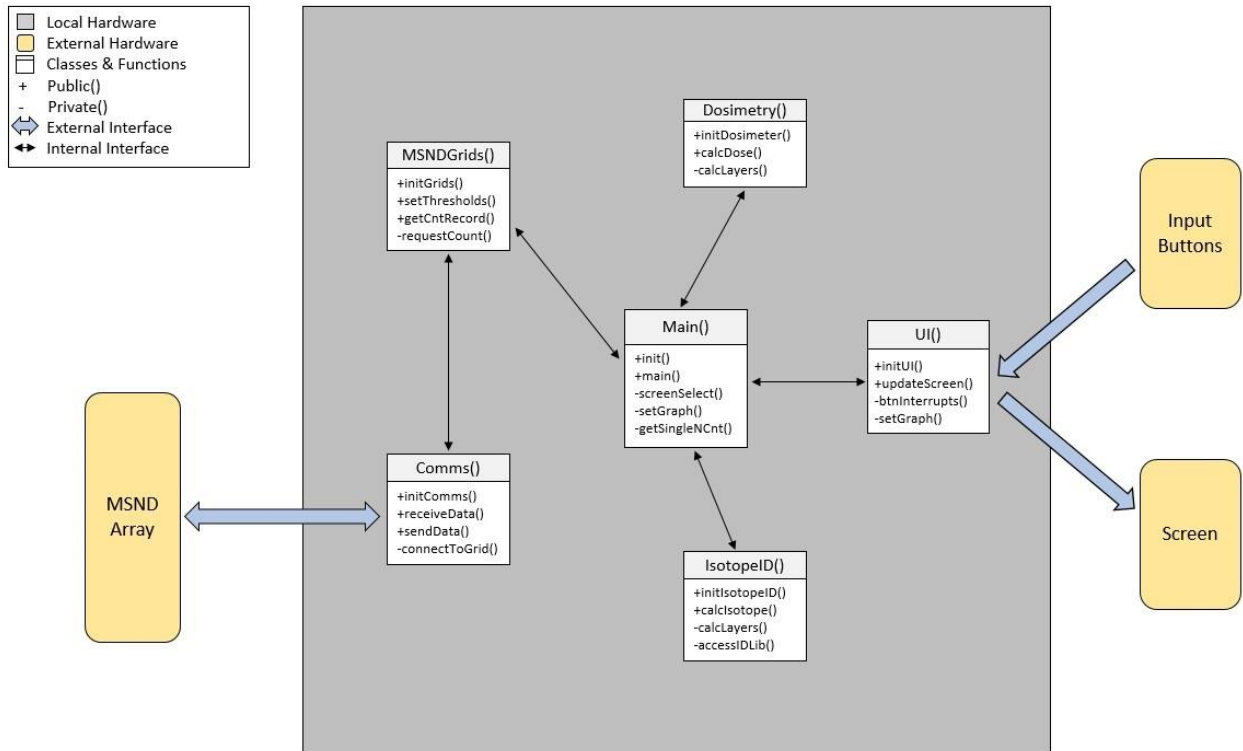


Figure 57: Block diagram on high-level software functions.

3.2.5. Housing/Packaging

The rugged mil. spec. design was based on the phase II prototype and Mirion's SpiR-ID shown in Figure 58. RDT focused on a package that is used to house the moderator, detectors, acquisition electronics, readout display, and batteries for the commercial ready NRID instrument. Drawing packages were developed for each component, and multiple prototypes were created for actualization and iteration-on the component assembly/fitting, compact packaging, weight reduction, ergonomic features (e.g., weight distribution, handle size/location), thermal/heat restrictions, and ruggedization to meet an IP67 environmental packaging metric.



Figure 58: Picture of the Mirion SpiR-ID gamma-ray ID instrument ruggedized for military use. The NRID were packaged in a similar designed handheld housing.

3.2.5.1 NRID V1 Packaging and Housing Development

The NRID housing was initially investigated to be made from either anodized Al metal or molded carbon fiber. RDT designed a package that was used to house the moderator, detectors, acquisition electronics, readout display, and batteries for the commercial ready NRID instrument. Drawing packages were developed for each component, and multiple prototypes were created for actualization and iteration-on the component assembly/fitting, compact packaging, weight reduction, ergonomic features (e.g., weight distribution, handle size/location), thermal/heat restrictions, and ruggedization to meet an IP67 environmental packaging metric. The gen. 0/1 housing was either be made from anodized Al metal or molded carbon fiber.

Initial case designs are shown below. Focus was on designing the moderator casing from extruded aluminum that were bolted to gasketed end pieces milled or water jet from aluminum. A custom handle, battery pack, electronics housing, and display were mounted to the top of the extruded aluminum piece. The goal was to optimize ruggedness, IP protection, and weight with this design.

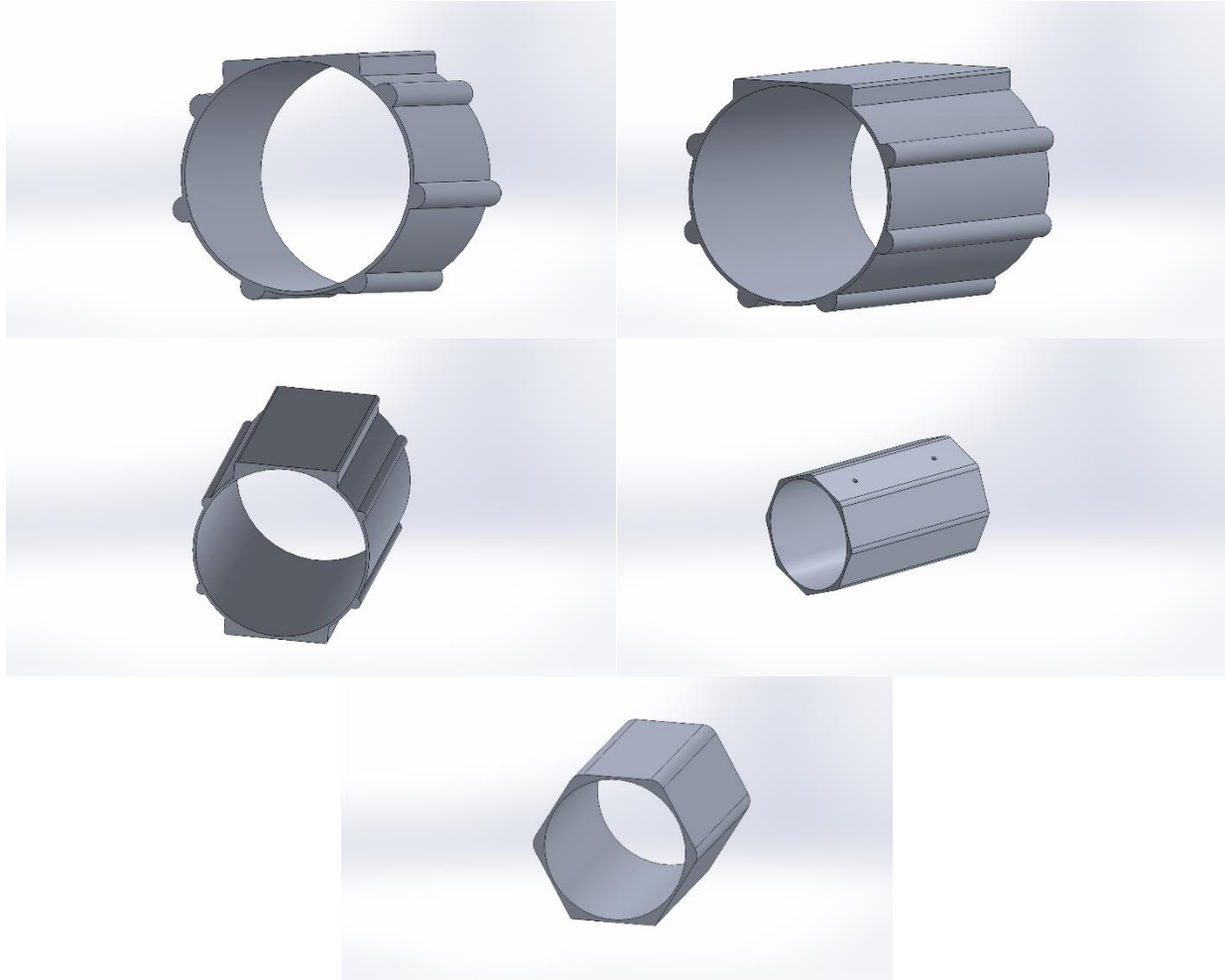


Figure 59: Gen. 0 extruded aluminum moderator case designs. A final design was down selected and refined.

The case/housing design diverged from extruded aluminum, and a carbon fiber-based case with an aluminum backbone was explored and down-selected for the Gen. 1 NRID housing build. In this design (Figure 60) a waterproof carbon fiber veneer is wrapped around and the HDPE moderator cylinder and attached to the aluminum plate with bolt-on carbon fiber veneer. The veneer is also applied to the ends of the NRID. Two CNC-machined carbon fiber end plates were attached to the moderator, aluminum plate and encompass the edges of the veneer. A gasket was used to complete the water-tight seal. The estimated weight of the case (without display/UI/batteries) is 1.2 lbs, which brings the total to 8.5 lbs for this Gen. 1 design. Layout of the battery, CPU, handle, and screen was completed. NRID V1 uses 4, 18650 batteries. These batteries were rechargeable and field swappable.

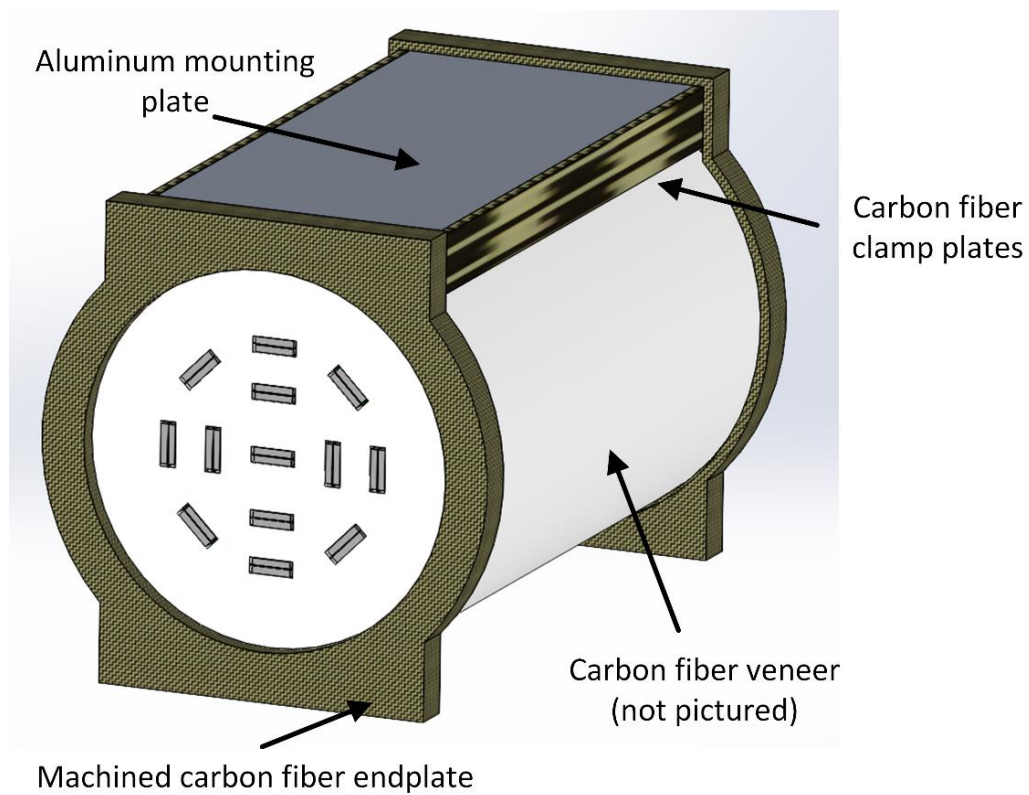


Figure 60: Preliminary rendering of carbon-fiber-based NRID case.

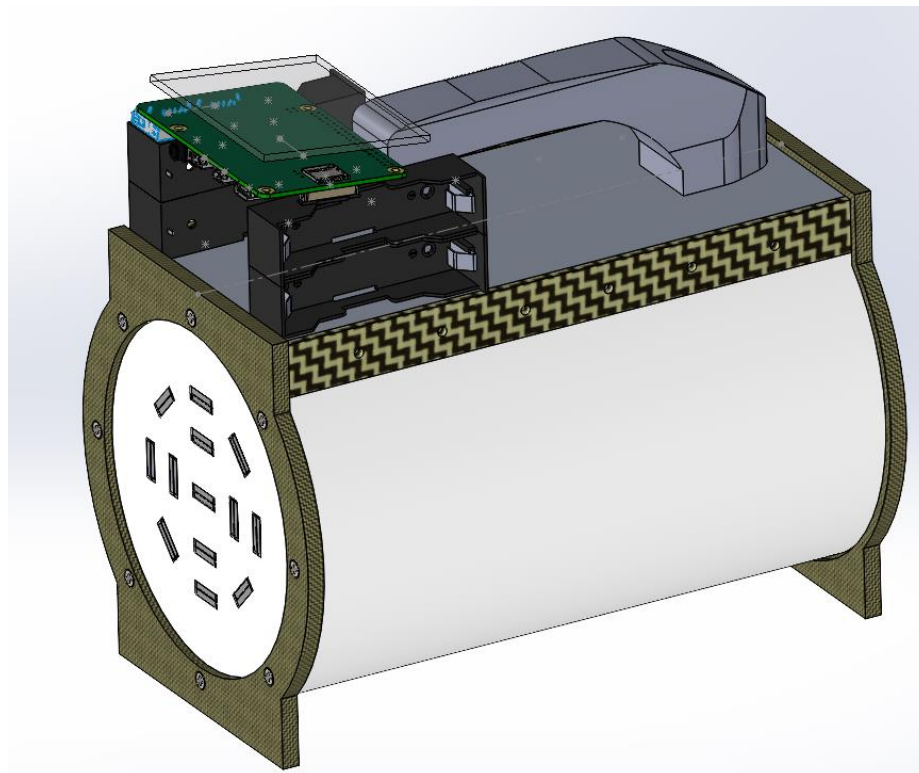


Figure 61: Updated rendering of carbon-fiber-based NRID case.

The first prototype carbon fiber endplates were milled (see Figure 62). The endplates are cut from 6" x 6" x 6-mm carbon fiber stock. A 3-mm inset is machined on the interior rim to where the HDPE moderator were seated. The CNC tabs and rough edges are shown in the pictures. These were sanded down before assembling the prototype. The center of the endplate was removed to reduce neutron interactions in the endplate before entering the detector and to reduce weight.

