**United States Department of Energy**

**Savannah River Site**

# Results from the SILENE Criticality Accident Dosimetry Exercise, October 2009 (U)

**SRNS–STI-2010-00372**

**Revision 0**

**06/2010**

**Prepared by: T. R. Sullivan and S. G. Dyer; Health Physics Services; Radiological Protection Department**
**Savannah River Nuclear Solutions, LLC**
**Savannah River Site**
**Aiken, SC 29808**

**Prepared for the U. S. Department of Energy Under Contract No. DE-AC09-08SR22470**

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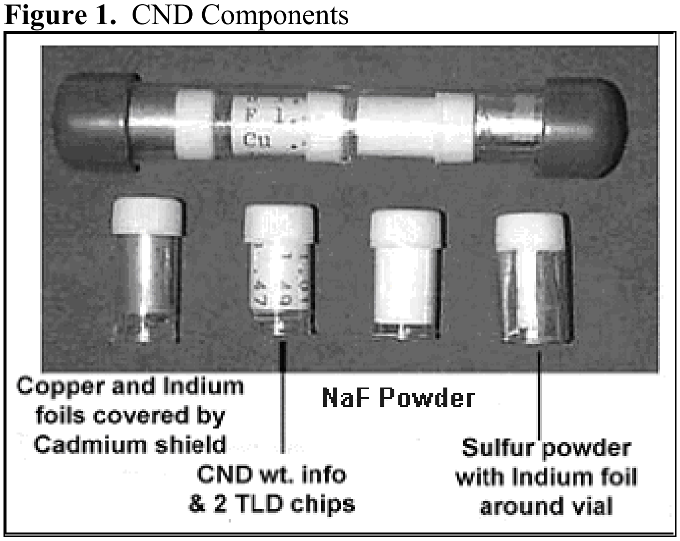
**Introduction**
October 9-20, 2009, Savannah River Site (SRS) participated in a criticality accident dosimetry exercise at Commissariat À L'énergie Atomique Et Aux Énergies Alternatives (CEA) Valduc, France. The exercise was funded by the U.S. Department of Energy Nuclear Criticality Safety Program and coordinated through Lawrence Livermore National Laboratory (LLNL). Other facilities represented included LLNL, Pacific Northwest National Laboratory, Y-12, Los Alamos National Laboratory (LANL), and Oak Ridge National Laboratory (ORNL).

The exercise was conducted using the SILENE reactor, which is a liquid solution assembly, operated in the pulse mode. Three exposures were performed consisting of a pulse with the assembly shielded by 10 cm lead, an unshielded (bare) low-power pulse, and a bare high-power pulse.

**Background**
The SRS Criticality Neutron Dosimeter (CND) contains four vials containing activation foils, activation powders, listing of weights, and two Harshaw TLD-700 LiF chips (Figure 1).

**Figure 1.** CND Components




The SRS CND design has been modified over the years. The components of the original CND were placed inside a plastic tube 3-5/8 inches long and 1/2 inch in diameter. Four 3/4 inch long by 3/8 inch diameter vials containing various materials to measure gamma and neutron exposures were placed inside the outer tube. To protect against breakage, vials and their contents were arranged in a specific order to identify these materials.

The CNDs were modified in 1993. The CND's components are assembled in a 3-5/8 inch long by 1/2 inch diameter mylar tube. A clip is attached so it can be placed on the wearer's pocket. Indium and copper foils were shaped into hollow cylinders to lessen directional effects. These foils, along with specific amounts of sodium fluoride powder, sulfur powder and TLD-700 chips, are contained in four small polystyrene vials. Exact weights of all the activation materials are listed in the dosimeter during assembly. These materials are pre-weighed to expedite processing after an accident. The two TLD-700 chips are contained in one of the polyethylene vials.

The cylinder tube design was modified in 2002. The mylar tube was replaced with a polycarbonate tube which is stronger and is UV resistant. The CND components are listed in Table 1.

