Results of South-East Flux Trap Dosimetry Measurements for the Advanced Test Reactor Critical Facility in support of Advanced Sensors and Instrumentation Development.

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***Abstract*— Reactor dosimetry measurements are commonly used to validate simulation and modeling in nuclear reactor experiments. Numerous standard dosimeter materials exist which are commonly utilized for their sensitivity to different energy ranges of neutrons. At the Advanced Test Reactor, cobalt alloy and pure nickel wires are installed every cycle to monitor thermal- and fast-neutron fluence rates. However, there is growing interest in exploring less commonly used materials which are either more sensitive to different parts of the neutron energy spectrum, or which can incorporate multiple activation paths in a single material. Epithermal and fast-neutron energies beyond the typical 1-MeV threshold are of particular interest. Two Advanced Test Reactor Critical Facility Flux Runs took place during 2024; each flux run included supplemental dosimetry packages in the South-East Flux Trap. The focus of the dosimetry package for flux run 23-4 was to test two novel dosimetry methods that can provide simultaneous thermal and threshold (fast) sensitivity in a single dosimeter wire. A selection of 3% gold-in copper alloyed wires were available that provided sensitivity to fast and thermal neutrons through 5 different reactions. Likewise, iron offers multiple interaction pathways with sensitivity to both thermal and fast neutrons. The main question to be answered by these irradiations was if sufficient radioactivation would take place in the Advanced Test Reactor Critical Facility South-East Flux Trap during a nominal 20-minute irradiation at typical power levels (near 600 W_{th}) to allow the observation of the threshold reactions with smaller activation cross-sections than the thermal reactions, without being saturated by interfering interactions and Compton continuum during the High-Purity Germanium measurements. The results from comparing the measurement results to anticipated activity levels provide confidence in our ability to activate both traditional and novel dosimetry materials in Advanced Test Reactor Critical Facility, however not all the measured values matched with the predicted activities. This leaves further room for investigation both on the experimental and computational approaches for future irradiation experiments.**

***Keywords* —ATR-C, Reactor Dosimetry, ASI.**

I. Introduction

Reactor dosimetry measurements are commonly used to validate simulation and modeling in nuclear reactor tests. Numerous standard dosimeter materials exist which are commonly utilized with sensitivities to different energy ranges of neutrons [1]. At the Advanced Test Reactor (ATR), cobalt alloy and pure nickel wires are installed every cycle to monitor thermal- and fast-neutron fluence rates [2]. However, there is growing interest in exploring less commonly used materials which are either more sensitive to different parts of the neutron energy spectrum, or which can incorporate multiple activation paths in a single material, shown in Fig. 1. Epithermal and fast-neutron energies beyond the typical 1-MeV threshold are of particular interest.

The classical dosimeter materials shown in Fig. 1 do not provide coverage over the neutron energy range from 1 eV – 100 keV. For light-water reactors, the thermal neutron flux is of the greatest interest, however, continued interest in fast-spectrum nuclear reactor development has expanded the need for dosimetry methods in the > thermal energy regions. To this end, an irradiation campaign has been executed to demonstrate capabilities to conduct conventional dosimetry measurements and to begin investigation of novel reactions for epithermal- and fast-neutron measurements.

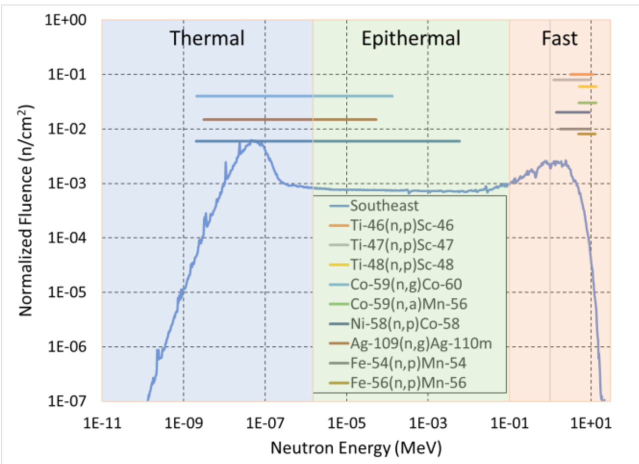


Figure 1. Distribution of traditional dosimeter interaction sensitivities utilized in flux run 24-1 relative to the normalized SEFT neutron energy profile in ATR-C.

