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Developing a Safe Test System for High-energy Electron Flux Environments Testing

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Radiation Safety Design For High Energy Electron Flux Environments Testing

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Radiation in Space

Spacecraft in low earth orbit (LEO) through geostationary Earth orbit (GEO) undergo significant electron flux from trapped particles in earth's magnetosphere due to solar wind [1]. Solar wind is the continuous flow of high energy electrons, protons and free ions ejected from the sun through coronal holes.

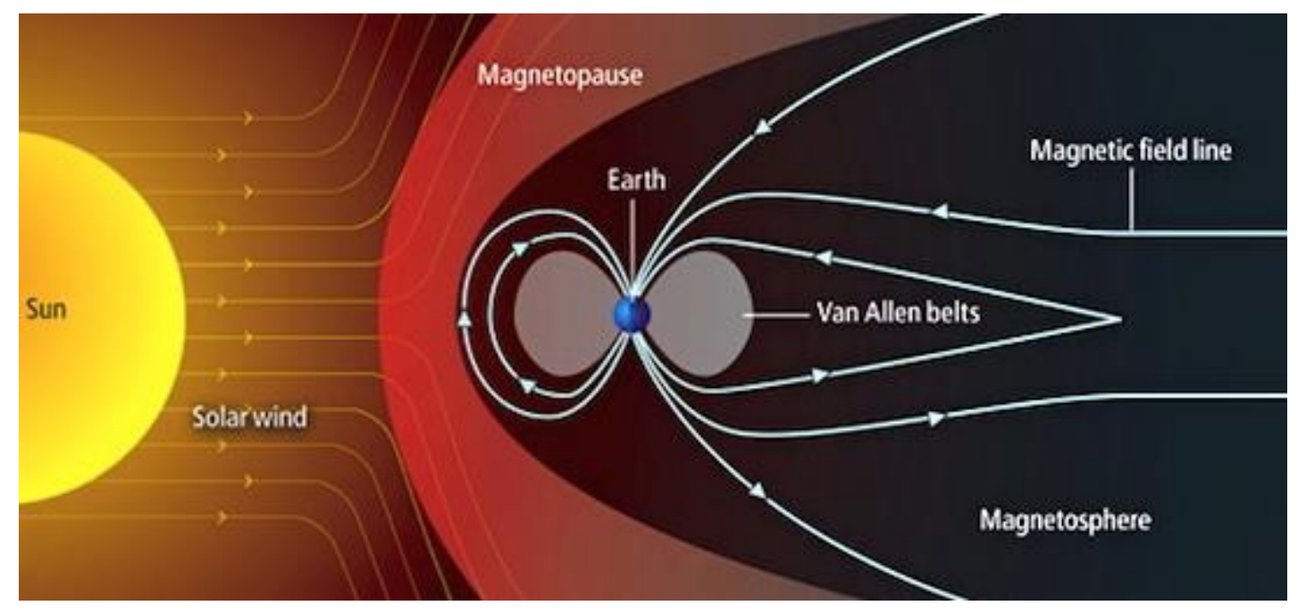


Figure 4 Solar wind and Earth's magnetosphere structure.

Electron radiation can damage sensitive electronics, alter optical properties, deteriorate components, and reduce the overall lifetime of satellites and spacecraft [2].