**Table 1.** CND Components:

| Vial No. | Material Contained | ~Size (in.) or Weight (g) |
|---|---|---|
| **1** | Cadmium shield* | 1 piece of 1 x 5/8 x 1/32 in.<br>2 pieces of 3/8 dia. x 1/32 in. |
| | Indium foil* (Cd-covered) | 15/16 x 5/8 x 0.005 in. |
| | Copper foil* (Cd-covered) | 15/16 x 5/8 x 0.005 in. |
| **2** | Sodium fluoride powder | 1.50 gram ± .20 gm |
| **3** | Indium foil (bare foil around outside of vial) | 1 7/16 x 5/8 x 0.005 in. |
| | Sulfur powder | 1.00 gram ± .20 gm |
| **4** | Paper with weight data (not shown) | ~1.2 x 5/8 in. |
| | Harshaw TLD-700 chips | 2 chips |

SRS participated in DOE intercomparisons at the Health Physics Research Reactor (HPRR) at ORNL until the unit was shut down in 1986. The SRS CND performed well in these exercises. After the HPRR was shut down the number of exercises were greatly reduced. In 1993 and again in 2003, SRS participated an international intercomparison in Valduc, France. In 1995, SRS participated in a DOE intercomparison at LANL. The basic fluence and dose conversion factors developed in 1986 have been adjusted to improve response to various spectra; however the basic methodology and algorithm has remained the same.

**Methods**

In the first exposure, SRS Criticality Neutron Dosimeters (CNDs) were placed on the front and rear of a water filled phantom placed two meters from the source. The purpose was to compare the neutron dose algorithm for front and rear exposures from a lead shielded pulse.

The second exposure was the same as the first except the pulse was bare (unshielded). Again, the purpose was to compare the neutron dose algorithm for front and rear exposures from a bare (unshielded) pulse.

In the third exposure, SRS CNDs were placed for a side exposure, one CND was centered on the phantom torso, one CND was placed slightly forward of center, and one CND was placed slightly to the rear of center. The purpose was to determine how much affect this directional variation had on the dose algorithm.

After each exposure the CNDs were disassemble and activated materials were placed in planchets for beta counting. NaF powder, $NaHCO_3$ powder, Copper foil, and Indium foils were beta counted using a ThermoEberline Hand*E*Count alpha beta scintillation detector. Beta counting was also performed using LLNL's gas flow proportional counter. The Copper foil and Indium foils were counted using LLNL's Falcon 5000 electronically cooled high purity germanium (HPGe) detector. The Harshaw TLD-700 chips were counted at SRS using a Panasonic UD-513A gas heated thermoluminescence reader.

The activation results, weights, and time since criticality for each CND are entered into the CNDCALC (Microsoft Access) program. This program determines neutron dose results as well as CND orientation.

Sodium fluoride (NaF) powder is used to determine the direction of exposure. Since the CND is normally worn on the front of the person and its activation is affected by the body's shielding and moderation, it is critically important to know the direction from which the person was exposed. If a correction for direction of exposure is not made, the dose estimate may be low in cases where the exposure was received from the back of the individual. By comparing the activation of the $^{24}Na$ in the individual's blood with the activity of the $^{24}Na$ produced in the sodium fluoride powder in the dosimeter, the direction of exposure can be correctly predicted.

In the first exposure, NaF activation and $NaHCO_3$ activation were compared. As NaF is a hazard if ingested, $NaHCO_3$ was investigated as a possible substitute. A longer tube was used and a vial of $NaHCO_3$ was added to each CND.

Neutron doses are corrected for orientation using the correction factors listed in Table 2.

**Table 2** Neutron Dose Orientation Correction Factors

| Orientation | Front | Side | Rear |
|---|---|---|---|
| Thermal (0.0 eV to 0.4 eV) | 0.23 | 1 | 0.64 |
| Epithermal (0.4 eV to 2 eV) | 0.35 | 1 | 1.60 |
| Resonance (2 eV to 1 MeV) | 0.45 | 1 | 2.00 |
| Medium Energy (1 MeV to 3 MeV) | 0.79 | 1 | 5.40 |
| Fast (3.0 MeV to 10 MeV) | 0.72 | 1 | 6.70 |

Gamma doses from TLD-700 chip measurements were corrected for orientation using the correction factors listed in Table 3.