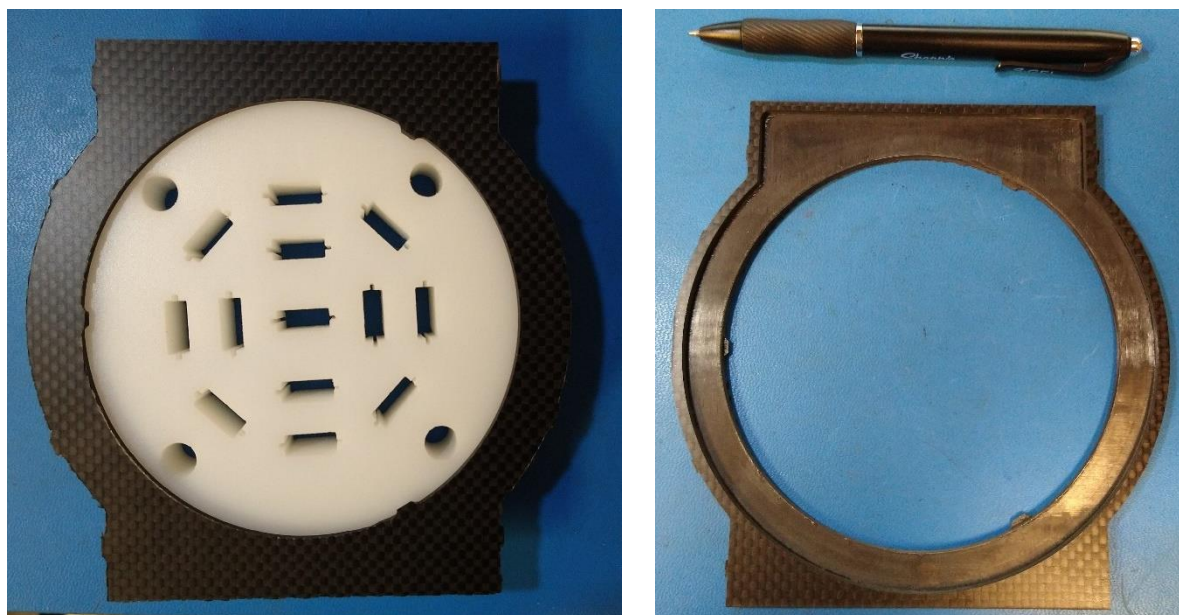


Figure 62: Prototype carbon fiber endplates. Countersunk holes were added to the front plate and the CNC tabs were sanded away before attaching to the NRID.

The carbon fiber/aluminum hybrid case has been redesigned and is shown in Figure 63 and Figure 64. 3D printing prototypes were fabricated to rapidly test and iterate design features for the NRID V1 housing (Figure 68). The top-plate, battery cover, and handle were machined from aluminum, and the endplates and HDPE covering was a carbon fiber wrap. Silicone gaskets sealed the endplates to the housing and carbon fiber veneer. The handle was designed such the operator's hand is positioned over the center of mass. The total weight of the system is approximately 11 lbs. The Al-top plate is the most complex component of the system. Minor changes to lessen the machining complexity were implemented based on feedback from the CNC-milling companies.

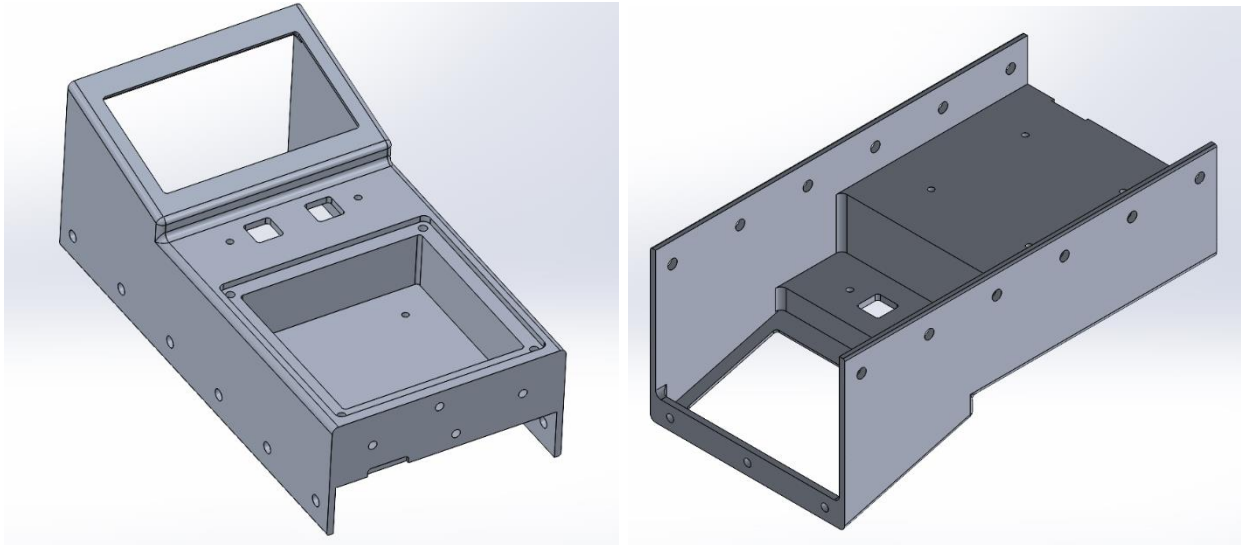


Figure 63: Near-final version of NRID V1 top-plate. We are procuring quotes from CNC-milling companies to manufacture this part.

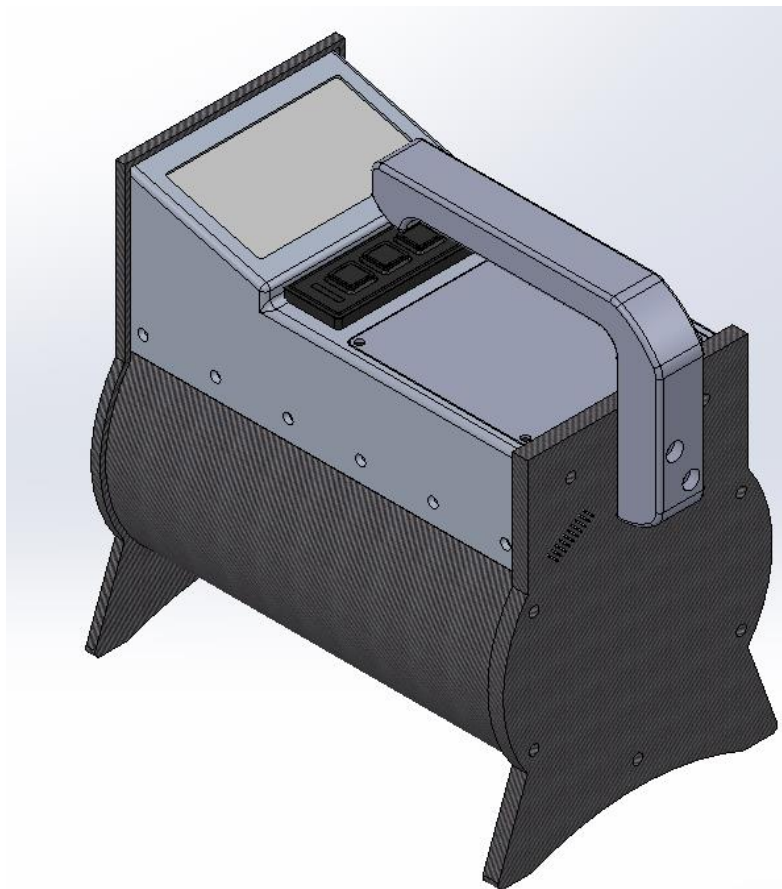


Figure 64: Updated NIRD V1 gen. 1 case. The top-plate, battery cover, and handle were machined from aluminum, and the endplates were machined from carbon fiber. A water-tight carbon fiber wrap encases the HDPE and attaches to the Al top-plate.

The aluminum portions (top plate, clamp plates, handle, battery cover) of the NRID case have been machined and anodized (Figure 65). The carbon fiber components were milled on RDT's CNC, which has been retrofitted to mill carbon fiber plates submerged in water to mitigate hazardous carbon fiber dust. The front and back plates were milled from carbon fiber plates and a carbon fiber veneer, which was wrapped around the exposed sides of the moderator and mounted between the top plate and clamp plates.



Figure 65: Anodized aluminum components of the NRID V1 gen. 1 case have been machined and assembled.

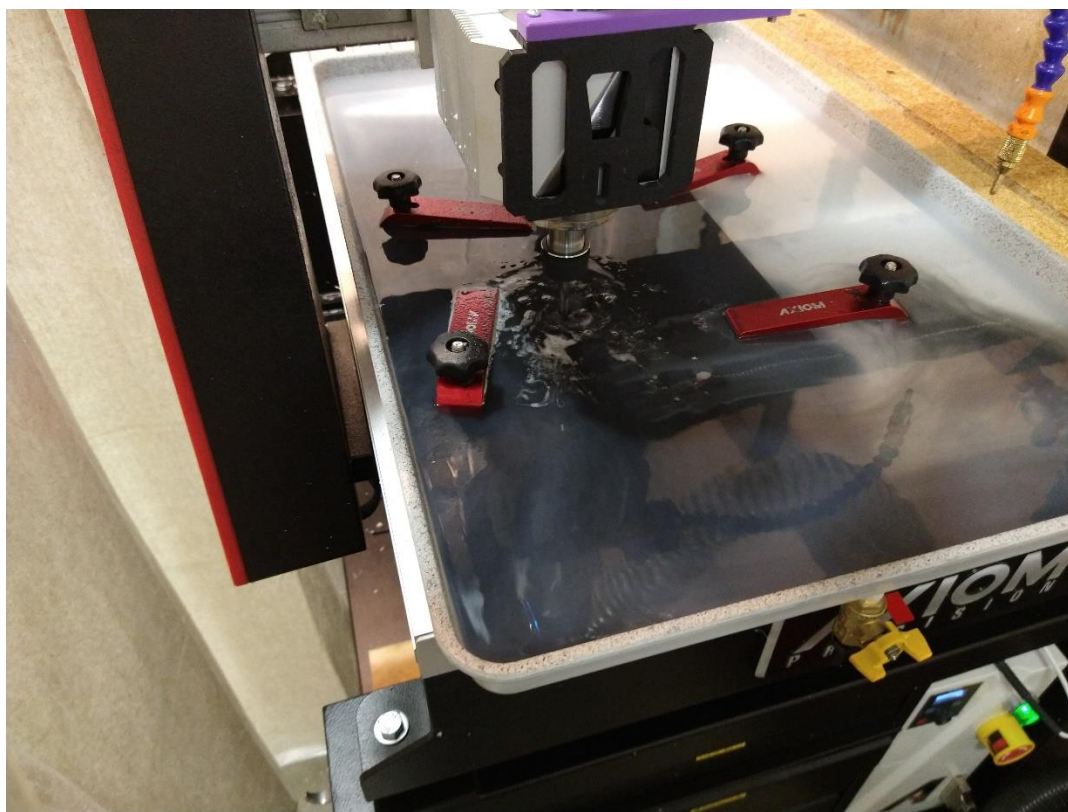


Figure 66. Water bath for milling carbon fiber plates.

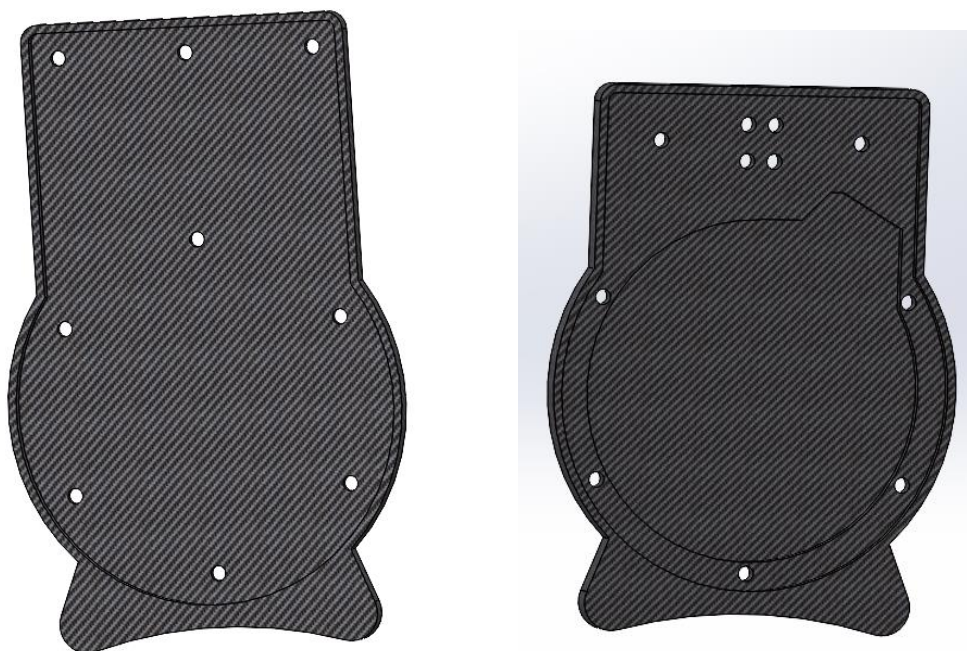


Figure 67. Models of the NRID V1 carbon fiber endcaps.



Figure 68: 3D printed prototyping on NRID V1 top-plate and handle options.

The carbon fiber and aluminum housing for NRID V1.0 was completed and assembled (Figure 69). The top-plate, battery cover, and handle are machined from 6061 aluminum and subsequently anodized. The end plates and HDPE-covering veneer are machined from carbon fiber. M5 bolts attach the carbon fiber components and handle to the aluminum top plate. The 4-button control plate and screen are also mounted to the top plate. Two USB-C ports mounted to the side of the NRID are for data output and fast charging. In addition to being rechargeable with NRID, the four 18650 batteries mounted beneath the battery cover (4 screws) are swappable. Without batteries and MSND strips/backplate (~0.5-1 lb), the NRID weighs 10.4 lbs. The NRID V1 at this point is much lighter than some of the traditional neutron sensors (e.g., AN/PDR-70 “Snoopy” at 25 lbs).



Figure 69: NRID V1 assembled gen. 1 housing/case.

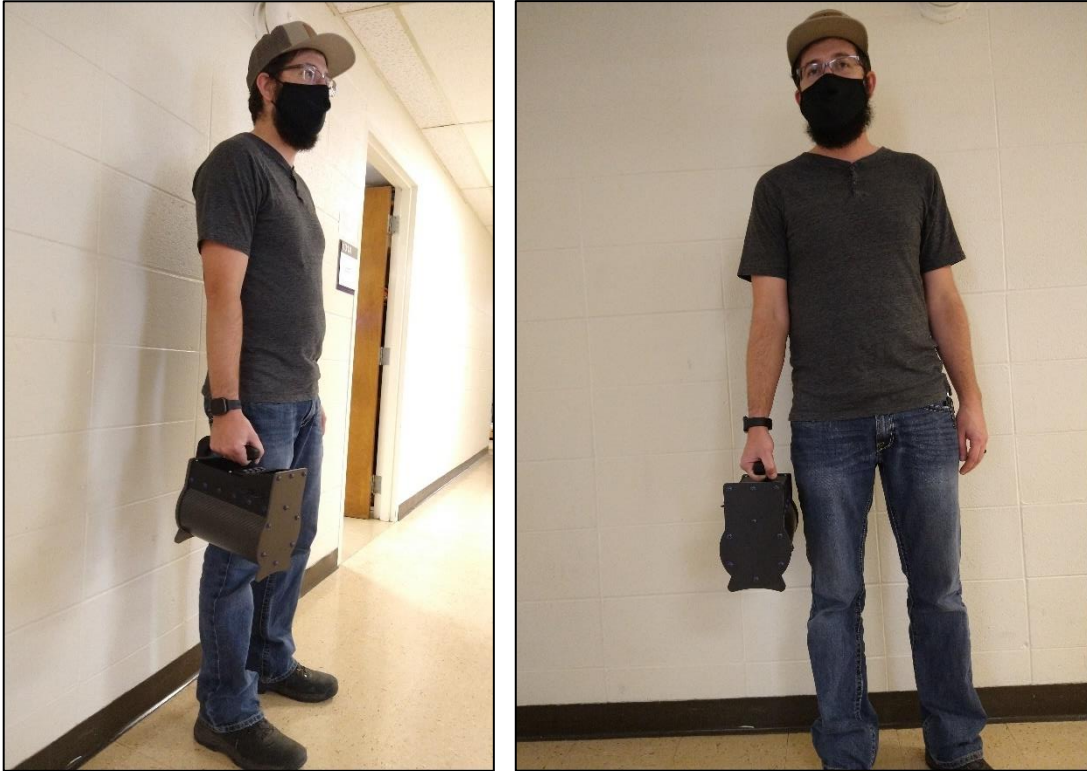


Figure 70: NRID V1 in carried position. The center of mass (COM) of is slightly in front of the handle, creating a propensity for slight forward lean. The NRID V2 was adjusted to remove this COM bias.