Mimicking the Electron Energy Spectra of LEO/GEO

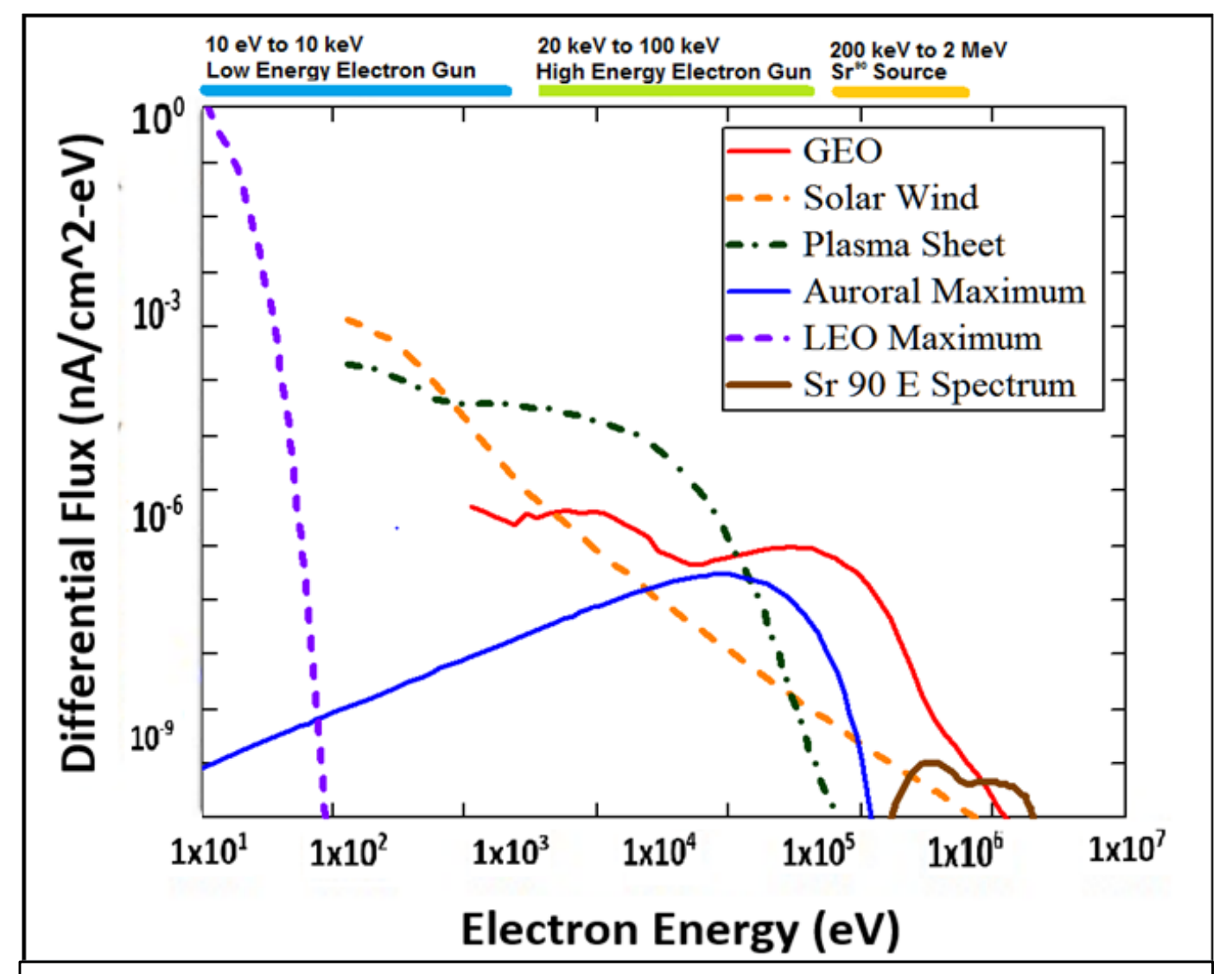


Figure 2 Representative electron flux spectra for geostationary earth orbit, solar wind at the mean earth orbital distance, plasma sheet environment, maximum aurora environment, and low earth orbit. The Sr^{90} source emission spectrum is also show [3]

A 100 mCi Sr-90 beta radiation source approximately mimics the high energy electron spectra of GEO. The source was installed into the SST chamber to irradiate various materials, in-the-loop hardware, and components in order to forecast radiation damage, predict lifetimes of electronics, and authenticate the ability of the test chamber to mimic space environment.