**Table 3** Gamma Dose Orientation Correction Factors

| Gamma Corrections | |
|---|---|
| **Direction of Exposure** | **Correction Factor** |
| Front | 0.7 |
| Side | 1.0 |
| Back | 2.1 |

**Results:**
The averaged dose results for each exposure are provided in Table 4. Detailed dose and neutron fluence results are provided in Appendix A and gamma dose results are provided in Appendix B. Appendix C contains data on the CND material weights. Appendix D contains the beta counting data results and Appendix E contains HPGe counting results for the cadmium shielded indium foil.

**Table 4** CND Dose Results Summary

| Run | Location | SRS Neutron Dose (rad) | SRS Gamma Dose (rad) | Valduc Reported Dose Neutron Dose (rad) | Valduc Reported Dose Gamma Dose (rad) | % Difference Neutron | % Difference Gamma |
|---|---|---|---|---|---|---|---|
| 1 | 2 m Phantom (Front) | 546 | 262 | 690 | 50 | -20.9 | 424.0 |
| | 2 m Phantom (Rear) | 365 | 313 | 690 | 50 | -47.1 | 526.0 |
| | | | | | | | |
| 2 | 2 m Phantom (Front) | 425 | 494 | 320 | 380 | 32.8 | 30.0 |
| | 2 m Phantom (Rear) | 483 | 642 | 320 | 380 | 50.9 | 68.9 |
| | | | | | | | |
| 3 | 6 m Phantom (Side) | 154 | 295 | 150 | 150 | 2.7 | 96.7 |

The neutron dose results of the first exposure were significantly lower than the reported delivered neutron dose. Evaluation of the data shows the difference was due to low fluence calculation in the 1 to 3 MeV range. The fluence in this range is derived from activation of the cadmium shielded $^{115m}$In foil. A count of the unshielded $^{115m}$ In foils yielded essentially the same results. The reason for this low fluence is being evaluated. The gamma results for the first exposure were much higher than the reported delivered dose but were consistent with other participants.

The neutron dose results for the second exposure were higher than the reported delivered dose. The #9 CND was significantly higher (75.6%) due to a high result from the cadmium shielded $^{115m}$In foil. Due to high activity, the #9 cadmium shielded $^{115m}$In foil was reduced in size prior to counting. This could have affected the geometry or the foil may have been weighed incorrectly.

The neutron dose from the third exposure revealed the importance of orientation. CND # 11 was supposed to be placed on the phantom slightly to the left of the phantom's vertical centerline. Pictures indicate it was placed on the vertical centerline. CND # 12 was placed on the phantoms vertical centerline and CND #13 was placed to the right of the phantoms vertical centerline. The oval shaped phantom was rotated 90 degrees resulting in CNDs # 11 and #12 being on the vertical centerline and CND # 13 more towards the front. The neutron dose algorithm for a side exposure worked well with CNDs #11 and # 12. With the #13 CND being more towards the front of the phantom, the side exposure algorithm over predicted the neutron dose (+33%) while the front exposure algorithm under predicted (-31%) the neutron dose.

Because SRS did not bring a HPGe detector to the exercise, gamma activity in the foils was calculated by LLNL personnel using their equipment and software. This was a disadvantage as some counting times were reduced and only one count of each sample was performed. In future exercises SRS should bring all needed equipment. Due to time limitations, beta counting of the SRS samples on the first exposure were only performed once on the Hand*E*Count.

On the second and third exposures, samples were counted twice on the Hand$_E$Count. In addition, all samples were beta counted with LLNLs gas flow proportional counter. The dose results from these counts are shown in Table 5. Differences in calibration between the Hand$_E$Count and LLNL's gas flow proportional counter resulted in a lower prediction of dose by LLNLs gas flow proportional counter.