II. METHOD

Two Advanced Test Reactor Critical Facility (ATR-C) flux runs took place during FY 2024, described in Table I. ATR-C serves as a prototypical irradiation environment to complement ATR with a similar flux distribution, but operated a much lower power (typically <1 kW_{th}). Each flux run included supplemental dosimetry packages in the South-East Flux Trap (SEFT) filler depicted in Fig. 2. For each of flux runs, 23-4 and 24-1, duplicate dosimetry packages were installed into the SE-2 and SE-4 positions. The loading for each flux run was different, as described in App. A. The dosimeter wires in all cases were encapsulated within a 0.075-in. outer diameter by 0.050-in. inner diameter pure aluminum tube, within a standard BR holder (DWG-035561-2), held in position by crimping onto the end of a 0.040-in diameter spacer wire.

The focus of the dosimetry package for flux run 23-4 was to test two novel dosimetry methods that can provide simultaneous thermal and threshold (fast) sensitivity in a single dosimeter wire, shown in Fig 3. A selection of 3% Au in Cu alloyed wires were available at the ATR Radiation Measurements Laboratory (RML). These wires provide sensitivity to fast and thermal neutrons through 5 reactions. Likewise, Fe offers multiple interaction pathways with sensitivity to both thermal and fast neutrons.

The main question to be answered by these irradiations was if sufficient radioactivation would take place in the ATR-C SEFT during a nominal 20-minute irradiation at typical power levels (near 600 W_{th}) to observe the threshold reactions that have smaller activation cross-sections than the thermal reactions without being saturated by interfering interactions and Compton continuum during the High-Purity Germanium (HPGe) measurements. The reported total uncertainty includes components from standard measurement, mass (0.00009 g), systemic (1%), and random (1%), combined by quadrature.

The focus of flux run 24-1 was related to the expanded testing of numerous threshold reactions in the SEFT position. Fe wires were irradiated in both flux runs, but the additional dosimetry in flux run 24-1 was comprised entirely of conventional materials that have been well documented by institutionally accepted standard test methods [3]. Predicted activities for all reactions were determined by numerical integration of the a-priori neutron energy spectrum with cross-section data from IRDFF-II [4] using the assumed values in Table II. A total flux of 1 x 10^9 $n \cdot cm^2 \cdot s^{-1}$ was assumed based on scaling from 250 MW_{th} flux estimates in the ATR SEFT [5].