Several slight modifications and additions to the NRID top plate were made. A bracket was designed that mounts to the top plate and holds the screen and Raspberry Pi in place. During final assembly of the Gen 1 housing prototype, the display was glued to the inside of the top plate with a watertight silicone adhesive. M-lok polymer rail slots were added to the sides of the top plate so that swivel mounts for a sling could be added to the NRID to improve ergonomics. Recall that the NRID weighs approximately 11 lbs. The sling was help relieve strain on long missions without affecting performance.



Figure 71: Updated NRID V1 top plate with rails for sling mounts and the screen and Pi-computer bracket.

The NRID V1 case has been completed assembled, shown in Figure 72, which serves as a good first-generation prototype, however, nylon-carbon fiber alternatives are being investigated to reduce manufacturing costs and weight. See NRID V2 gen. 2 case in section 3.5.1.



Figure 72: NRID V1 carbon fiber - aluminum case. USB-C ports are used for battery charging (optional, can be swapped) and data I/O.

3.2.6. NRID V1 Software

The UI software previously developed under the Phase II spectrometer contract was reevaluated and adapted to fit the features of the NRID.

1. Algorithms, Data Processing & Organization – The core functionality of the project. This portion is performed first because the most amount of testing and iteration was required. Pre-created data samples were also be used in lieu of live readings while hardware finishes development. Focus was on data organization for the various storage and processing needs and for basic algorithm development (e.g., dose rate and isotope ID) using the pre-made data.
2. Comms – By developing the UART I/O between the Pi and FPGA and subsequently the data transfer to the Data Organization section of the code. The second portion were developing the USB interface for the external USB file export port on the device.
3. Data Display & UI – development of the user interface required taking the data being collected and displaying it in a visual format for easy analysis were the primary objective, followed by any interactive elements for the user (screen settings, menus, etc.). The algorithm and data handling were completed, as well as the base for the SPI interface to the detector hardware. The Directionality algorithm was completed. Different coordinate systems were tested to ensure maximum directional angle accuracy (see Figure 73).

After the SPI communications has been completed, the data storage and USB transfer interface were developed, as well as the background setup of the UI linking the current data and commands to UI elements. Initial alarming and isotope ID were implemented in NRID V1, as well as the static background calibration. The directionality algorithm was completed, and full functionality was achieved in NRID V1 once a proper set of detector position vectors had been decided. The SPI communication to the rest of the hardware was completed. The initial focus for the NRID V1 software development was the user interface and its connections to the rest of the package system.

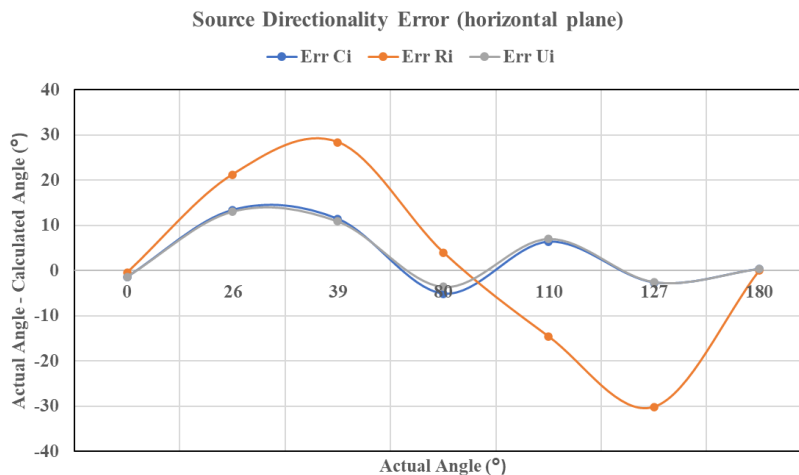


Figure 73: Error in source angle calculation using Rectangular (Ri), Spherical (Ci), and Normalized Spherical (Ui) vectors to denote the detector location. These detector location definitions were modified to maximize directional accuracy.

Over the PoP, the software has expanded greatly. The User Interface has been completed to initial specification for the main operation screen and operates smoothly. Data management between the algorithms, detector object code, and UI has been completed. A Raspberry Pi has also been configured and had the software uploaded, with current software capabilities running seamlessly. Screenshots of the on-board gen. 1 application are show in Figure 74.

The SPI interface to the detector backplate was integrated. The incorporation of the device buttons was developed. The final software component with external interaction were the data export via USB were completed. Dose algorithm and improvement of the directionality detector positions, and an addition of a menu will continue after the PoP has ended.

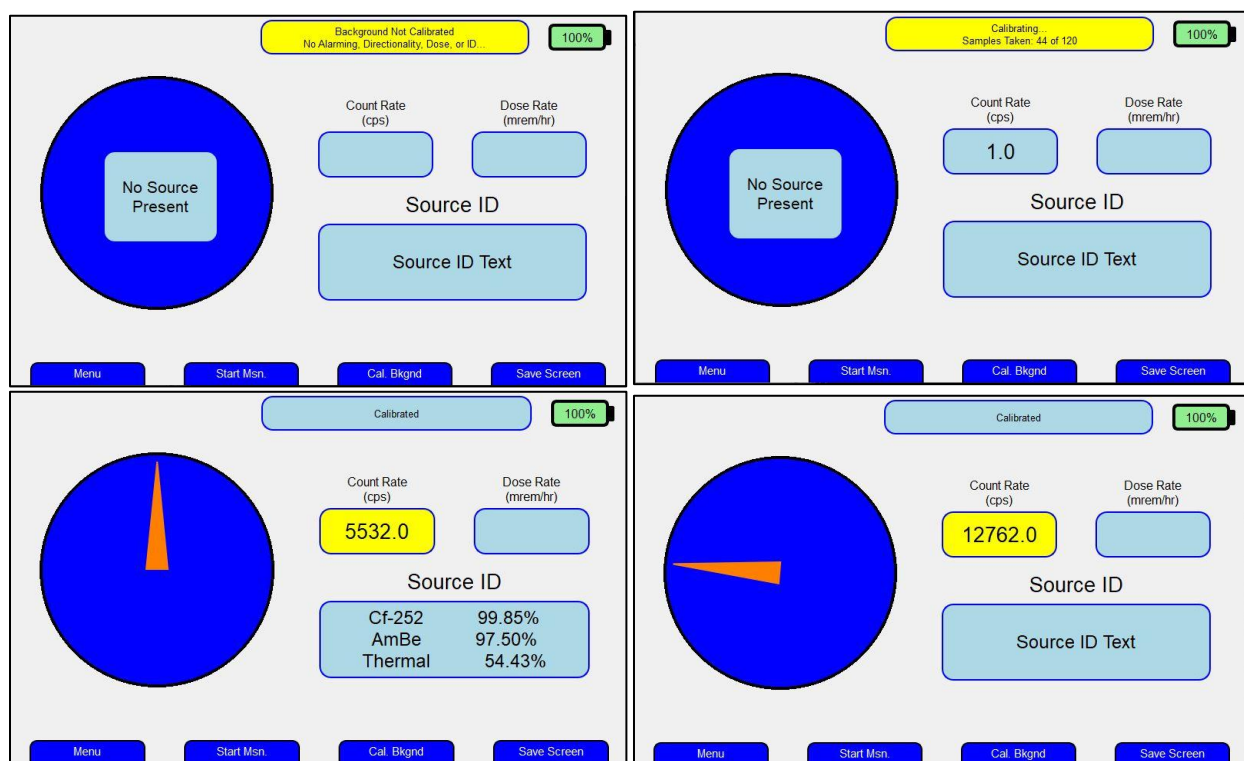


Figure 74: Screenshots of the NRID V1 user interface. (top left) App just after start up (top right) during background calibration (bottom left) alarming and ID for bare ^{252}Cf . (bottom right) alarming and directionality with source on user's left hand side. Note, Dummy/simulation data was feed to the application to yield these results. Experimental confirmation to follow. Additionally, source ID percentages are Pearson CC scores, they were converted to confidence levels in the final application.

Full functionality of the system and algorithms were able to showcase the following.

- Neutron count rate
- Source alarming
- Rough directionality calculation and display (was need fine tuning following laboratory measurements)
- Source ID for bare neutron sources (additional modeling required for moderated sources)
- System health, e.g., battery level, system temperature

Software for the UI and algorithm calculations was a primary focus for the NRID V2 software build, where building out the menu options and functionality (Figure 74) was immediately important. Each menu option is connected on the backend to variables that adjust alarm levels, algorithms, display, logging, debugging, and output.



Figure 75: Screenshots of the NRID options menu. Functionality was built in that allows for easy of operation, optimization of algorithms, and data logging for initial debugging.

Significant work went into testing and debugging the first complete iteration of the NRID software package. Effort was dedicated to finalizing external I/O buttons, software interrupts, SPI comms, and USB comms, as well as testing and debugging the main functions of the software. Smaller tasks were include adjustments to overall GUI appearances and functionality, finalizing output data formats, and packaging software and Pi for use by others outside RDT.

Features that interface with the CPU through the SPI interface include menu items like neutron detector (MSND) bias and threshold/discriminator read and write commands. These settings are used to factory calibrate the NRID at RDT's facility before deployment. Additionally, count rate data from the detector backplate is communicated through the SPI line. On the other end, data loading (e.g., source libraries, ID algorithms) and mission data output interface to the CPU over SPI between the USB-C I/O ports on the NRID case. Adjustments to the information output by the N42.42 formatting were made to ensure the most useful and streamlined output document possible for the end users.

The button inclusion required a little more development time than was anticipated. The library used for GPIO interrupt recognition has been used in previous projects and had worked flawlessly. In this particular instance, since the entire application is being ran through the PyQt5 library and not looping in the main function, certain library items (i.e., timers) cannot be called from a thread

created outside the GUI, which the button interrupts were. The fix was to instead of starting the timers with the button press, start the necessary timers at the initialization of the GUI and use the buttons to jump in and out of the timers when needed. Further development was done to write in the originally intended functionality, as this is slightly more robust and lead to easier development of timer-based needs in the future.

Including the live data stream went a bit more smoothly than the integration of the buttons, as most of the parsing had been set up to facilitate live counts in the beginning, and more development was actually needed to use pre-created count data. Refined settings and data management was the majority of information handling development. USB comms need more work and testing. Continue designing multiple new renditions of the current main GUI.

The following development tasks were completed for the NRID V2 software.

- Data logging
 - Improvements to the onboard storage and data stream output for algorithms testing and mission results.
- Source ID processing
 - Provide ability to output a first-guess, on-the-fly ID shortly after a neutron alarm.
 - Provide on-board instructions on how to obtain high accuracy ID (e.g. place/keep detector stationary, estimated time-to-answer, instruct to move closer to source if activity is too low)
- Remote operation.
- Audible alarm option
 - Were provided in NRID V2 package
- Rolling window plot of count rate vs time that is continually updated over the past 60-second period
- Redesign of UI for high-visibility and easier screen navigation
- Integration of new button array
 - Additional pin assignments and software interrupts for moving from 4 buttons to 6.
 - Change in UI interactions to fit the new button format of 4 buttons as a directional pad, and the remaining 2 as function buttons.

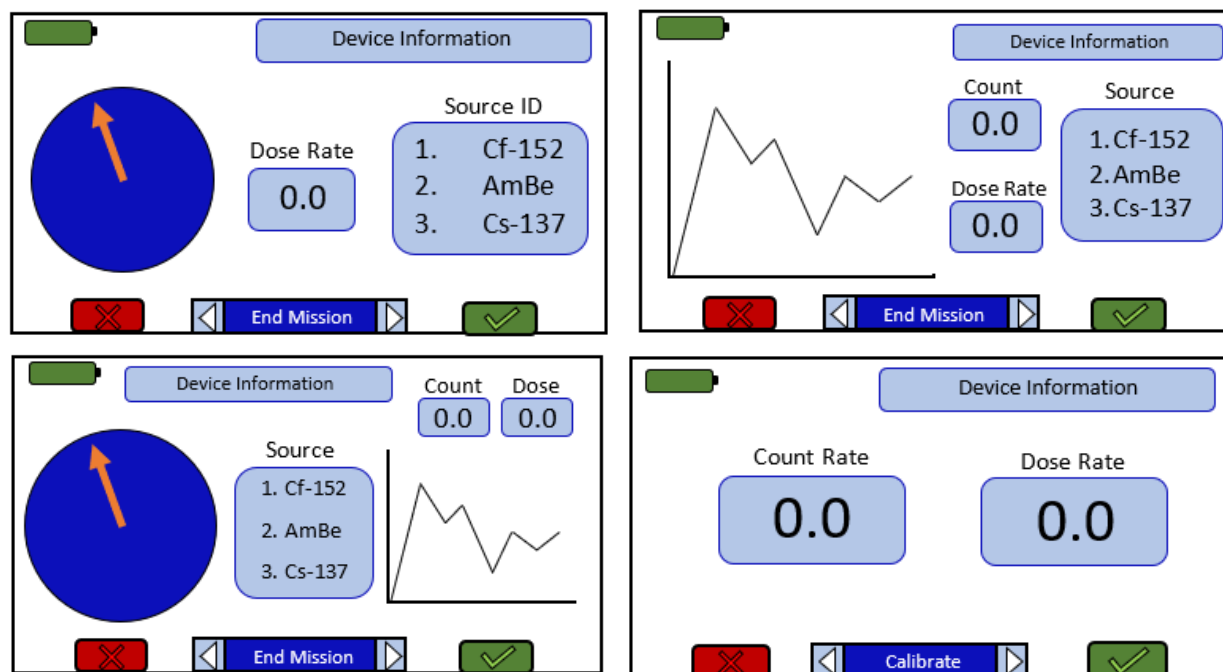


Figure 76: Whiteboard examples of new UI design layouts considered.

The gen. 2 software for the new UI for the commercial NRID (NRID V2) was developed. Although a good portion of this version of the UI was developed for the new custom button array and its more viable usability, most of the work on the front end has been put towards expanding the available options for screen layouts. This declutters the original single main screen page and lets the user choose more distinctly what they want to focus on or how they want that data displayed.

At the top of the screen, there is a screen page selection bar that allows users to cycle through the preset layouts with the left and right arrow buttons. The original main screen (Figure 77) remains similar to its original form with the exception of the source ID. This was a general-purpose screen for the beginning of the mission to scope out the area, look for hot spots and eventually use the directionality wheel to pinpoint the source before switching to the next screen. The sourceID page were mainly focused on just that. The majority of the screen was taken up with the identification so that more information can be displayed easily like result timers and high-count and low-count warnings. The current count rate, as well as a smaller version of the directionality compass remained on the screen for the user to reference while they run or set up the sourceID. The next page is the Time Plot. If the user would like to see a running graphical view of the counts for the last 60 seconds, they can use this page to do so. Once the device has been calibrated, a line was drawn across the graph as well indicating the level that counts must remain over for a certain period to trigger the alarm. Also included on this screen for reference are the count and future integrated dose rates.