**Table 5** Comparison of neutron dose results from recounts on SRS and LLNL beta counting equipment.

| | SRS 1st Count | SRS 2nd Count | % Difference | LLNL β Count | % Difference |
|---|---|---|---|---|---|
| CND # 1 | 598 | -- | -- | 513 | **-14.2%** |
| CND # 2 | 494 | -- | -- | 427 | **-13.5%** |
| CND # 3 | 363 | -- | -- | 299 | **-17.8%** |
| CND # 4 | 368 | -- | -- | 276 | **-24.9%** |
| CND # 6 | 402 | 393 | **-2.4%** | 339 | **-7.4%** |
| CND # 7 | 452 | 452 | **0.2%** | 431 | **-2.3%** |
| CND # 8 | 403 | 405 | **0.5%** | 402 | **-0.3%** |
| CND # 9 | 595 | 529 | **-11.1%** | 494 | **-6.1%** |
| CND # 11 | 139 | 138 | **-0.8%** | 120 | **-6.4%** |
| CND # 12 | 141 | 132 | **-6.2%** | 120 | **-6.1%** |
| CND # 13 | 215 | 183 | **-15.1%** | 160 | **-9.7%** |

Due to health hazards associated with NaF, $NaHCO_3$ was evaluated as a possible substitute. For this test, a box of baking soda was purchased from a local grocery store. The purity of the $NaHCO_3$ is unknown. The mass fraction of Na in NaF is 0.561 and in $NaHCO_3$ is 0.274 or roughly half (0.488) of NaF. The results in Table 6 show the relative differences in the response in the 5 CNDs that had both NaF and NaHCO3. The results show that $NaHCO_3$ can be a good replacement for NaF but will require a small change to the orientation algorithm.

**Table 6** NaF and $NaHCO_3$

| CND # | NaF DPG (disintigrations/gram) | $NaHCO_3$ DP ½G (disintigrations/ ½ gram) | Difference |
|---|---|---|---|
| 1 | 1.16E+06 | 1.01E+06 | -12.9% |
| 2 | 1.58E+05 | 1.62E+05 | 2.5% |
| 3 | 4.26E+04 | 4.39E+04 | 3.1% |
| 4 | 3.29E+04 | 3.45E+04 | 4.9% |
| 5 | 6.04E+04 | 5.92E+04 | -2.0% |

**Discussion:**

The results of this exercise provided many opportunities for improvement. The CNDs did not perform as well in this exercise as they have in the past. While the neutron dose algorithm under predicted neutron dose in the first exposure, it over predicted the neutron dose in the second exposure. The activation cross sections used in the algorithm need further refinement for better accuracy in multiple spectra. There is an overlap in activation of sulfur powder and the indium foil. The cross section for the inelastic scattering of fast neutrons by $^{115}$In remains significant to values above 5 MeV. Thus, the fluence of neutrons above 3 MeV, as determined from the activation of sulfur, must be subtracted from the fluence calculated using the indium foil activation.

The difference represents the neutron fluence from 1 to 3 MeV. The CNDCALC program subtracts the fluence of the sulfur from the fluence of the indium foil to obtain the fluence for 1 to 3 MeV. In several instances this resulted in negative fluence in the 1 to 3 MeV range.

As evidence in Exposure 3, small variations in orientation can result in large variations in activation. Further study is needed to determine if orientation neutron dose correction factors can be improved.

Gamma dose date may have been elevated. After each exposure the CNDs were stored with other activated dosimetry and material until distribution to personnel for disassembly and counting. It is not know how much additional dose was accumulated during this time. This would not be an issue in a real event; however, for future exercises, it may be beneficial to retrieve gamma dosimetry early.