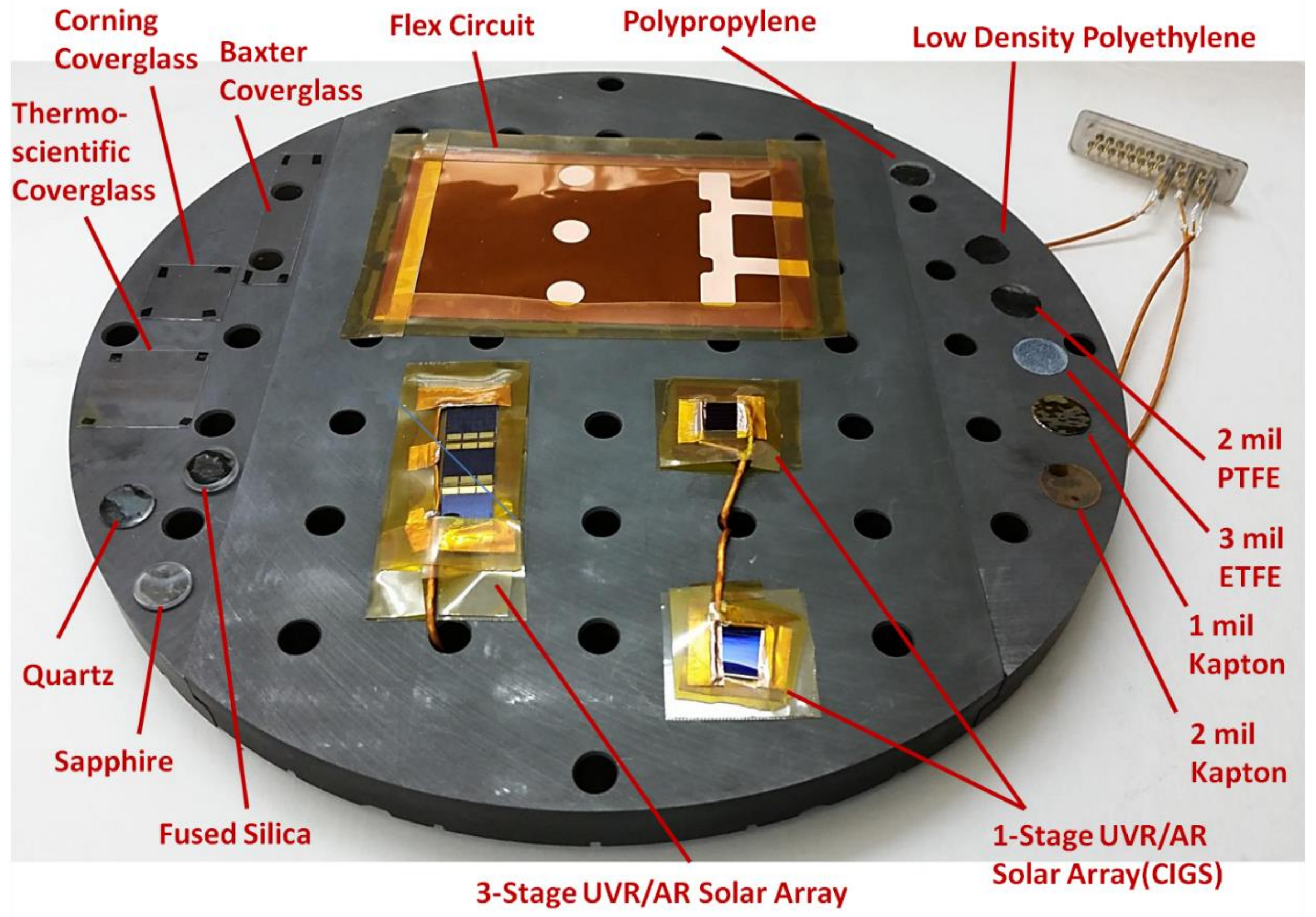


Figure 3 Sample plate with various optical, materials, and electrical samples attached.

Simulation Capabilities

The Space Survivability Test (SST) chamber is a versatile accelerated ground-based test facility designed to simulate environmental-induced modifications in LEO/GEO. Simulation capabilities include neutral gas atmosphere and vacuum environments ($< 10^{-6}\ Torr$), temperature ($\sim 60\ K - 450\ K$), ionizing radiation, electron fluxes ($\sim 10\ eV - 2.5\ MeV$), and photon fluxes ranging from far-ultraviolet to near-infrared (FUV/VIS/NIR).

Overview

In order to predict and mitigate adverse environmental effects prone to spacecraft in orbit about Earth, a versatile pre-launch test capability for assessment and verification of small satellites, systems, and components was developed by Utah State University's Materials Physics Group. To further diversify this project, a 100 mCi Sr-90 beta radiation source (0.5 MeV – 2.5 MeV) was exploited to simulate high energy electron flux characteristic of geostationary orbit. Various samples including in-the-loop hardware, spacecraft materials, optical components, and solar arrays are irradiated to gain a better understanding of how these materials and electronics break down in space environments. For employee protection, various high and low-Z shielding materials were implemented to minimize x-ray dose rates near the test chamber. In order to forecast employee dose while working around the source, x-ray attenuation through the various shielding materials was calculated. Upon discovering a deficiency in shielding capability, additional lead shielding was implemented to lower dose rates outside of the test chamber to nearly background. Prediction of attenuated dose rates strongly correlate with actual measurements post installation of the source.