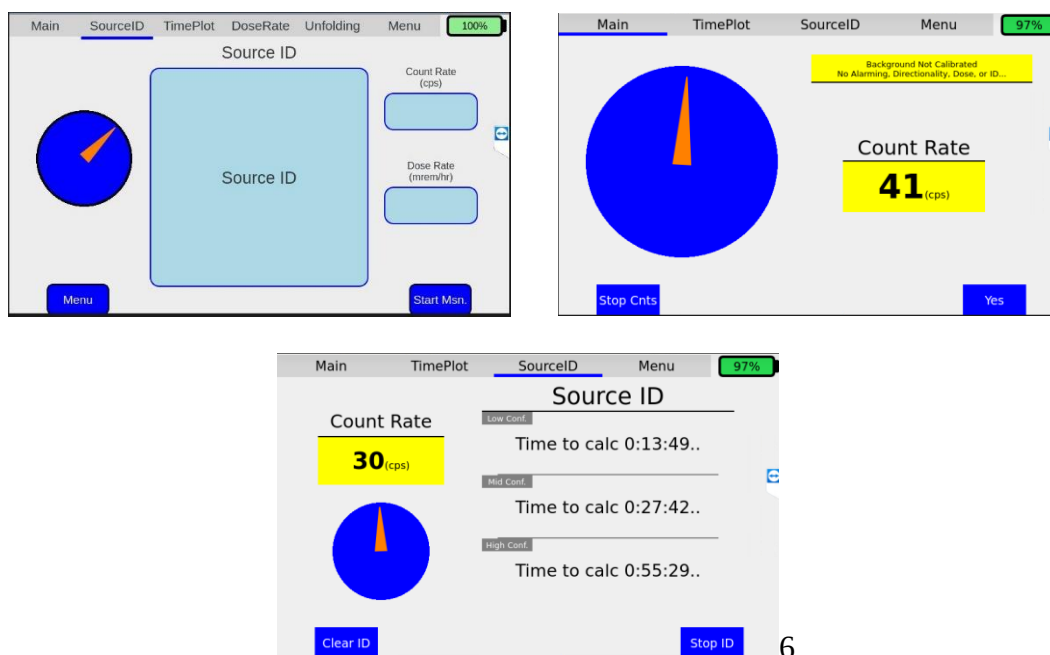


Figure 77. Main (directionality), Source ID, and TimePlot operational screens for the NRID V2.

3.3. Task 3: Initial Product Integration of Updated Electronics

The contractor shall manufacture and procure the component parts as determined in the functional design document (FDD).

All parts were procured and assembled into NRID V1 and V2. Figure 78 shows an example of an MSND strip mounted to the backplate. The FPGA is programmed to interface with the MSNDs to read in counts for each detector and output the counts to the CPU on the Pi for algorithmic processing and display. It is predicted that the NRID can interface and readout all detectors within 1 ms, which should yield high accuracy for alarming, directionality, and source ID algorithms. After the FPGA on the backplate was programmed, the functionality of each detector strip was tested. Then, the detector strips were inserted into the HDPE moderator volume and soldered in place to the NRID backplate. The moderator/detector assembly was then be inserted in the case, wired to the Pi and battery pack, and then were ready for empirical measurements and demonstration.



Figure 78: MSND strip inserted into backplate for functionality testing prior to soldering in place.

Significant work went into programming firmware on the FPGA on the NRID backplate. The FPGA interfaces between the NRID CPU and the MSNDs. Downstream, FPGA programs the detector bias and pulse-height rejection threshold. Upstream, the FPGA aggregates counts from each detector, formats the count-rate data string, and send the data to the CPU based on an internal clock frequency on the FPGA. Additional time was required to develop the FPGA interface, because it is new to the MSND technology. The time costs were offset by the improvements in board-to-brains interface simplicity, discrete electronic component quantity and costs, operating power, and electronic board size/footprint reduction. FPGA development time were much shorter for the 2nd/final NRID development. Figure 80 and Figure 81 show updates to the FPGA programming.

The firmware for the FPGA uses basic SPI communications with the Pi and is synchronized to the incoming clock line provided by the Pi. Careful consideration was made when transitioning between the clock domain of the internal oscillator used for the state machine logic, and the clock domain of the SPI module. Below is the generated FPGA gate configuration of both the SPI module and the test setup used for checking data integrity and synchronization between clock domains.

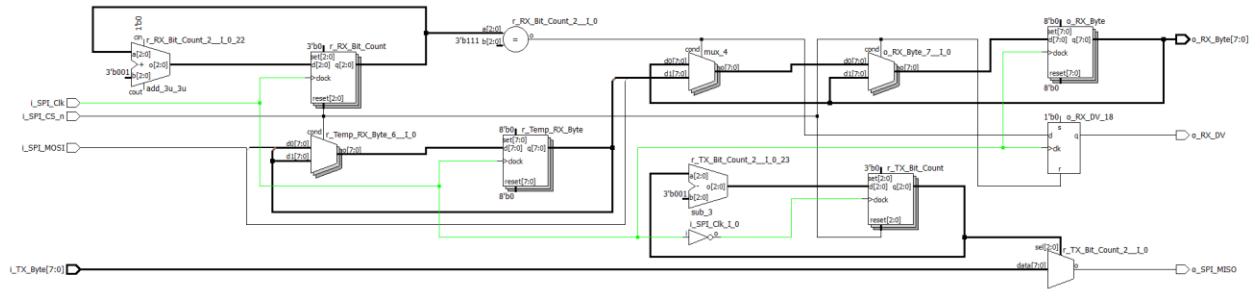


Figure 79: Generated gate configuration of the SPI module.

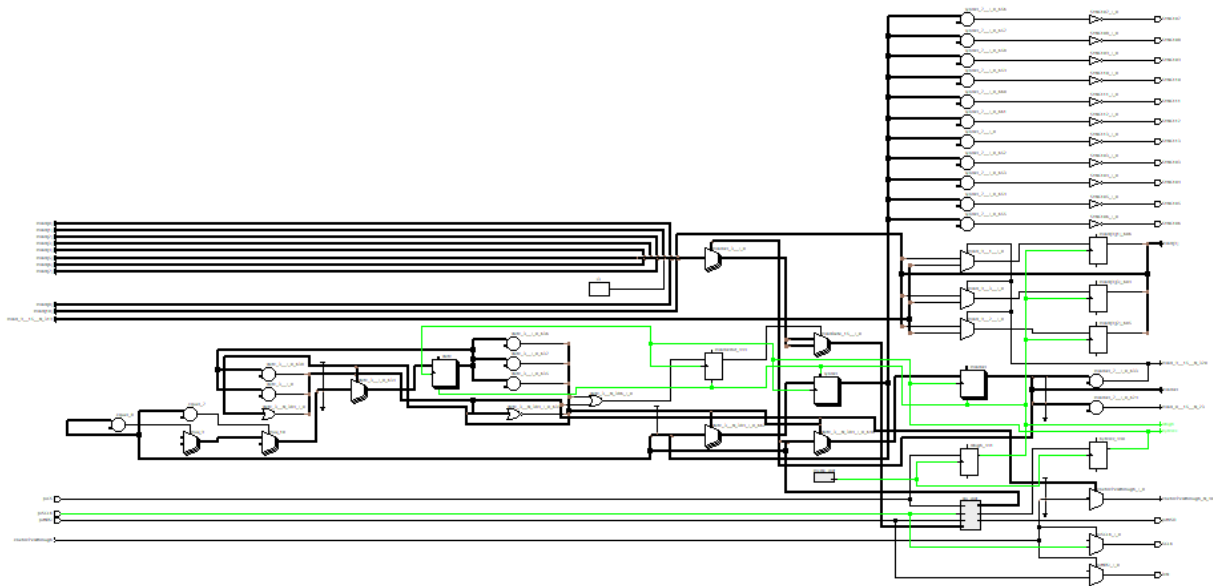


Figure 80: Generated gate configuration of the Main SPI State Machine. This logic represents the processing and high-level communications.

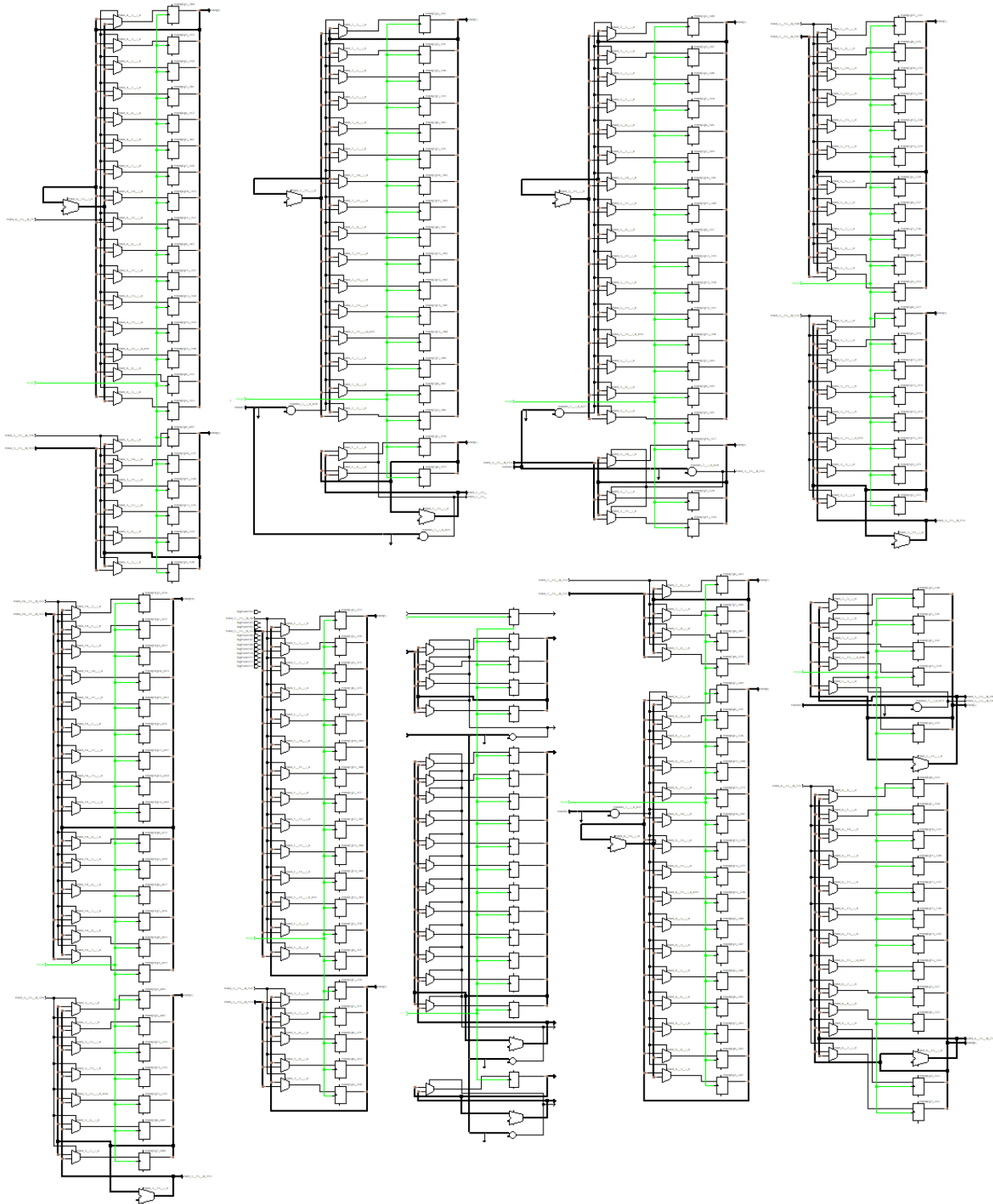


Figure 81: Generated gate configuration of all individual MSND functions. This includes the logic for individual counting and multiplexing through setting each MSND's LLD.

The internal USB-C board was revised (Figure 82). This board was soldered to the small internal pins on the panel-mount, IP67-rated USB-C port that passes through the case of NRID. The internal

USB-C breakout boards have recharging circuitry for the 18650 on-board 18650 batteries and data communications for offloading mission/measurement data from the Pi.

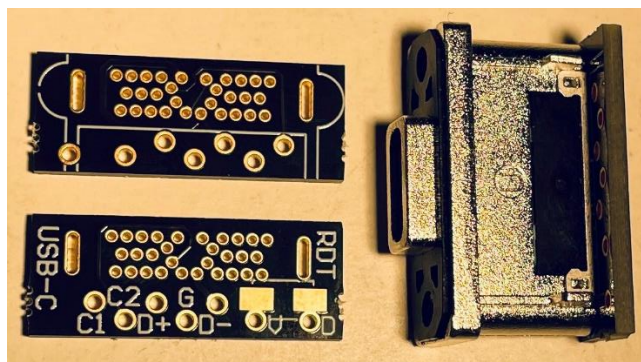


Figure 82: USB breakout boards (internal) and USB-C case feedthrough.

During the assembly of the strips into the backplate, an issue was encountered with ringing on the shared clock line. The ringing phenomena stems from the long, non-terminate, MSND strips that extend out of the backplate. This ringing can improperly trigger read/write commands and improperly count neutron pulses. Impedance matching and terminating the line would significantly increase power consumption, so an RC filter was used instead. Due to the low clock speed in comparison to the fast rise times, the overall data rate was not affected by this modification. Testing has shown an improvement of signal integrity (see Figure 83).

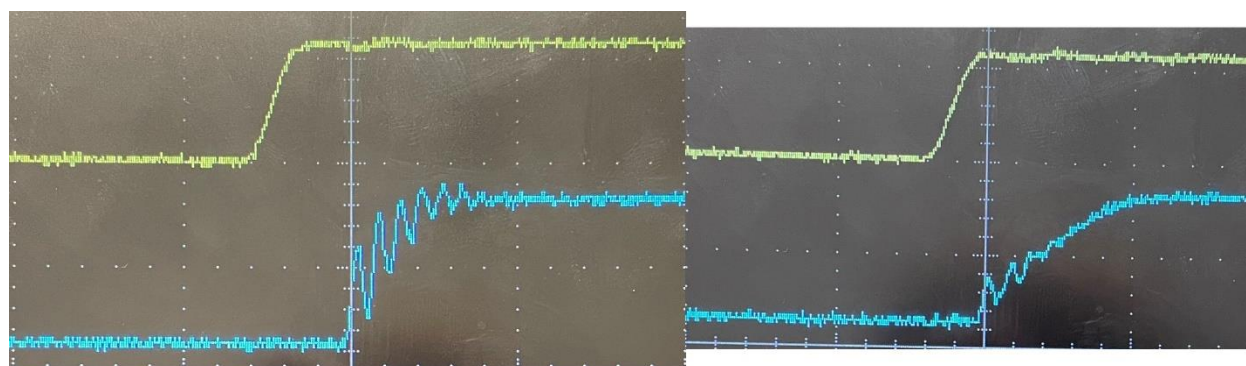


Figure 83: Left is before filtering, right is after.

The external communication interface between the Backplate and the Raspberry Pi exhibited a similar ringing issue, which was corrected by oversampling the clock and averaging the results. Test software was developed in Labview, interfacing with a microcontroller development board and the Backplate. The software (Figure 85) allows for testing and calibration of the individual detectors, along with exporting a configuration file that were used by the full system.