**Appendix A** CND Fluence and Neutron Dose Details; 1st Exposure

| **1st Exposure; Lead Shielded Pulse @ 2 meters** | | |
|---|---|---|
| **CND #1 Front Exposure (Lead)** | **Fluence** | **Dose** |
| Thermal (0.0 eV to 0.4 eV) | 1.74E+09 | 0.01 |
| Epithermal (0.4 eV to 2 eV) | 1.01E+10 | 0.78 |
| Resonance (2 eV to 1 MeV) | 7.55E+11 | 424.88 |
| Medium Energy (1 MeV to 3 MeV) | 1.96E+10 | 44.51 |
| Fast (3.0 MeV to 10 MeV) | 3.70E+10 | 128.02 |
| **Total** | **8.24E+11** | **598.20** |
| | | |
| **CND #2 Front Exposure (Lead)** | **Fluence** | **Dose** |
| Thermal (0.0 eV to 0.4 eV) | 5.09E+10 | 0.37 |
| Epithermal (0.4 eV to 2 eV) | 8.47E+09 | 0.65 |
| Resonance (2 eV to 1 MeV) | 6.14E+11 | 345.20 |
| Medium Energy (1 MeV to 3 MeV) | 1.64E+10 | 37.22 |
| Fast (3.0 MeV to 10 MeV) | 3.20E+10 | 110.46 |
| **Total** | **7.21E+11** | **493.90** |
| | | |
| **CND #3 Rear Exposure (Lead)** | **Fluence** | **Dose** |
| Thermal (0.0 eV to 0.4 eV) | 1.01E+10 | 0.21 |
| Epithermal (0.4 eV to 2 eV) | 1.35E+09 | 0.48 |
| Resonance (2 eV to 1 MeV) | 1.03E+11 | 257.75 |
| Medium Energy (1 MeV to 3 MeV) | -5.62E+07 | -0.87 |
| Fast (3.0 MeV to 10 MeV) | 3.28E+09 | 105.54 |
| **Total** | **1.18E+11** | **363.10** |
| | | |
| **CND #4 Rear Exposure (Lead)** | **Fluence** | **Dose** |
| Thermal (0.0 eV to 0.4 eV) | 1.20E+10 | 0.25 |
| Epithermal (0.4 eV to 2 eV) | 1.35E+09 | 0.47 |
| Resonance (2 eV to 1 MeV) | 1.10E+11 | 275.15 |
| Medium Energy (1 MeV to 3 MeV) | No Data | No Data |
| Fast (3.0 MeV to 10 MeV) | 2.86E+09 | 91.96 |
| **Total** | **1.26E+11** | **367.83** |

**Appendix A** CND Fluence and Neutron Dose Details; 2nd Exposure

| **2nd Exposure; Unshielded Pulse @ 2 meters** | | |
|---|---|---|
| **CND #6 Front Exposure** | **Fluence** | **Dose** |
| Thermal (0.0 eV to 0.4 eV) | 7.28E+11 | 5.36 |
| Epithermal (0.4 eV to 2 eV) | 3.14E+09 | 0.24 |
| Resonance (2 eV to 1 MeV) | 2.43E+11 | 136.51 |
| Medium Energy (1 MeV to 3 MeV) | 7.16E+10 | 162.23 |
| Fast (3.0 MeV to 10 MeV) | 2.83E+10 | 97.75 |
| **Total** | **1.07E+12** | **402.09** |
| | | |
| **CND #7 Front Exposure** | **Fluence** | **Dose** |
| Thermal (0.0 eV to 0.4 eV) | 8.69E+11 | 6.39 |
| Epithermal (0.4 eV to 2 eV) | 3.70E+09 | 0.29 |
| Resonance (2 eV to 1 MeV) | 2.57E+11 | 144.61 |
| Medium Energy (1 MeV to 3 MeV) | 6.67E+10 | 151.16 |
| Fast (3.0 MeV to 10 MeV) | 4.32E+10 | 149.18 |
| **Total** | **1.24E+12** | **451.63** |
| | | |
| **CND #8 Rear Exposure** | **Fluence** | **Dose** |
| Thermal (0.0 eV to 0.4 eV) | 1.69E+11 | 3.46 |
| Epithermal (0.4 eV to 2 eV) | 7.78E+08 | 0.27 |
| Resonance (2 eV to 1 MeV) | 5.33E+10 | 133.30 |
| Medium Energy (1 MeV to 3 MeV) | 9.14E+09 | 141.71 |
| Fast (3.0 MeV to 10 MeV) | 3.87E+09 | 124.47 |
| **Total** | **2.36E+11** | **403.22** |
| | | |
| **CND #9 Rear Exposure** | **Fluence** | **Dose** |
| Thermal (0.0 eV to 0.4 eV) | 1.56E+09 | 0.03 |
| Epithermal (0.4 eV to 2 eV) | 4.29E+04 | 0.00 |
| Resonance (2 eV to 1 MeV) | 6.30E+10 | 157.45 |
| Medium Energy (1 MeV to 3 MeV) | 1.86E+10 | 288.07 |
| Fast (3.0 MeV to 10 MeV) | 4.66E+09 | 149.83 |
| **Total** | **8.78E+10** | **595.38** |