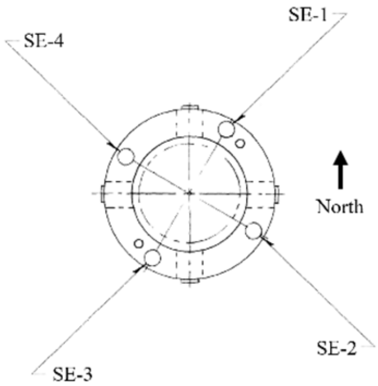


Figure 3. ATR-C SEFT Filler

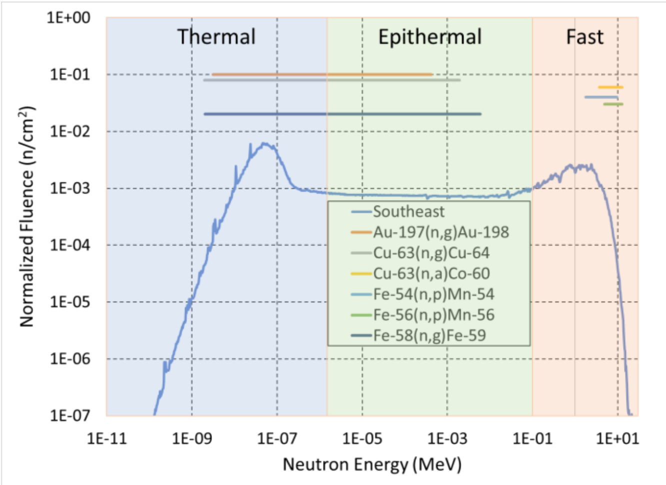


Figure 2. Distribution of traditional dosimeter interaction sensitivities utilized in flux run 23-4 relative to the normalized SEFT neutron energy profile in ATR-C.

TABLE I
ATR-C FLUX RUN SCRAM DATES/TIMES.

Flux run	SCRAM Date	SCRAM Time
23-4	05/30/2024	09:52:56
24-1	07/09/2024	09:20:28

TABLE II
ASSUMED VALUES USED IN CALCULATION OF PREDICTED ACTIVITIES.

Parameter	Value
Neutron Energy Profile	ATRC Southeast Flux Trap
Neutron Flux (n/cm2/sec)	1.00E+09
Irradiation Time (sec)	1200
Decay Time (sec)	3600