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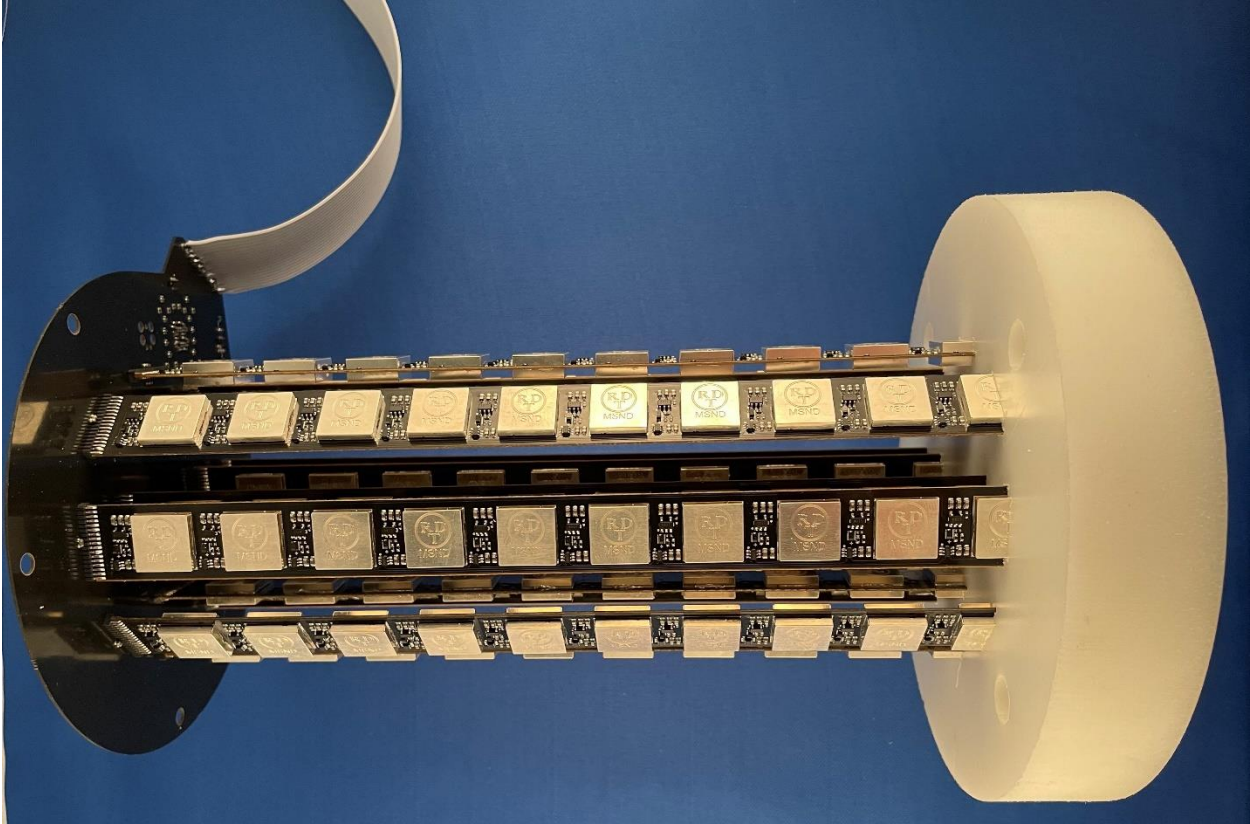


Figure 84: All 13 strips assembled into the backplate, with a section of moderator to hold them in place.

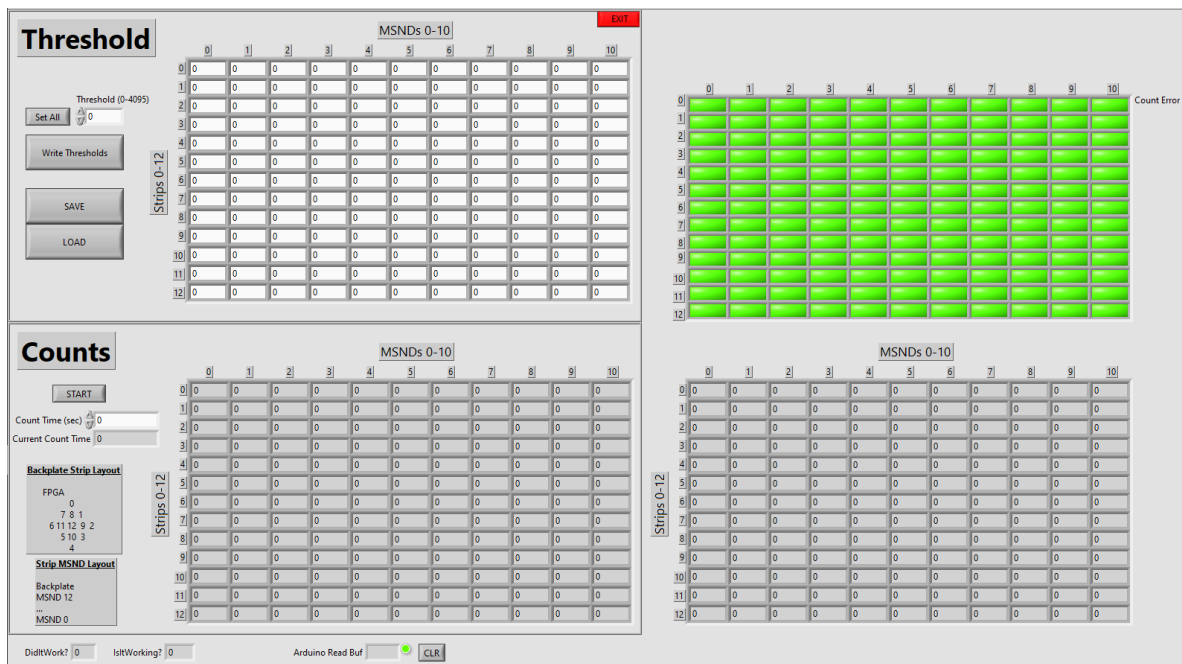


Figure 85: LabVIEW Software for Testing and Calibration.

3.4. Task 4: Test & Validation

The contractor shall conduct testing on the year 1 trial-design NRID prototype implementing the improvements suggested from prior phase II and the functional design document developed.

A test configuration was setup to test individual NRID strips installed onto the backplate to test for response, noise, and bias/threshold functionality. Unfortunately, mis-matched voltage levels and ground references for the MSND detectors (3V) and FPGA (5V) was injecting noise on the system. A new testing apparatus was developed to correct this issue (the issue is on the NRID testing jig, not the NRID backplate). After this was corrected and strip-backplate functionality was confirmed, all the strips were soldered to the backplate and installed in NRID for full system evaluation.

Troubleshooting of the MSND pulse processing and readout electronics was completed and the NRID detector core was assembled (Figure 84). The next step for test and validation was to calibrate the individual MSNDs to have the same neutron detection efficiency. This process was somewhat tedious and requires placing a neutron source next to each detector in a precise manner and adjusting the pulse height discriminator for each MSND individual. Fortunately, for commercial production, once we have a “NRID standard” we can calibrate future NRIDs quickly by matching the efficiency to the standard for a given source configuration.

After the NRID was characterized, neutron radiation measurements were performed with bare and moderated, AmBe and ^{252}Cf sources available to RDT. The results of the measurements were compared to the simulated results and the newly developed source ID algorithms were tested against live data. Additionally, training data was also generated with live measurements, see Figure 87.

A LabView GUI was built to interface and calibrate the detection thresholds for each MSND on the NRID (Figure 86). Two bugs were identified and corrected: (1) Two MSND ID/Location values were swapped. (2) Pulse height discrimination values (thresholds) were not being properly set. After these issues were fixed, the initial calibration was performed so that the NRID showed good sensitivity to neutrons and minimal sensitivity (<0.25 cps) in very high (>100 mR/h) gamma-ray fields. In moderate gamma-ray fluxes, ~ 10 mR/hr, the MSNDs response is indiscernible from background (i.e., negligible).

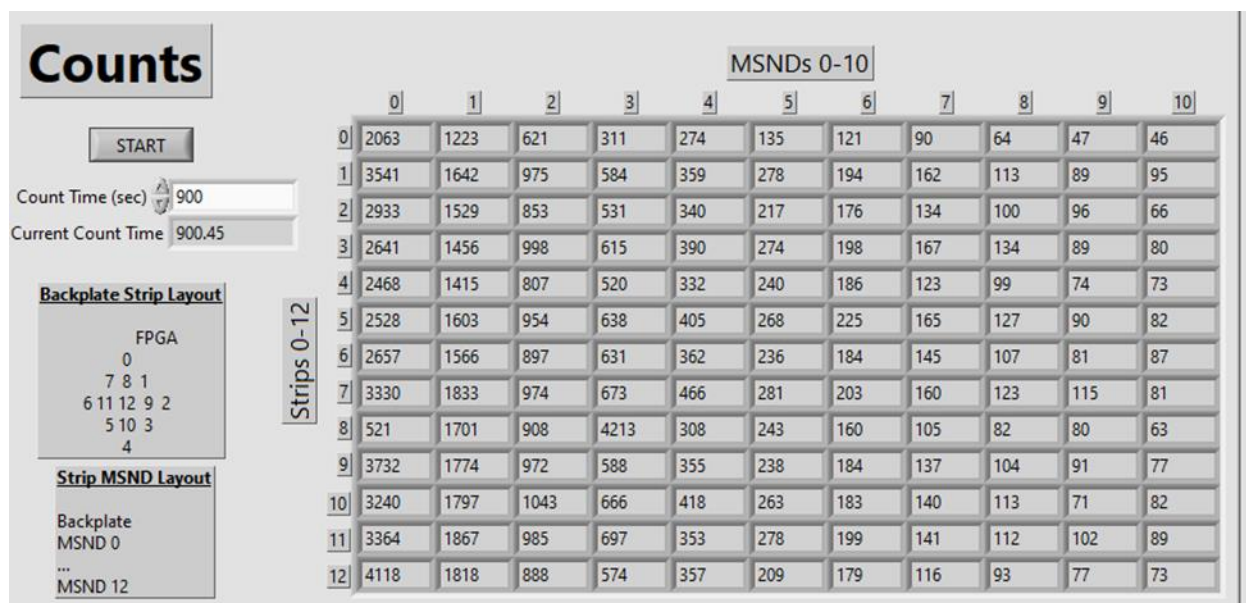


Figure 86: Subsection of LabView GUI for NRID threshold calibration.

The fully assembled NRID was taken to SOFIC to showcase to potential users and garner feedback for the final design. After the conference, measurements were performed to verify and validate the MCNP simulations and test source ID and directionality algorithms. We also plan to seek out more opportunities to demonstrate the hardware to potential user groups to inform design refinements for future generations of NRID.

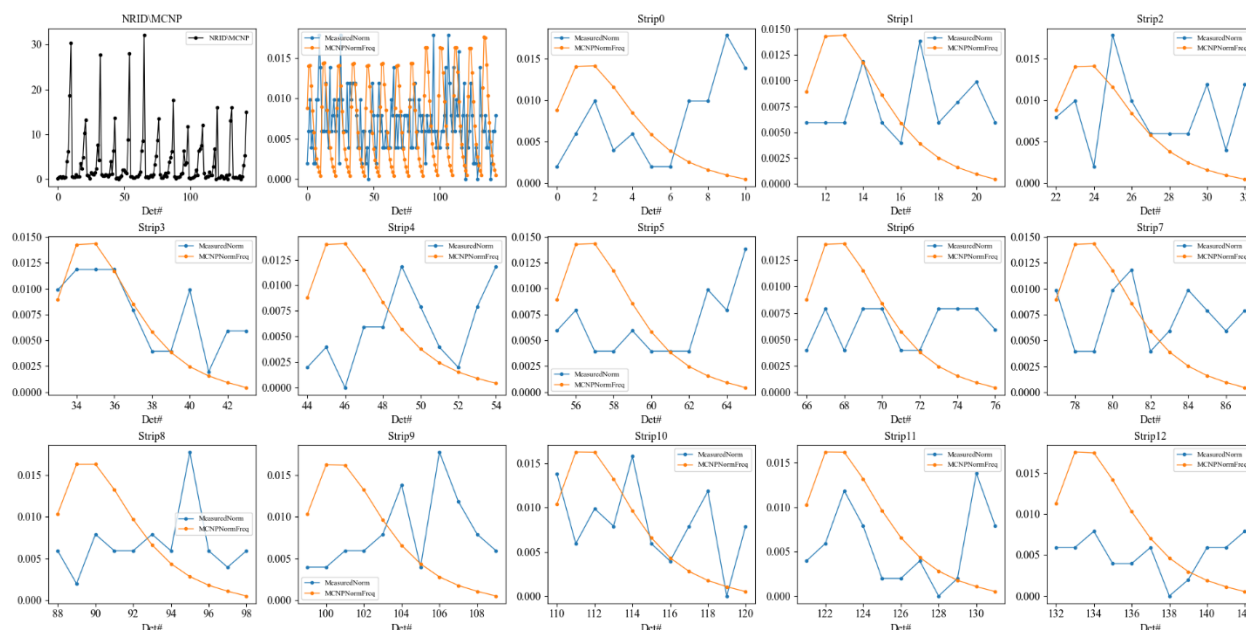


Figure 87. Detector calibration interface. The plots were generated on a non-calibrated NRID.

Remote communications to the NRID were established to speed up the calibration process and a script was developed and used to semiautomatically adjust individual MSND detector thresholds

to match the measured responses to our simulated “truth” responses. During calibration, we noticed a bug which would manifest in over 65,000 counts being reported from one detector during one second (see Figure 88). We have identified the most likely culprit to be miscommunication between the FPGA, where counts from each MSND are aggregated, and the CPU, which is responsible for parsing the data, running algorithms, and displaying the output. This communication issue was fixed and calibration was completed once corrected. The 65k count rate error **was resolved** by switching to a UART readout instead of a SPI readout for the NRID V2.

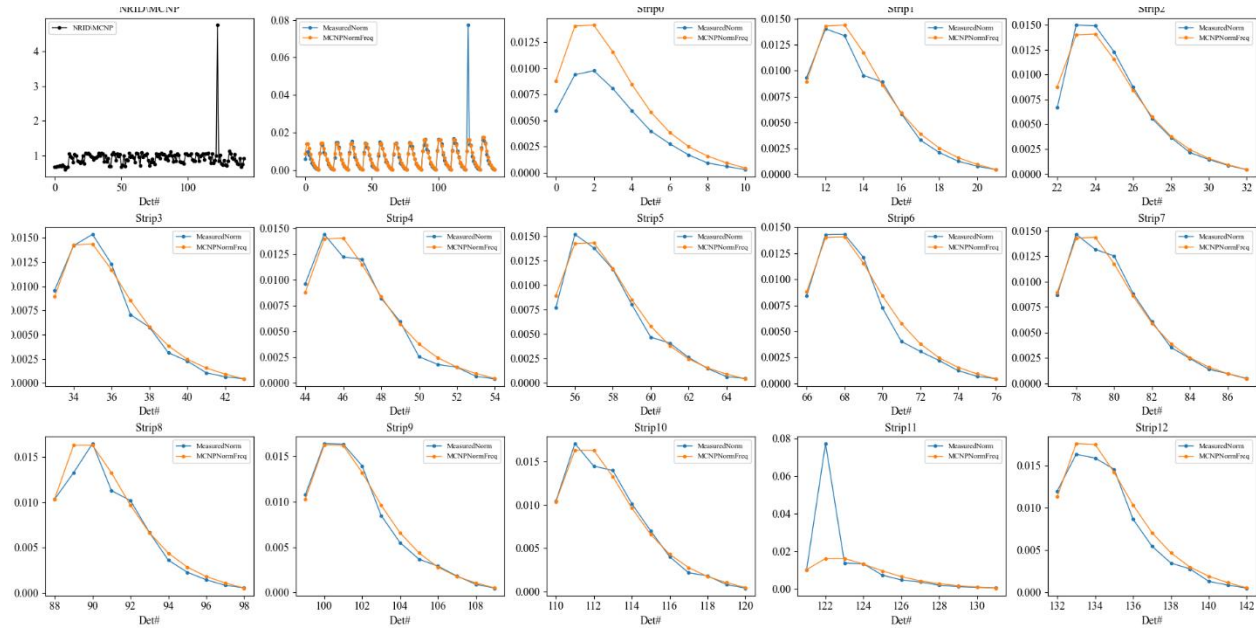


Figure 88: Example of NRID readout when at 65k count rate error occurred in MSND 122.