**Appendix A** CND Fluence and Neutron Dose Details; 3rd Exposure

| **3rd Exposure; Unshielded pulse @ 6 meters** | | |
|---|---|---|
| **CND # 11 Side Exposure** | **Fluence** | **Dose** |
| Thermal (0.0 eV to 0.4 eV) | 6.25E+10 | 2.00 |
| Epithermal (0.4 eV to 2 eV) | 2.96E+08 | 0.07 |
| Resonance (2 eV to 1 MeV) | 7.82E+10 | 97.71 |
| Medium Energy (1 MeV to 3 MeV) | 8.92E+08 | 2.56 |
| Fast (3.0 MeV to 10 MeV) | 7.59E+09 | 36.46 |
| **Total** | **1.49E+11** | **138.79** |
| | | |
| **CND # 12 Side Exposure** | **Fluence** | **Dose** |
| Thermal (0.0 eV to 0.4 eV) | 6.41E+10 | 2.05 |
| Epithermal (0.4 eV to 2 eV) | 2.78E+08 | 0.06 |
| Resonance (2 eV to 1 MeV) | 8.14E+10 | 101.76 |
| Medium Energy (1 MeV to 3 MeV) | -4.55E+08 | -1.30 |
| Fast (3.0 MeV to 10 MeV) | 7.94E+09 | 38.10 |
| **Total** | **1.53E+11** | **140.67** |
| | | |
| **CND # 13 Side Exposure** | **Fluence** | **Dose** |
| Thermal (0.0 eV to 0.4 eV) | 9.17E+09 | 0.29 |
| Epithermal (0.4 eV to 2 eV) | 1.59E+09 | 0.35 |
| Resonance (2 eV to 1 MeV) | 1.13E+11 | 141.65 |
| Medium Energy (1 MeV to 3 MeV) | 1.23E+09 | 3.53 |
| Fast (3.0 MeV to 10 MeV) | 7.69E+09 | 36.89 |
| **Total** | **1.33E+11** | **182.71** |

**Appendix B** TLD Gamma Dose Results

| **Exposure 1** | **Chip #1** | **Chip #2** | **Ave.** | **Orientation** | **Oreintation C/F** | **γ Dose (Rad)** |
|---|---|---|---|---|---|---|
| CND #1 | 365 | 339 | 352 | Front | 0.7 | 246 |
| CND #2 | 401 | 392 | 397 | Front | 0.7 | 278 |
| CND #3 | 167 | 130 | 149 | Rear | 2.1 | 312 |
| CND #4 | 144 | 155 | 150 | Rear | 2.1 | 314 |
| | | | | | | |
| **Exposure 2** | | | | | | |
| CND #6 | 765 | 664 | 715 | Front | 0.7 | 500 |
| CND #7 | 730 | 664 | 697 | Front | 0.7 | 488 |
| CND #8 | 329 | 277 | 303 | Rear | 2.1 | 636 |
| CND #9 | 311 | 306 | 309 | Rear | 2.1 | 648 |
| | | | | | | |
| **Exposure 3** | | | | | | |
| CND # 11 | 281 | 275 | 278 | Side | 1 | 278 |
| CND # 12 | 315 | 283 | 299 | Side | 1 | 299 |
| CND # 13 | 290 | 325 | 308 | Side | 1 | 308 |

**Appendix C** Material Weight Data

**Mass in grams (weighed @ SRS)**

| CND# | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| NaF | 1.390 | 1.500 | 1.540 | 1.600 | 1.480 | 1.570 | 1.600 |
| S | 1.130 | 1.150 | 1.090 | 1.180 | 1.060 | 1.150 | 0.910 |
| Cu | 0.446 | 0.420 | 0.420 | 0.433 | 0.445 | 0.415 | 0.445 |
| In-Cd | 0.247 | 0.248 | 0.262 | 0.256 | 0.253 | 0.237 | 0.258 |
| In-B | 0.447 | 0.451 | 0.471 | 0.467 | 0.444 | 0.443 | 0.456 |
| NaB | 1.919 | 1.652 | 1.752 | 1.757 | 1.781 | 1.779 | 1.767 |