III. RESULTS AND CONCLUSIONS

THE MEASUREMENT RESULTS FROM DOSIMETER WIRES ARE SUMMARIZED IN

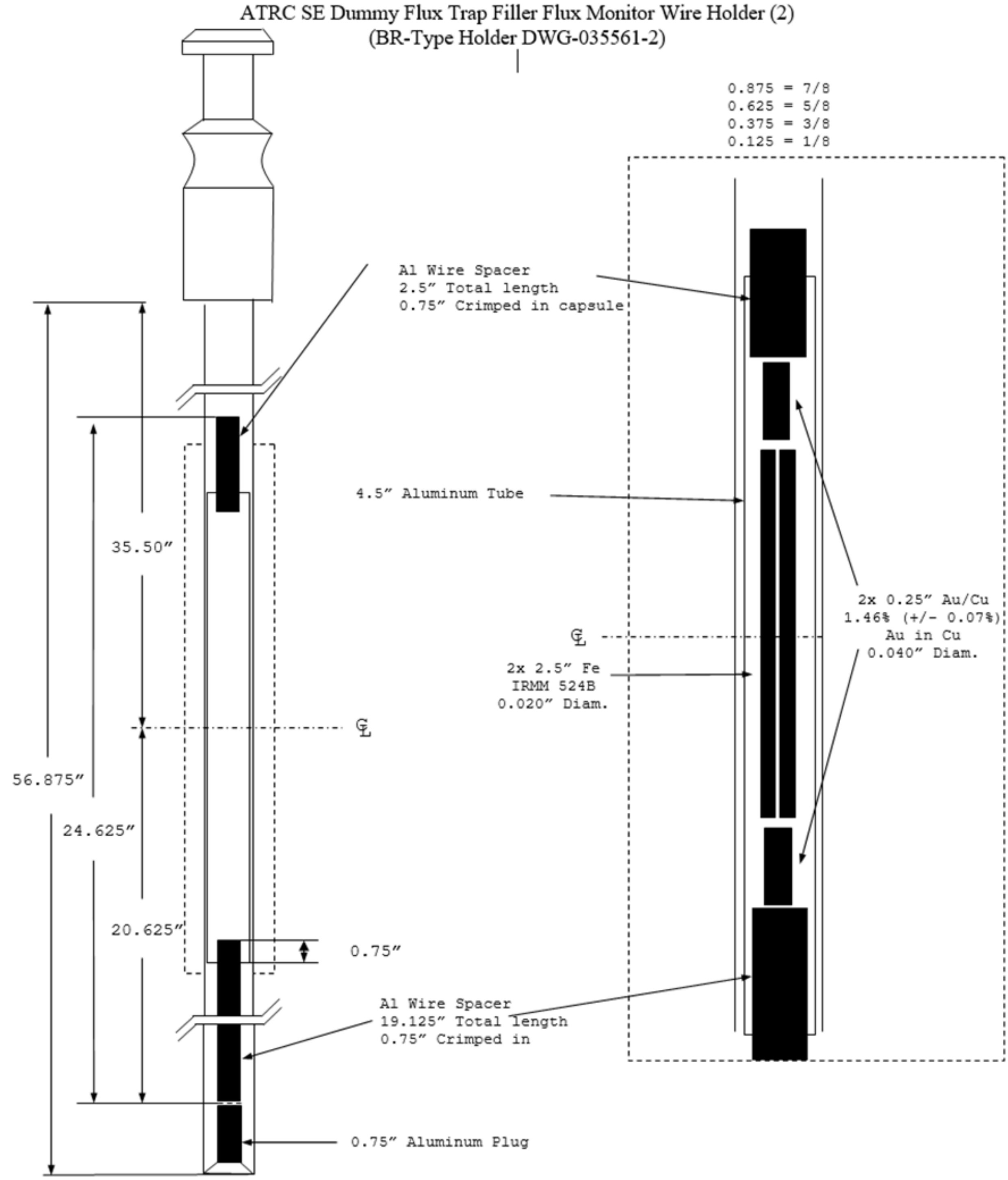
Table III Although they do provide confidence in our ability to activate both traditional and novel dosimetry materials in ATR-C, the measured values do not match with the predicted activities, shown in the computational to experimental (C/E) values. This leaves further room for investigation both on the experimental and computational approaches. First, the assumed a-priori neutron energy profile was a scaled version of the generic spectrum in the same position in ATR. It is well-known that differences exist between ATR and ATR-C which could impact the neutron energy spectrum, and it is recommended that a dedicated model be used in future experiments. Furthermore, several of the dosimeters required multiple measurements to capture activity from reaction products of various half-lives. This experience has already improved measurement techniques by illustrating the importance of measurement sequence, indicated in the reduced uncertainty in the iron wire activities measured in both flux runs 23-4 and 24-1. As indicated in Table 3, our predictions indicated that the iron activation between flux run 23-4 and 24-1 should be the same. These results did not match as well as expected. The measurement uncertainty and minimum detectable activity for activation in the 23-4 run was much higher. This was observed during the measurement process and improved for the 24-1 run. Further, the specific location (see Appendix A and Appendix B) was slightly different. At the core centerline region, this small difference shouldn't matter much but could contribute to the difference. The availability of numerous HPGe detectors was critical in our ability to accurately measure many of these dosimeters. It was only possible to conduct the long measurement of several of the low-activity reaction products by measuring the samples for several days. If only one or two detectors were used for these measurements the activity of other important reaction products would have decayed while competing measurements were taking place. For future irradiation experiments, careful consideration of the counting plan should be made to ensure that sufficient resources (both time and hardware) are available to measure the reactions of interest. The project planning team will have to make decisions regarding the amount and selection of dosimetry materials to balance the ability to measure the samples. This may require multiple irradiations for future experiments, expansion of counting capabilities, or reduced dosimetry. Further improvement could be made, however, by using detectors with higher counting efficiency and by performing multiple measurements of each dosimeter on numerous detectors to determine an average and standard deviation for sample activity. The method employed herein relied on only a single measurement of activity in many cases which lends the results to inheriting any biases or systemic issues that could exist in the detectors or methods. These issues could be associated, for instance, with the calibration of the detectors or placement of the sample by the measurement technicians. These problems can only be identified and resolved if sufficient time and resources are available to measure each wire multiple times.

The RML performed quality assurance and quality control checks applicable to the gamma-ray measurement for the detector system utilized for these measurements. The RML gamma-ray counting systems were “in control” for all relevant parameters.