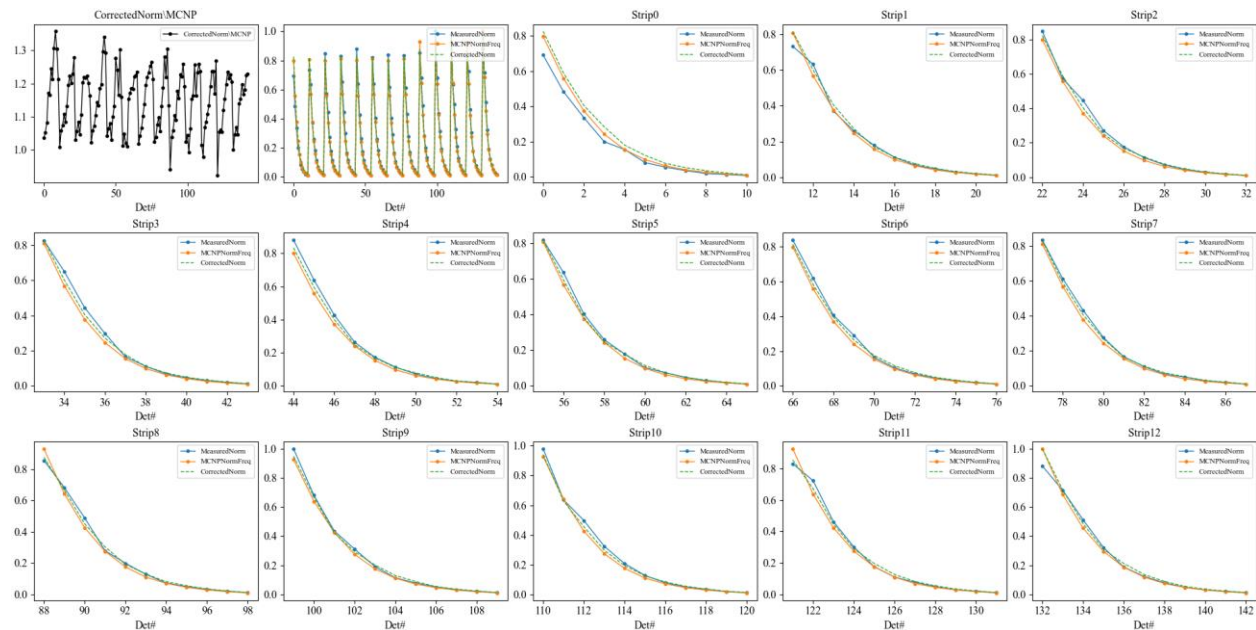


Figure 89. Example of NRID readout after 65k count rate error was resolved.

3.5. Task 5: Revision & Modification based on Task 3 & 4 Results

The contractor shall redesign the optimal moderator and absorber type, geometry, thickness, and housing configuration based on year 1 results and full-scale implementation design needs.

During the initial prototype NRID V1 build, the following improvement areas have been identified and were implemented in NRID V2.

- Weight distribution – the center of mass needs shifted slightly toward the back of the of system. Mounting points/clips for a shoulder harness were added.
- Handle ergonomics – the handle height was increased slightly and ridges to fit the hand more comfortably were added.
- Button positioning – We was look for (or fabricate) alternative button layouts with the buttons shifted more towards the edges of the instrument rather than beneath the handle for easier access.
- Battery plate screws – thumb screws were used instead of hex key screws so that the batteries can be swapped without a hex wrench.
- USB-C port consolidation – Charging and data I/O were handled with one USB-C port rather than two.
- Custom battery board – We was design and fabricate a custom battery board in NRID V2 rather than retrofitting the current COTS solution.

3.5.1. NRID V2 “Scorpion” Case Modification

The NRID V2 gen. 2 case/housing was redesigned to improve manufacturing, reliability (i.e., reducing points of water or dust ingress), ergonomics, and to reduce cost. Additionally, the housing weight was reduced by ~10% (from 12 to 11 lbs.). The new package, code-name Scorpion, is composed of carbon fiber sleeve, in which the moderator/detector assembly is mounted, an aluminum or nylon base, in which the carbon fiber sleeve fits, a carbon fiber handle, and dedicated screen and button assembly. The field-swappable, 18650 battery pack can be accessed at the detector’s aft, which also helped with center-of-mass balancing.

For NRID V2, we moved to a new vendor to manufacture the HDPE disks. The first batch of moderator disks have been received and have higher manufacturing tolerances than the previous vendor. Assembly and fitting of the NRID gen. 2 case was completed (see Figure 91). All the main case components had good fit and finish. The top half of the screen enclosure is a nylon-12 3D printed part. The decision was made to change the manufacturing process and material to CNC milled aluminum. The nylon parts were used for testing and then switched out for the aluminum part during final assembly.

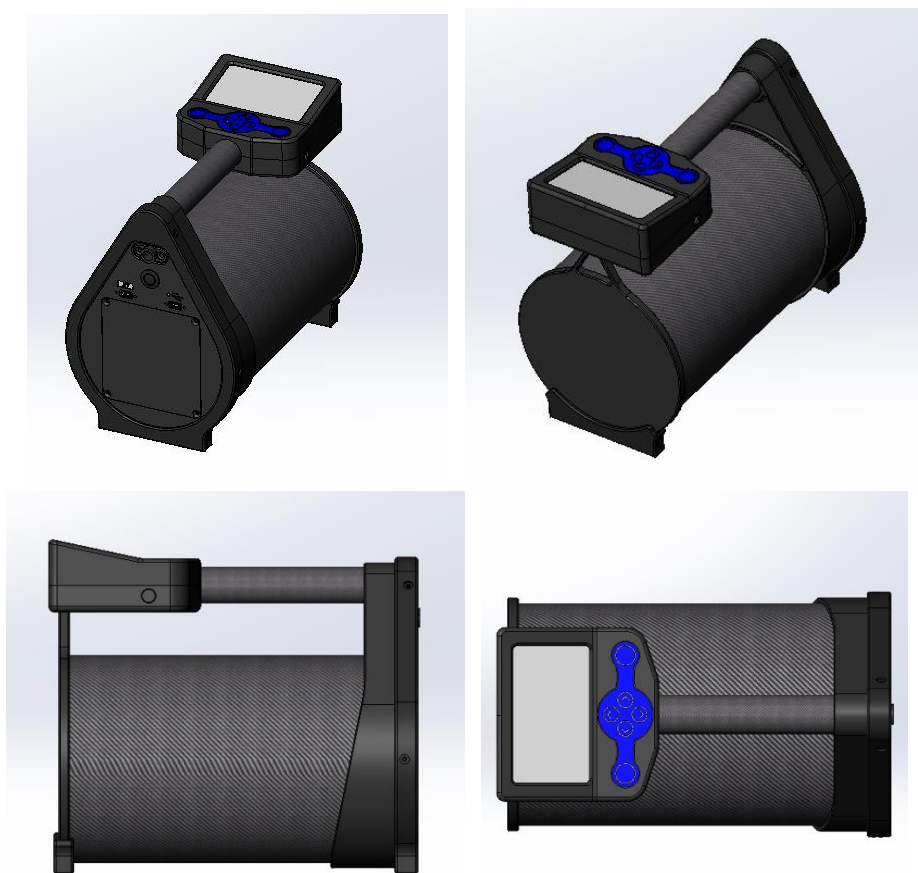


Figure 90: NRID V2 “Scorpion” gen. 2 housing/case design.



Figure 91: NRID V2 gen. 2 case components. Carbon fiber pieces were cut to size.

3.5.1.1 NRID V2 Product Line Variations

Based on the results of a market survey performed by one of RDT's distribution partners, we plan to study the feasibility of splitting the NRID product line to accommodate users that want to use the NRID for isotope ID and ultra-high precision dose, and to accommodate those who are just interested in basic area dose monitoring. The NRID ID with Dose+, where the core NRID technology is still in place, is currently being developed capable of isotope ID, neutron spectrum unfolding, and higher precision dose monitoring. The NRID Dose only version, were populated with fewer MSNDs to reduce costs to be price competitive (and performance superior) with common rem balls and AB/Snoopy-like dose monitors. The dose only version was help commercially sustain the NRID product line by providing a product to the market sector that may not require top-of-the-line ID and spectrum unfolding.

3.5.1.2 Electronics

The electronics backplate was redesigned for compatibility with the new gen. 2 case. A new connector was added that interfaces with the battery and CPU. This connector replaces wires that are directly soldered to the board in the V1 design. Additionally, filter circuitry was also added to prevent the SPI communication ringing from showing up on the detector signal line (a problem diagnosed and mitigated on the V1 boards).

Finally, we replaced the COTS battery board used in V1 with an internal design that is capable of fast charging (see Figure 93) and has more robust circuit protection [Figure 92]. The schematics for the battery board have been designed (see Figure 94) and the PCB has been fabricated (see Figure 95). Functionality was verified.

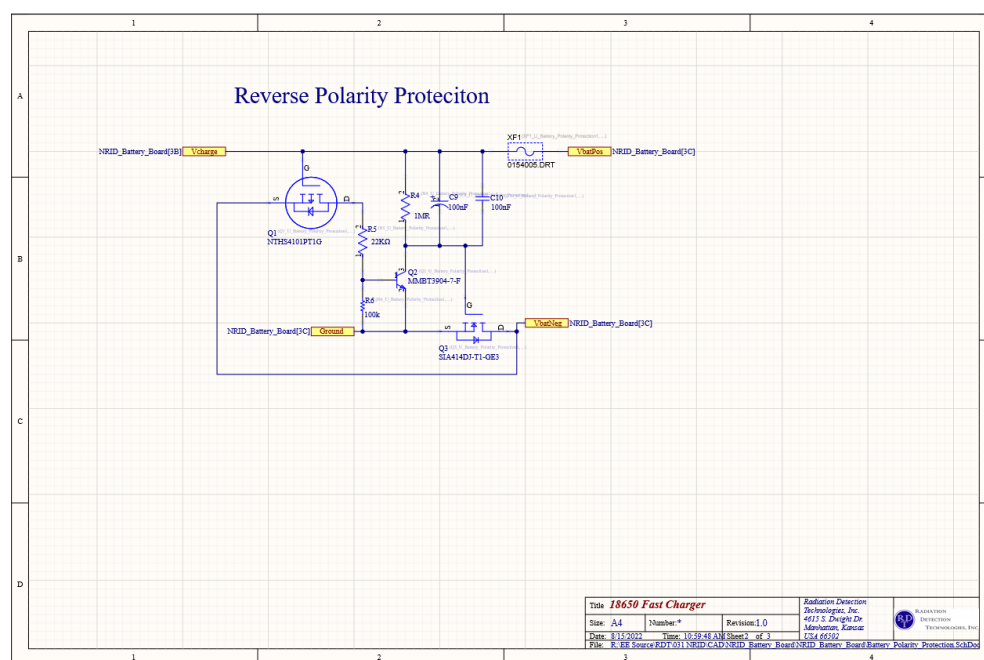


Figure 92: Per Cell Reverse Polarity and Short Circuit Protections.

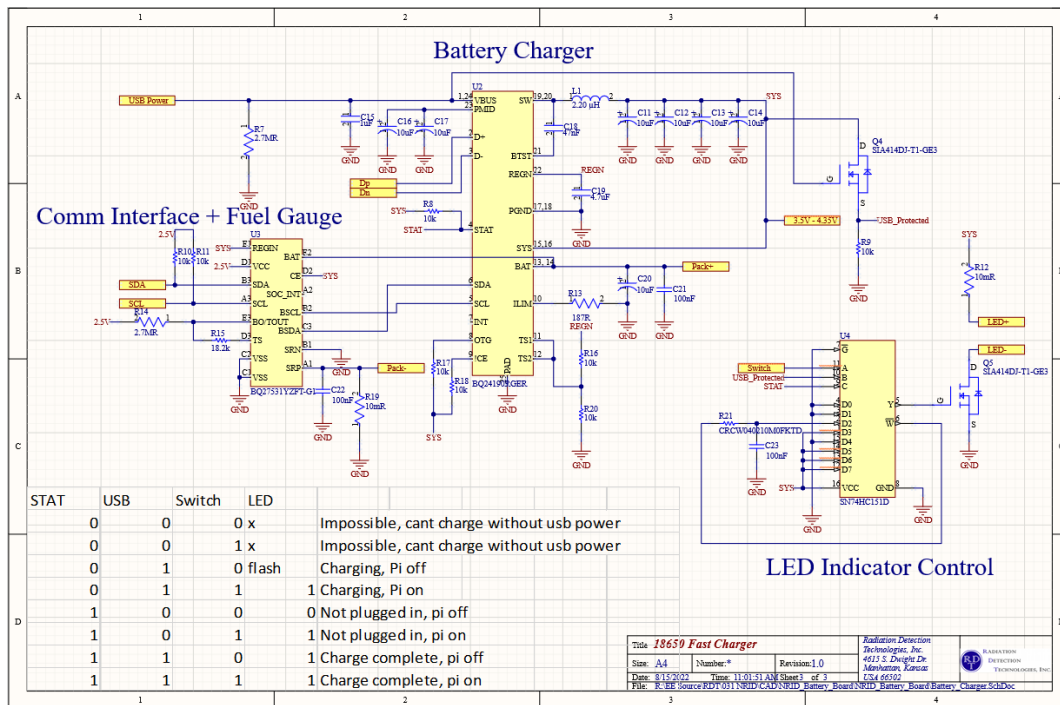


Figure 93: Battery Management Circuitry.

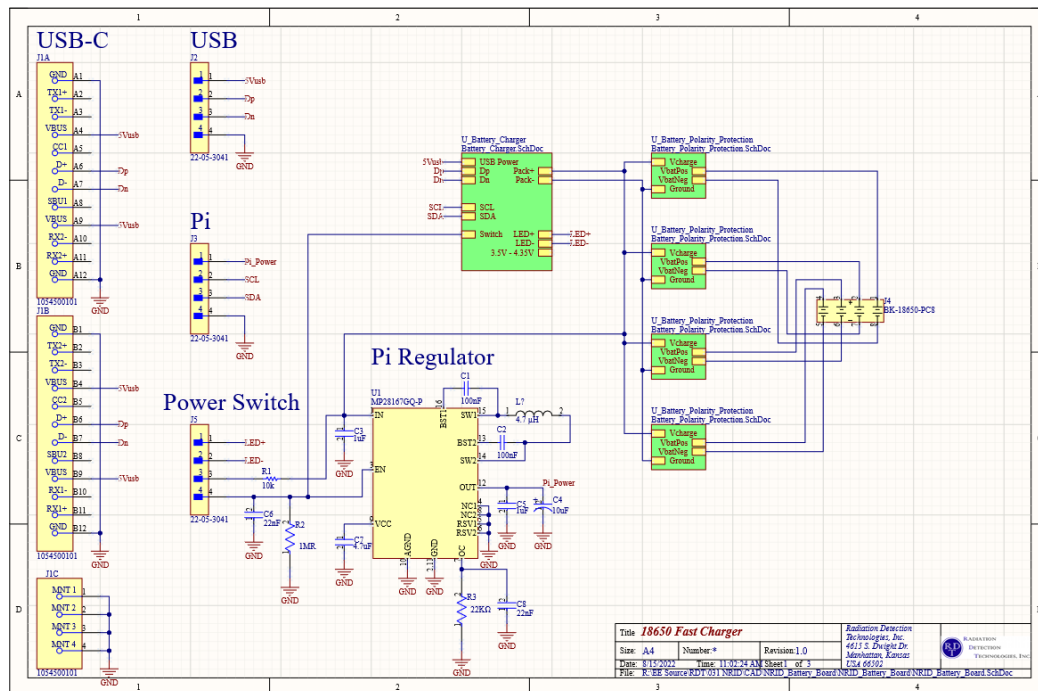


Figure 94: Top Level Master Schematic with Connectors, Regulator, and Battery Circuits.