The Space Survivability Test Chamber

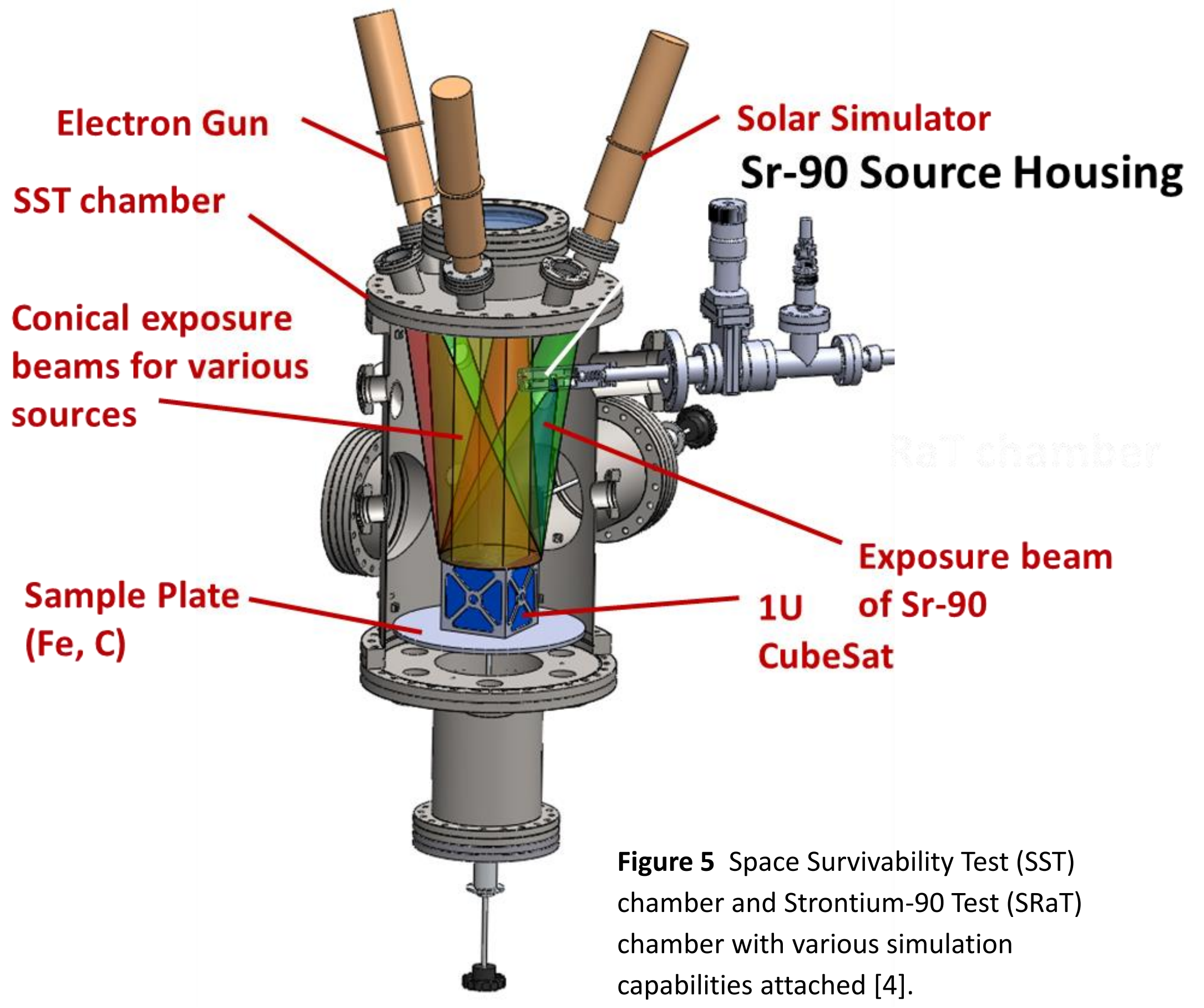


Figure 5 Space Survivability Test (SST) chamber and Strontium-90 Test (SRaT) chamber with various simulation capabilities attached [4].