| CND# | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|
| NaF | 1.640 | 1.650 | 1.460 | 1.540 | 1.620 | 1.500 | 1.620 |
| S | 1.090 | 1.020 | 1.170 | 1.150 | 1.190 | 1.130 | 1.120 |
| Cu | 0.397 | 0.433 | 0.471 | 0.448 | 0.452 | 0.445 | 0.458 |
| In-Cd | 0.240 | 0.231 | 0.254 | 0.252 | 0.268 | 0.251 | 0.250 |
| In-B | 0.424 | 0.456 | 0.450 | 0.443 | 0.460 | 0.445 | 0.480 |
| NaB | 1.766 | 1.842 | 1.860 | 1.692 | 1.730 | 1.838 | 1.787 |

**Foil Reductions for beta counts***

| CND# | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|
| InCd | 0.0745 | 0.0668 | 0.0603 | 0.0602 | Unknown |
| In-B | 0.0792 | 0.0793 | 0.0891 | No Change | Unknown |

| CND# | 11 | 12 | 13 | 14 |
|---|---|---|---|---|
| InCd | 0.0773 | 0.0774 | 0.0905 | 0.0531 |
| In-B | 0.0843 | 0.0844 | 0.1009 | 0.0456 |
| S | | | | 1.03 |

***Also for gamma spec counting on 6 thru 9**

**Foil Reductions specifically for gamma spec counts**

| CND# | 11 HPGe | 12 HPGe | 13 HPGe | 14 HPGe |
|---|---|---|---|---|
| InCd | 0.1745 | 0.1902 | 0.1596 | 0.1965 |
| In-B | 0.3409 | 0.3177 | 0.2817 | 0.4387 |

**Appendix D**: Beta Counting Data

| Exposure 1 | | SRS 1st Count | | SRS 2nd Count | | LLNL Count | |
|---|---|---|---|---|---|---|---|
| Sample ID | Wt(g) | net DPM | DeltaT | net DPM | DeltaT | net DPM | DeltaT |
| #01 S | 1.13 | 5968 | 339 | -- | -- | 4677.1 | 353 |
| #01 Cu | 0.45 | 33467 | 352 | -- | -- | 28101.8 | 330 |
| #01 Cd In | 0.25 | 3845 | 1420 | -- | -- | 2858.4 | 1592 |
| #01 Bare In | 0.45 | 7978 | 1544 | -- | -- | 620747 | 402 |
| | | | | | | | |
| #02 S | 1.15 | 5024 | 1592 | -- | -- | 4160.6 | 1431 |
| #02 Cu | 0.42 | 8315 | 1589 | -- | -- | 6700.8 | 1620 |
| #02 Cd In | 0.25 | 3226 | 1618 | -- | -- | -- | -- |
| #02 Bare In | 0.45 | 7493 | 1624 | -- | -- | -- | -- |
| | | | | | | | |
| #03 S | 1.09 | 509 | 398 | -- | -- | 340.5 | 378 |
| #03 Cu | 0.42 | 4028 | 415 | -- | -- | 3351.6 | 399 |
| #03 Cd In | 0.26 | 536 | 1461 | -- | -- | 399 | 1639 |
| #03 Bare In | 0.47 | 1282 | 1538 | -- | -- | 1002 | 1639 |
| | | | | | | | |
| #04 S | 1.18 | 461 | 1605 | -- | -- | 268.2 | 1581 |
| #04 Cu | 0.43 | 1449 | 1647 | -- | -- | 1242.1 | 1581 |
| #04 Cd In | 0.26 | 533 | 1663 | -- | -- | 1057.7 | 1627 |
| #04 Bare In | 0.47 | 1309 | 1660 | -- | -- | 451.5 | 1627 |