Figure 95: Fabricated PCB for Fast Charging 18650 Batteries.

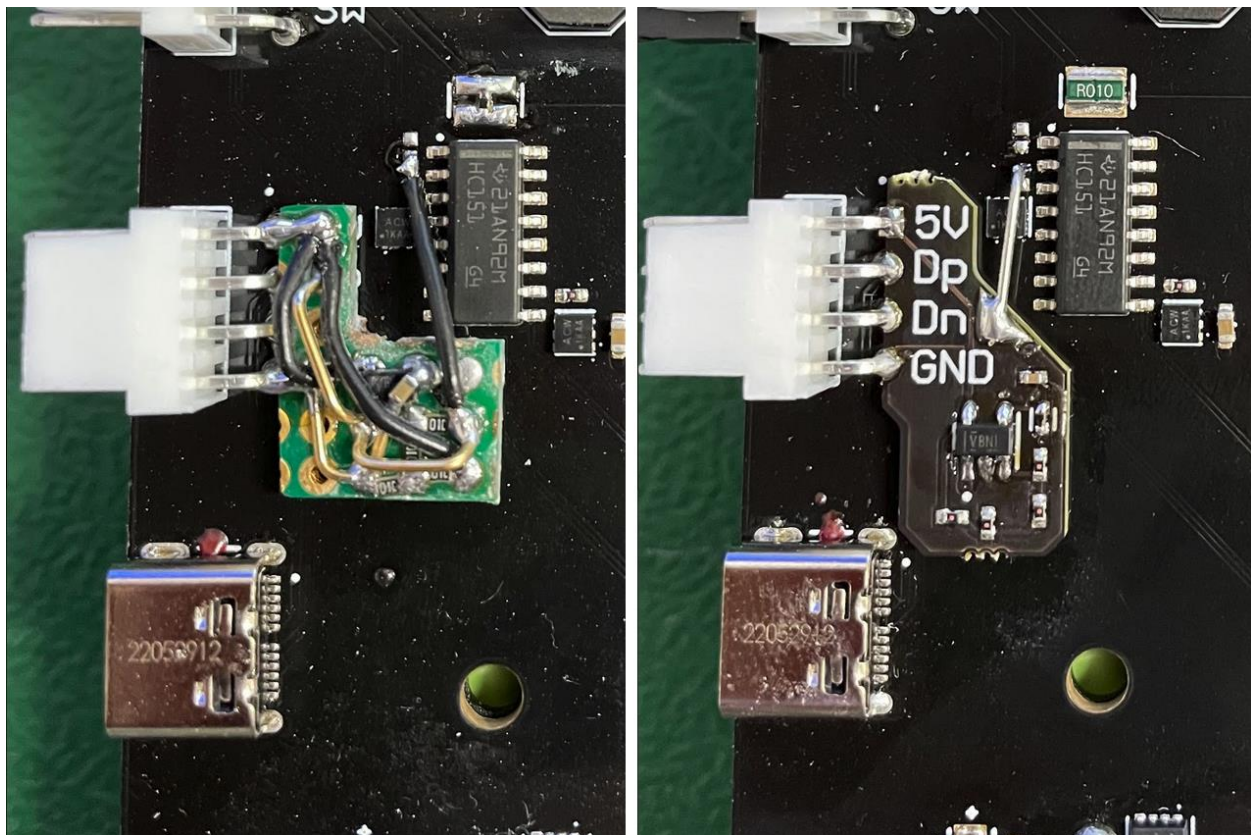


Figure 96: The handcrafted LED circuit (left) and the fabricated design (right).

3.6. Task 6: Re-test & Validation

The contractor shall conduct assembly-fit evaluation and radiological testing on the trial-design NRID prototype implementing the improvements suggested from year 1 work.

The second-generation electronics were evaluated at RDT. The MSND strips and backplates function properly. Final assembly of the detectors, moderator, and electronics was completed for the NRID V2.

The calibration method for the NRID V2 was modified such that maximum neutron detection efficiency was maintained whilst still being able to perform source identification. In this new method, the discrimination threshold was set such that good gamma rejection was attained (better than $1:10^7$) and then software correction factors were applied to each MSND such that the bare and moderated AmBe calibration measurements matched simulations for the same source-detector configuration. Figure 97 and Figure 98 show the results of the calibration. After the digital correction factors were calculated and applied to the response, the measured response matched the simulation response to $\sim\pm 20\%$. This was the first-time measurements were able to be performed with the completed NRID V2 system. While $\pm 20\%$ isn't ideal, it isn't a bad start. Additional work is required to refine the simulations such that they fall into tighter agreement with the measurements. The primary suspects of error include materials and density cards of the carbon fiber components, hdpe, and room scattering/albedo effects.

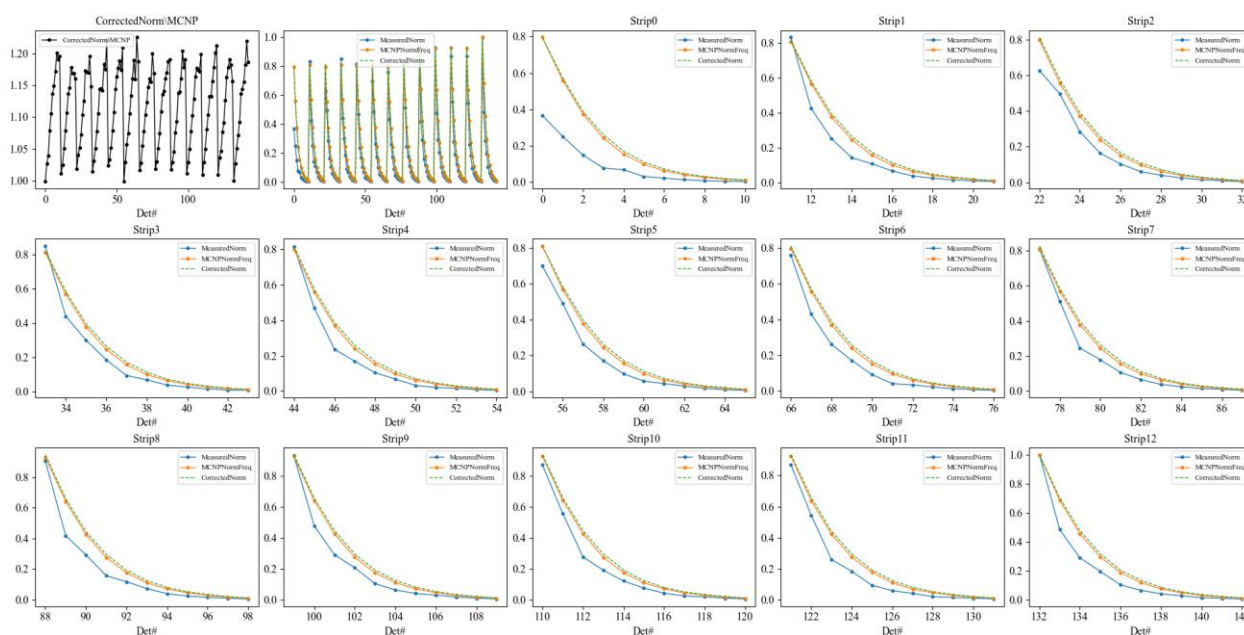


Figure 97: Moderated AmBe calibration results.

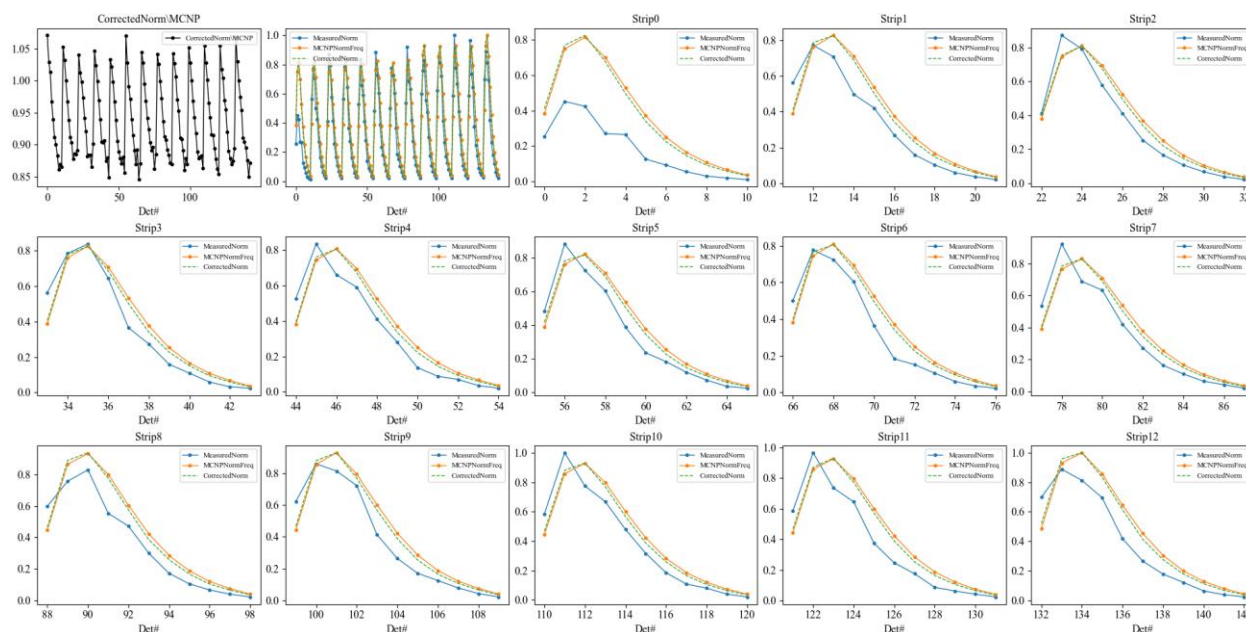


Figure 98: Bare AmBe Calibration results.

After calibration measurements were performed with bare and moderated Cf and AmBe sources, see Figure 99. Source ID was tested for each configuration with only minimal success. The measured spectra with low, mid, and high confidence (2500, 5000, 10000 counts) compared to the MCNP data on which the AI/ML algorithm (SPOCK) was trained on is shown in Figure 100. We believe the primary differences between measured response and simulated response stem from the following, all of which we believe to be surmountable with additional simulation/measurements/training cycles.

1. 20% error in calibration
2. Simulation data was in an “open” room with only floor scatter. The measurements were performed in a relatively small, concrete cinderblock walled room.
3. Simulation data was performed at source-detector distances of 1, 2.5, 5 meters, and the measurements were performed at 10-50 cm due to time and source size constraints.

With advancements and access to high performance computing networks, large data sets to address these shortcomings in simulation accuracy can be remedied relatively quickly. Figure 101 shows the NRID responses to bare and moderated AmBe and Cf plotted on each other. The responses are significantly different for each source which should allow for good source ID. **However, as the saying in the machine learning space goes, garbage-in equals garbage-out. Because our measured response doesn't match the spectra that the AI/ML algorithm was trained on, the NRID current struggles with source ID.** As mentioned previously, we believe we can make massive improvements to the source ID accuracy by identifying and correcting errors in the simulations as well as using measured data to bolster the training algorithm set. Finally, the NRID showed good directionality response accuracy, see Figure 102.

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Figure 99: NRID V2 measurements.

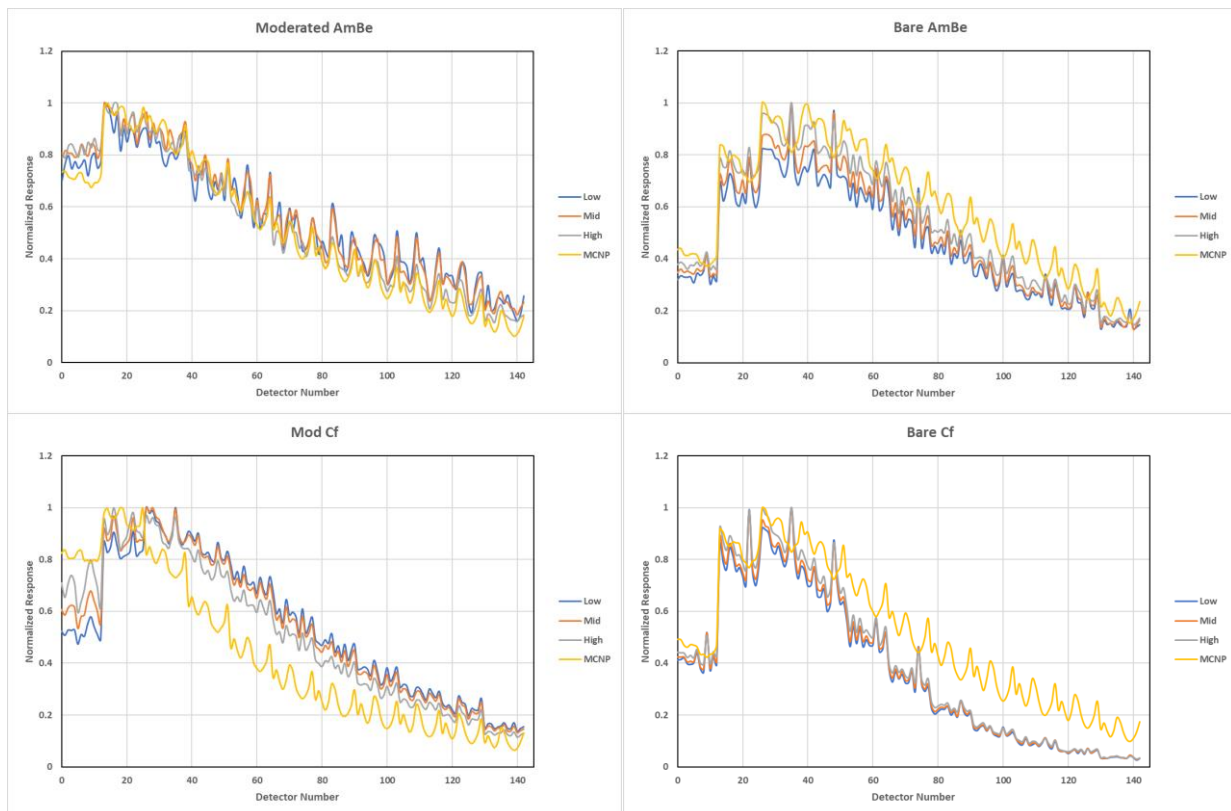


Figure 100: Measurement results for responses with 2500, 5000, and 10000 counts compared to MCNP simulated responses.