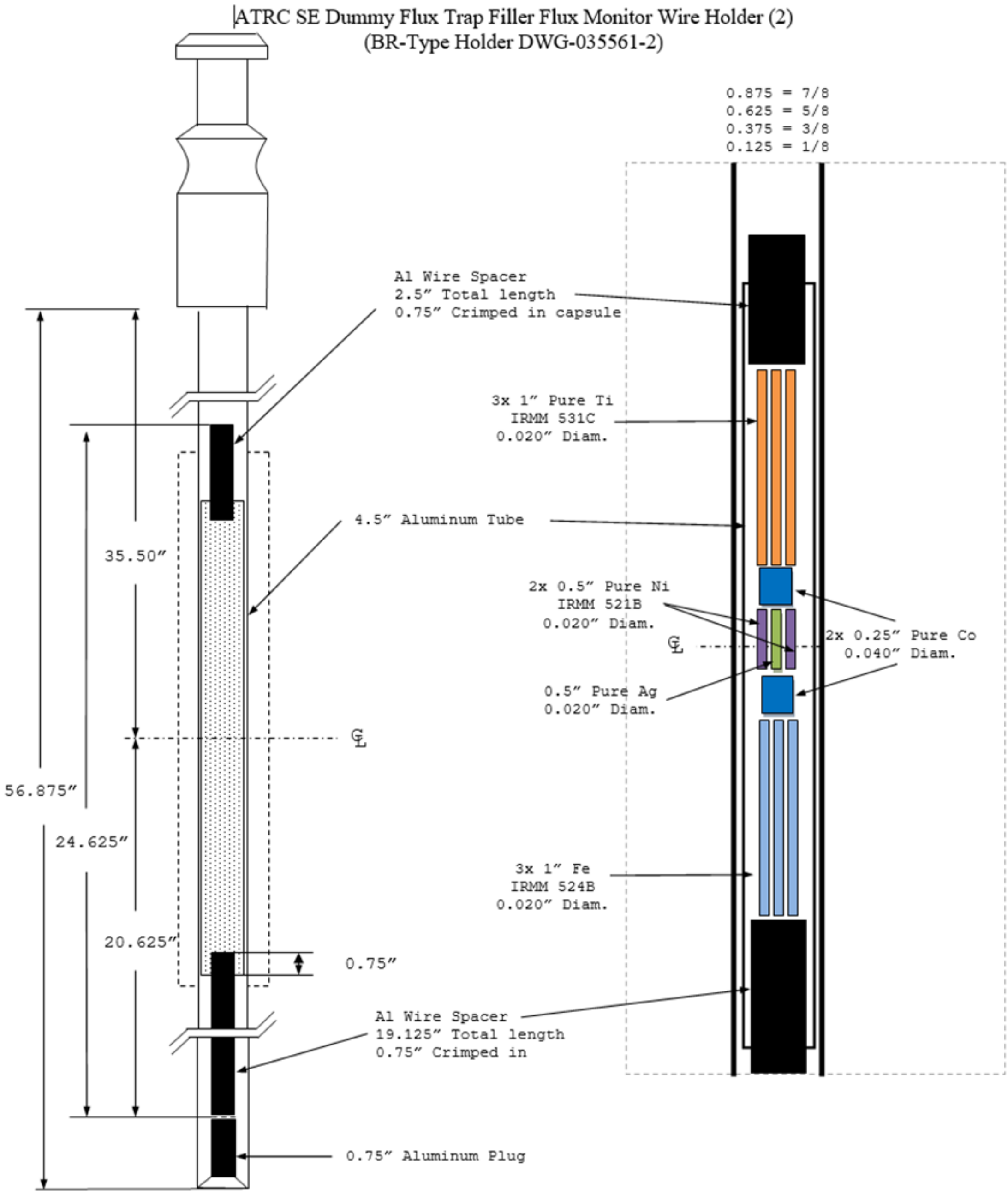
TABLE III
PREDICTED AND MEASURED SPECIFIC ACTIVITIES FOR DOSIMETRY INTERACTIONS IN ATR-C FLUX RUNS 23-4 AND 24-1.