**Appendix D**: Beta Counting Data

| Exposure 2 | | SRS 1st Count | | SRS 2nd Count | | LLNL Count | |
|---|---|---|---|---|---|---|---|
| Sample ID | Wt(g) | net DPM | DeltaT | net DPM | DeltaT | net DPM | DeltaT |
| #06 S | 1.15 | 4652 | 246 | 3797 | 1410 | 3309.9 | 1632 |
| #06 Cu | 0.42 | 10027 | 353 | -- | -- | 7883 | 391 |
| #06 Cd In | 0.07 | 485967 | 332 | 144705 | 345 | 538 | 1477 |
| #06 Bare In | 0.08 | 2798799 | 335 | 539176 | 348 | 368 | 1477 |
| #07 S | 0.91 | 5614 | 267 | 3030 | 1421 | 2667 | 1632 |
| #07 Cu | 0.45 | 11117 | 379 | -- | -- | 8867.7 | 391 |
| #07 Cd In | 0.07 | 603187 | 328 | 127452 | 350 | 347.8 | 1429 |
| #07 Bare In | 0.08 | 4247472 | 316 | 533296 | 352 | 551.5 | 1444 |
| #08 S | 1.09 | 603 | 265 | 229 | 1501 | 388 | 1645 |
| #08 Cu | 0.4 | 2025 | 384 | -- | -- | 1663.1 | 384 |
| #08 Cd In | 0.06 | 131574 | 324 | 20602 | 365 | 53 | 1429 |
| #08 Bare In | 0.09 | 956612 | 315 | 96645 | 368 | 131 | 1444 |
| #09 S | 1.02 | 680 | 231 | 126 | 1550 | 338.6 | 1645 |
| #09 Cu | 0.43 | 2586 | 386 | -- | -- | 1555.6 | 384 |
| #09 Cd In | 0.06 | 371 | 1445 | -- | -- | 64 | 1470 |
| #09 Bare In | 0.46 | 16828 | 374 | -- | -- | 498 | 1470 |

| Exposure 3 | | SRS 1st Count | | SRS 2nd Count | | LLNL Count | |
|---|---|---|---|---|---|---|---|
| Sample ID | Wt(g) | net DPM | DeltaT | net DPM | DeltaT | net DPM | DeltaT |
| #11 S | 1.15 | 1244 | 370 | 1039 | 1703 | 992 | 382 |
| #11 Cu | 0.45 | 3451 | 356 | 1076 | 1668 | 1089 | 2879 |
| #11 Cd In | 0.08 | 57596 | 317 | 100 | 1581 | 19049 | 379 |
| #11 Bare In | 0.08 | 300146 | 324 | 191 | 1569 | 114693 | 379 |
| #12 S | 1.19 | 1345 | 376 | 1168 | 1705 | 1133.4 | 382 |
| #12 Cu | 0.45 | 3495 | 387 | 1063 | 1640 | 1113.9 | 1438 |
| #12 Cd In | 0.08 | 43545 | 334 | 105 | 1603 | 20874 | 376 |
| #12 Bare In | 0.08 | 228350 | 346 | 188 | 1591 | 120572 | 376 |
| #13 S | 1.13 | 1339 | 382 | 1182 | 1717 | 1135 | 394 |
| #13 Cu | 0.45 | 5188 | 390 | 1607 | 1615 | 1602 | 1426 |
| #13 Cd In | 0.09 | 50601 | 363 | 220 | 1473 | 35673 | 372 |
| #13 Bare In | 0.1 | 289646 | 364 | 315 | 1487 | 192631 | 372 |

**Appendix E:** Cadmium Shielded Indium Foil Data; HPGe Counting Data

| Cd Shielded Indium Foil | Foil wt (g) | Activity (pCi) | Delta T (Hrs) | Activity @ Time Zero (pCi) |
|---|---|---|---|---|
| CND1 (front) | 0.247 | 19,400 | 5.98 | 48,896 |
| CND2 (front) | 0.248 | 1,045 | 23.87 | 41,738 |
| CND3 (rear) | 0.262 | 1,020 | 6.75 | 2,894 |
| CND4 (rear) | 0.256 | --- | --- | --- |
| CND6 (front) | 0.075 | 13,800 | 4.02 | 25,668 |
| CND7 (front) | 0.067 | 14,800 | 4.18 | 28,246 |
| CND8 (rear) | 0.060 | 1,690 | 4.33 | 3,301 |
| CND9 (rear) | 0.060 | 1,676 | 6.85 | 4,829 |
| CND11 (side) | 0.175 | 1,931 | 6.33 | 5,137 |
| CND12 (side) | 0.190 | 1,870 | 6.25 | 4,911 |
| CND13 (side) | 0.160 | 1,899 | 6.15 | 4,911 |