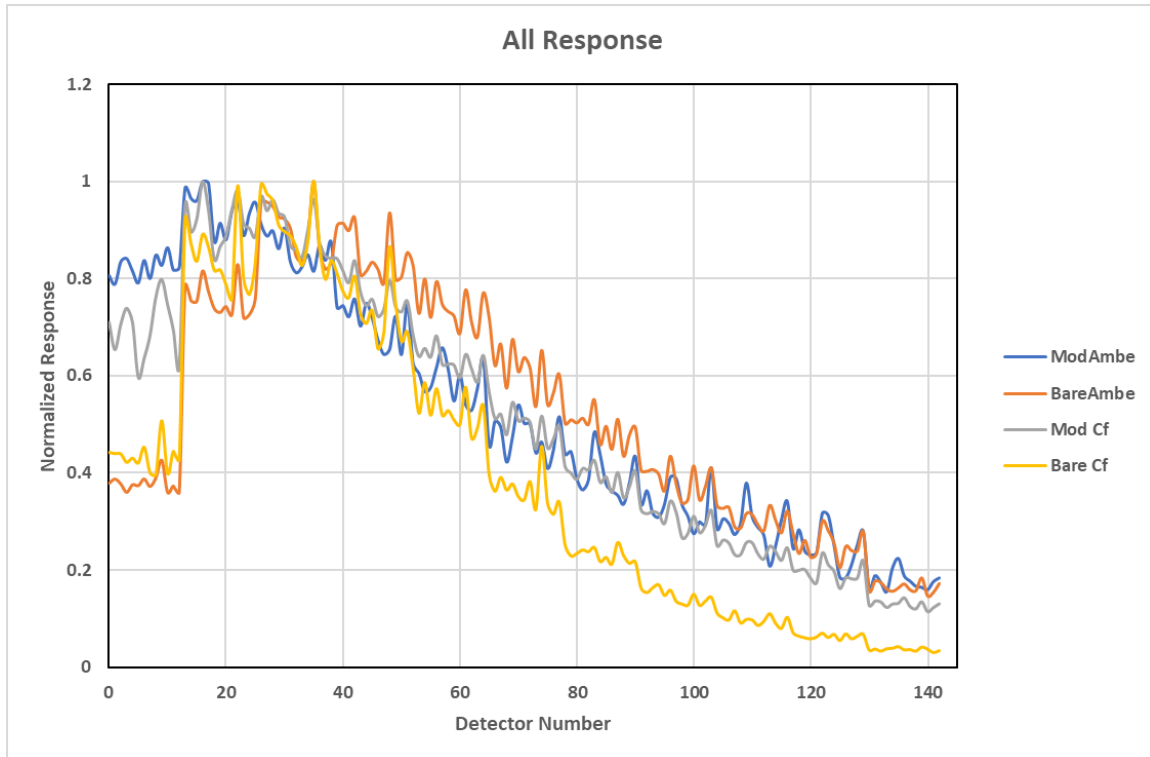


Figure 101: NRID measured responses for bare and moderated Cf and AmBe. The responses of each are significantly different which should allow for accurate source ID. Work remains to train the ID algorithms on data that matches the measured responses.



Figure 102: Source directionality testing. An AmBe source was located in the white HDPE cask.

3.7. Task 7: Build for Environmental/Physical Test

The contractor shall manufacture and procure the assembly hardware and housing parts as determined by the full-scale functional design developed at the end of year 1.

In addition to easing the manufacturing burden, the NRID V2 gen. 2 housing was designed with fewer points of ingress for dust and water than the V1 case. Our goal was to a better than IP66 rating, but at a minimum be splash proof and be able to be wipe-down decon compatible.

Epoxies were used to attach the case components and prevent water and dust ingress to the moisture sensitive electronics. Critical junctions include carbon fiber to aluminum junctions on the front and back of the case and the display screen to upper portion of the head unit.

3.8. Task 8: Complete Build of Engineering Prototype

The contractor shall manufacture, procure, and assemble the component parts as determined by the Task 5 & 7 revised functional design developed.

Fabrication of the V2 NRIDs is complete. All components fit to each other as expected and were permanently assembled, see Figure 103, before final calibration and demonstration.



Figure 103: Picture of NRID V2.

3.9. Task 9: Field Testing-Demonstrations

The contractor shall conduct testing to demonstrate meeting the technical objectives set forth for this NRID technology and prepare the Final Technical Report.

Final report completed herein. The NRID V2 was sent to DTRA for demonstration to potential user groups in January 2023. RDT is happy to submit/demonstrate/attend additional detector testing campaigns following the end of the contract throughout 2023.

4.0 Key Issues: Technical, Budget, and Schedule

Issues / Risks		Date	Issue Corrective Action / Risk Mitigation Strategy	T/B/S	Impact
1	NRID may not meet the required threshold objectives	8/15/20	Simulation indicate higher sensitivity is possible with Stacked MSND integration.	T/S/B	High
2	GUI interface software was take considerable time to develop.	8/31/20	Start the GUI software development early and try to implement core code along the way of the project dev. Was increase time available for software dev. to dedicate to NRID UI	S/B	Medium
3	COVID-19 Delay due to local community and/or government stop orders and work cannot be done remotely.	11/13/20	Continue to work under guidance of local health authorities. <u>No Cost Extension (NCE) given.</u>	S	High
4	Reduced size/weight of NRID reduces energy resolution thus increasing measurement time.	12/30/20	Provide “estimated time to ID” to operator Improve detection efficiency (DS-MSNDs)	T	High
5	Neutron reflectors did not improve energy resolution	1/26/21	- L-series NRID consideration. - Alert operator when multiple source IDs are reasonable (e.g. Cf and WGPu)	T	High
6	Pearson’s correlation can give “incorrect” ID in certain scenarios. (all linear responses score 1.0)	2/28/21	Investigate SAD and Cosine algorithms for library matching.	T	Low
7	Large error in source-detector angle calculation	8/30/21	Utilize AI/ML for directionality, continue work after PoP	T	High

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Issues / Risks		Date	Issue Corrective Action / Risk Mitigation Strategy	T/B/S	Impact
8	Large errors in initial unfolding algorithms.	9/17/21	Was train AI/ML for on-board unfolding, continue work with INL after PoP.	T	High
9	FPGA programming complications	1/26/22	More time spent on programming the FPGA the initial planned. Fixed	S	Med
10	Signal line ringing on FPGA/SPI command line	2/23/22	1. RC filtering for low power solution. 2. Pivot to line termination if RC filtering fail.	T/ S	Med
11	NRID can't be at two places at once. (Demonstrations and internal testing)	6/20/22	Was build 2-4 V2 NRIDs so at least one was always be at RDT for algorithm testing and debugging.	S	Low
12	Large datasets challenging to handle for AI/ML training	8/25/22	INL is working on new methods to handle the AI/ML training data sets on their server for faster algorithm development. Continue work with INL after PoP	T	Med
13	Random data miscommunication between FPGA and CPU	9/27/22	Mitigate erroneous read/bit flipping. Backup strategy is to prescreen and delete erroneous count rate data before fed into algorithms. Fixed	T	Low

Impact type: T/B/S means Technical, Budget, and/or Schedule; N/A means Not Applicable to project objectives.

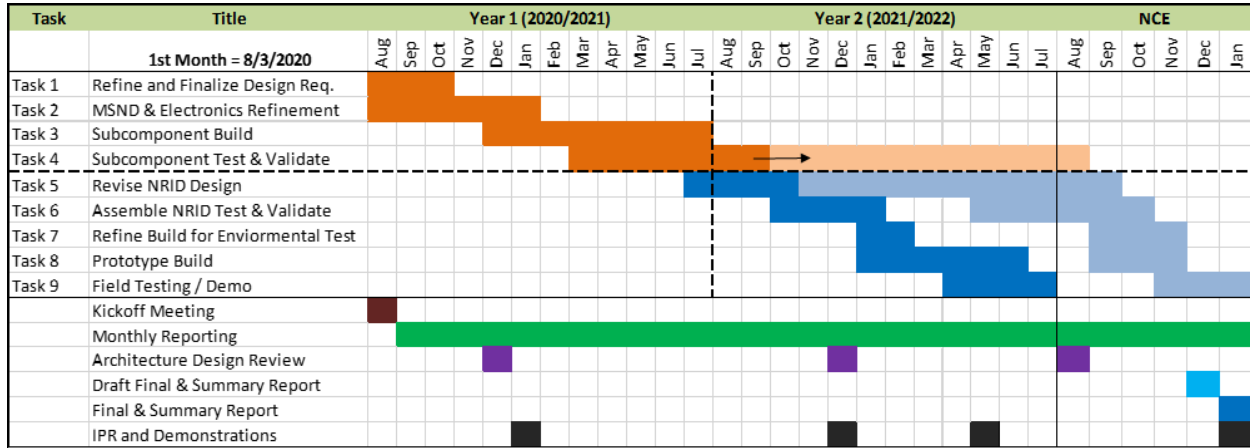
Severity Color Code: R=Project likely at risk, Y= Milestones/Deliverables likely at risk, G=Milestones/Deliverables slightly at risk, B=Issue resolved.

There has been delay to the project due to COVID-19 quarantine protocols; the project started in the middle of the COVID pandemic. Some of the required passive circuit components and integrated circuits (ICs) are currently out of supply or have excessively long lead-times, which was further delay work on the project.

5.0 Schedule of Tasks

Updated re-baselined planned work for the no-cost extension is given in Table 15.

Table 15: Gantt chart of tasking schedule.



6.0 Appendix

NRID UI Layout

Directionality and ID Operations Screen

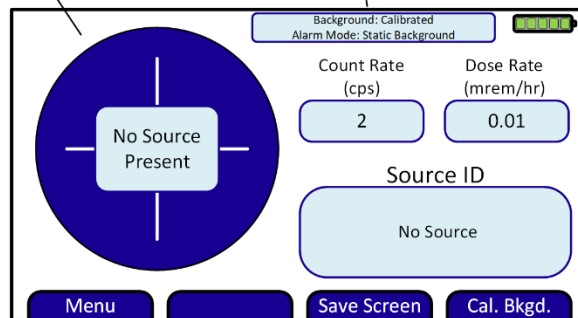
Directionality Compass. Turns on when source alarm triggers. Shows source direction in horizontal plane.

A. What to do about vertical alignment?
B. What if in isotropic field?

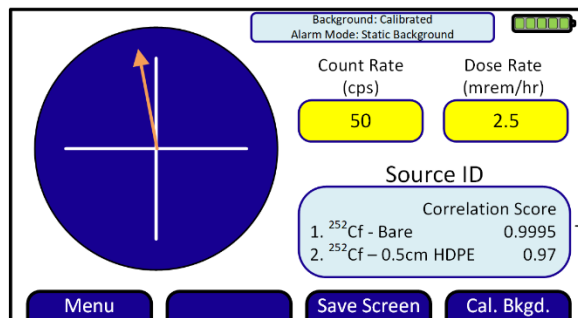
Status bar. Will typically look something like shown. But can display errors like "overtemp" or "uncalibrated".
Background – Calibrated/Uncalibrated
Alarm Mode – Static Background / Dynamic Background

Background: Uncalibrated
Alarm Mode: N/A Please Calibrate Background

Shows Battery Level
If charging, then shows time left until full charge

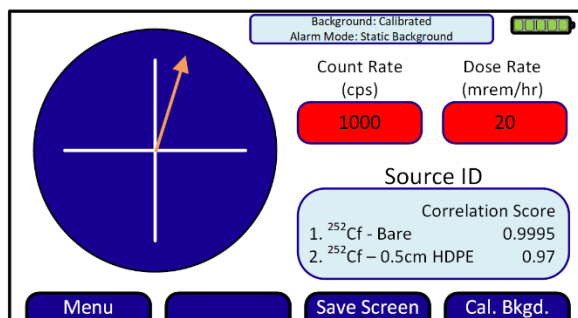


Count Rate and Dose Rate
Shows current count rate and dose rate updated once per second.
If source or dose alarm level 1 triggers, it flashes yellow (twice per second?).
If source or dose alarm level 2 triggers, it flashes red (twice per second?). Whatever looks good here



Source ID Box

Shows top two most likely source ID. Right now we can show correlation score, eventually I want to show confidence level. I just need to figure out how to calculate it.



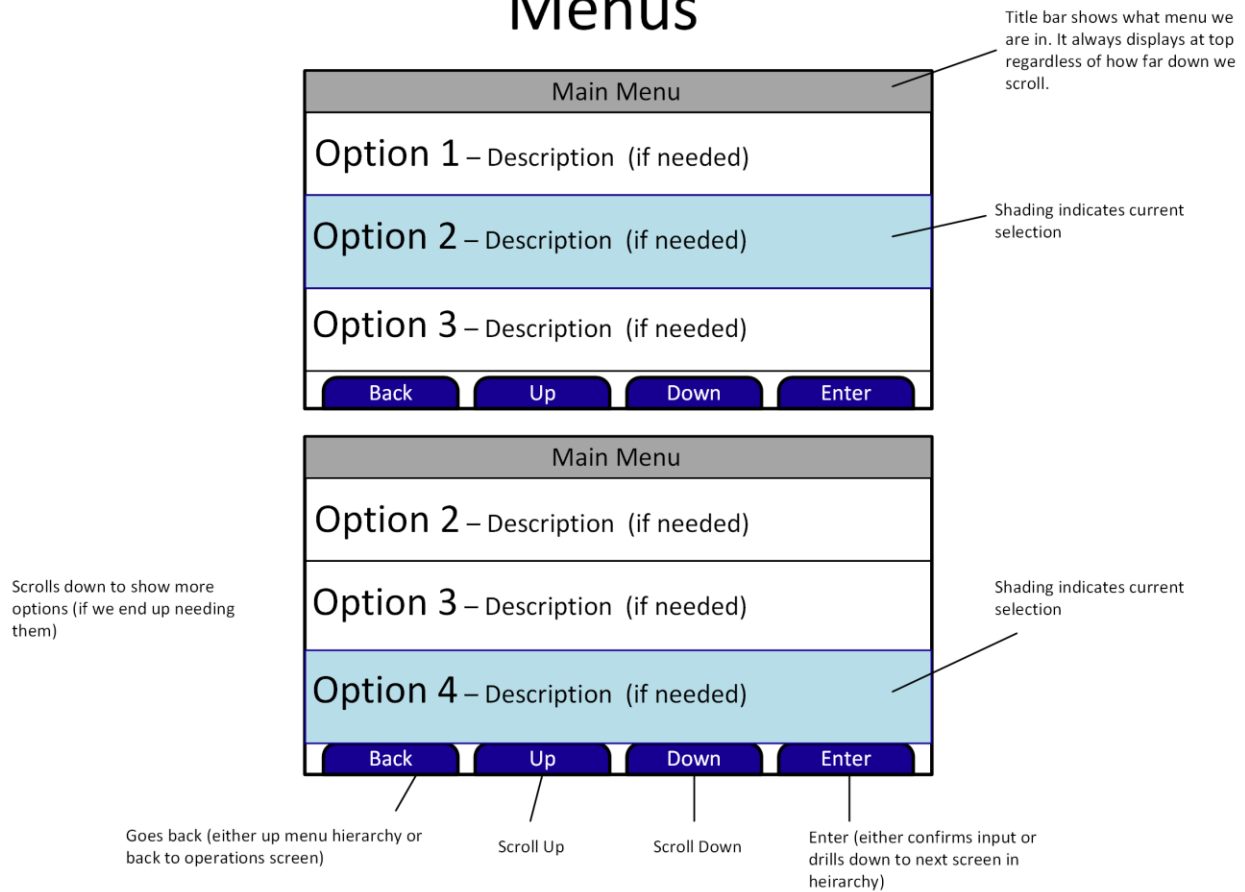
Might also show
"Please align NRID to Source"
"Need additional counts" - then maybe a timer based on count rate and how many counts we need. (down the road item)

Opens the Main Menu Screen

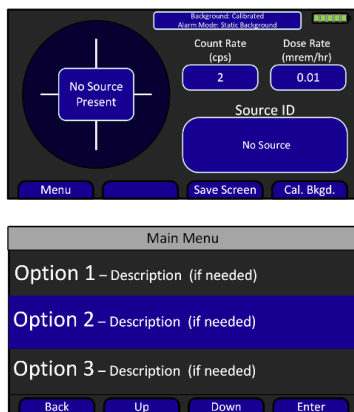
Saves Current Screen.
(Screenshots folder?)

Triggers a popup asking if they want to recalibrate the neutron background level.

Menus



Dark Mode Examples



6.1. References

- None