Element	Interaction	Predicted Activity (uCi/g)	SE-2 Measured Activity (uCi/g)	Total Uncert. (%) 2σ	C/E SE-2	SE-4 Measured Activity (uCi/g)	Total Uncert. (%) 2σ	C/E SE-4	SE-2/SE-4
Ti	^{46}Ti (n,p) ^{46}Sc [6]	1.74E-05	4.46E-05	17.86%	0.39	2.49E-04	9.51%	0.070	0.18
Ti	^{47}Ti (n,p) ^{47}Sc [6]	6.29E-04	1.34E-03	3.65%	0.47	1.65E-02	3.47%	0.038	0.08
Ti	^{48}Ti (n,p) ^{48}Sc [6]	1.74E-04	2.88E-04	7.26%	0.60	2.08E-03	4.26%	0.083	0.14
Co	^{59}Co (n,γ) ^{60}Co [7]	6.59E-02	3.97E-02	3.06%	1.66	5.39E-02	3.06%	1.22	0.74
Co	^{59}Co (n,α) ^{56}Mn [7]	7.78E-04	6.01E-01	3.17%	0.00129	8.08E-01	3.20%	0.00096	0.74
Ni	^{58}Ni (n,p) ^{58}Co [8]	6.53E-04	1.86E-03	9.37%	0.35	1.17E-03	16.36%	0.56	1.59
Ag	^{109}Ag (n, γ) ^{110m}Ag [7]	2.97E-02	1.07E-02	6.57%	2.77	1.16E-02	6.26%	2.55	0.92
Fe	^{54}Fe (n,p) ^{54}Mn [9]	1.97E-05	3.29E-05	18.73%	0.60	4.16E-05	17.00%	0.47	0.79
Fe	^{56}Fe (n,p) ^{56}Mn [9]	4.95E-03	2.29E-02	4.88%	0.22	1.84E-02	4.00%	0.27	1.24
Fe	^{58}Fe (n, γ) ^{59}Fe [9]	2.73E-04	3.25E-04	9.19%	0.84	2.59E-04	23.26%	1.05	1.25
Fe	^{54}Fe (n,p) ^{54}Mn [9]	1.97E-05	-	-	-	5.87E-05	48.03%	0.34	-
Fe	^{56}Fe (n,p) ^{56}Mn [9]	4.95E-03	-	-	-	1.93E-02	25.65%	0.26	-
Fe	^{58}Fe (n, γ) ^{59}Fe [9]	2.73E-04	3.13E-04	44.19%	0.87	3.89E-04	70.19%	0.70	0.80
Cu	^{63}Cu (n, γ) ^{64}Cu [10]	1.37E+01	1.49E+01	8.81%	0.92	1.66E+01	9.33%	0.82	0.90
Cu	^{63}Cu (n, α) ^{60}Co [10]	2.29E-07	-	-	-	3.11E-04	29.06%	0.00073	-
Au	^{197}Au (n, γ) ^{198}Au [1]	7.09E+01	6.76E+01	6.91%	1.05	8.00E+01	7.11%	0.89	0.84

APPENDIX A


ATRC SE Dummy Flux Trap Filler Flux Monitor Wire Holder (2)
(BR-Type Holder DWG-035561-2)
0.875 = 7/8
0.625 = 5/8
0.375 = 3/8
0.125 = 1/8
Al Wire Spacer
2.5″ Total length
0.75″ Crimped in capsule
4.5″ Aluminum Tube
35.50″
2x 0.25″ Au/Cu
1.46% (+/- 0.07%)
Au in Cu
0.040″ Diam.
CL
2x 2.5″ Fe
IRMM 524B
0.020″ Diam.
56.875″
24.625″
20.625″
0.75″
Al Wire Spacer
19.125″ Total length
0.75″ Crimped in
0.75″ Aluminum Plug

APPENDIX B



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