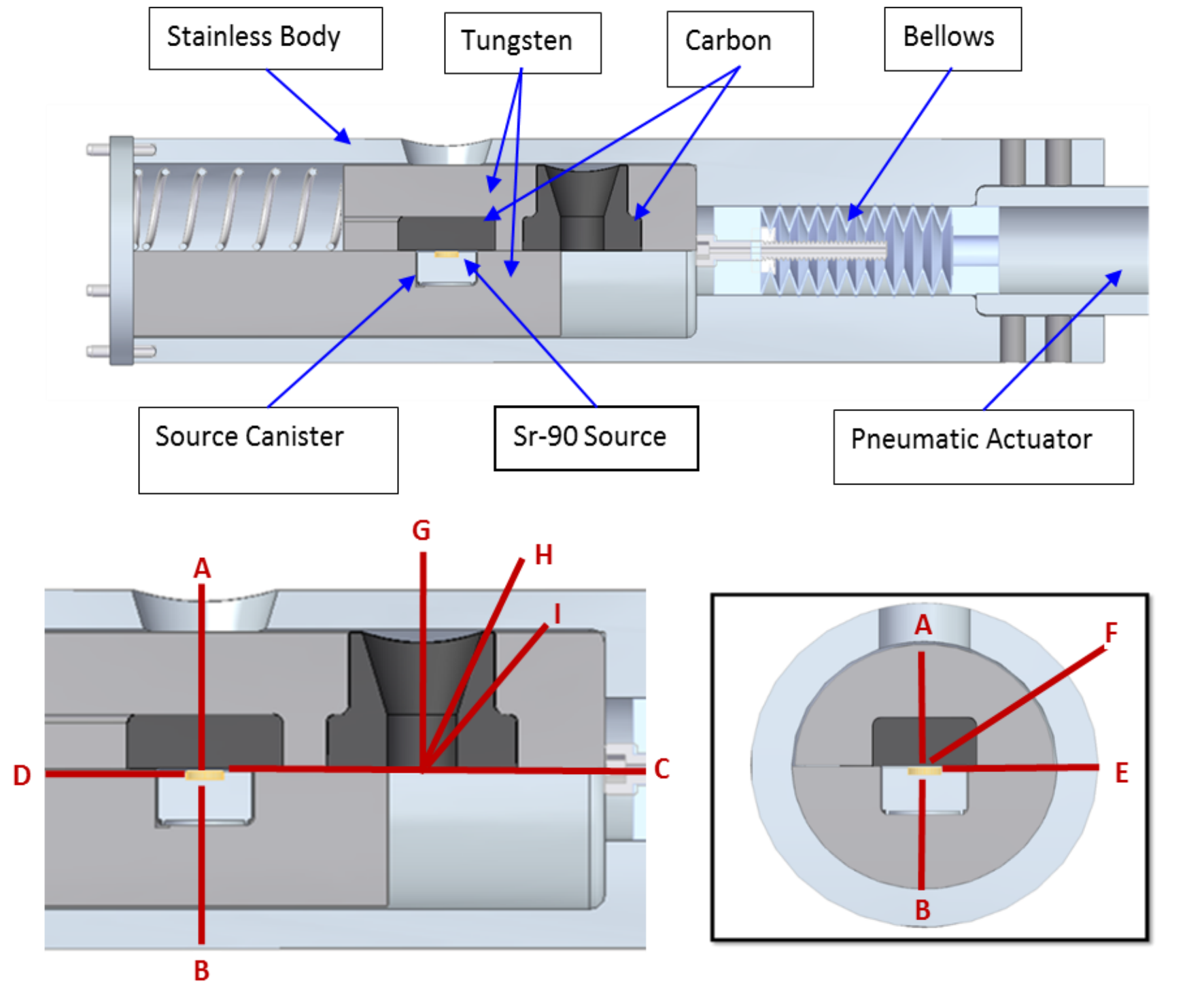


Figure 4. (Top) source housing shielding design. (Bottom) Cross section of various paths through shielding materials. **A** – Storage position, in direction of radiation beam, **B** – Opposite the beam of radiation, **C** – Towards the actuator rod. **D** – Toward the housing end cap, **E** – In the plane of the Sr-90 source, directly outward from the housing, **F** – 45° from the plane of Sr-90 source, **G** – Exposure position, **H** – 15° from exposure position, **I** – 45° from exposure position

Scattering Length and X-ray Attenuation of Shielding Materials

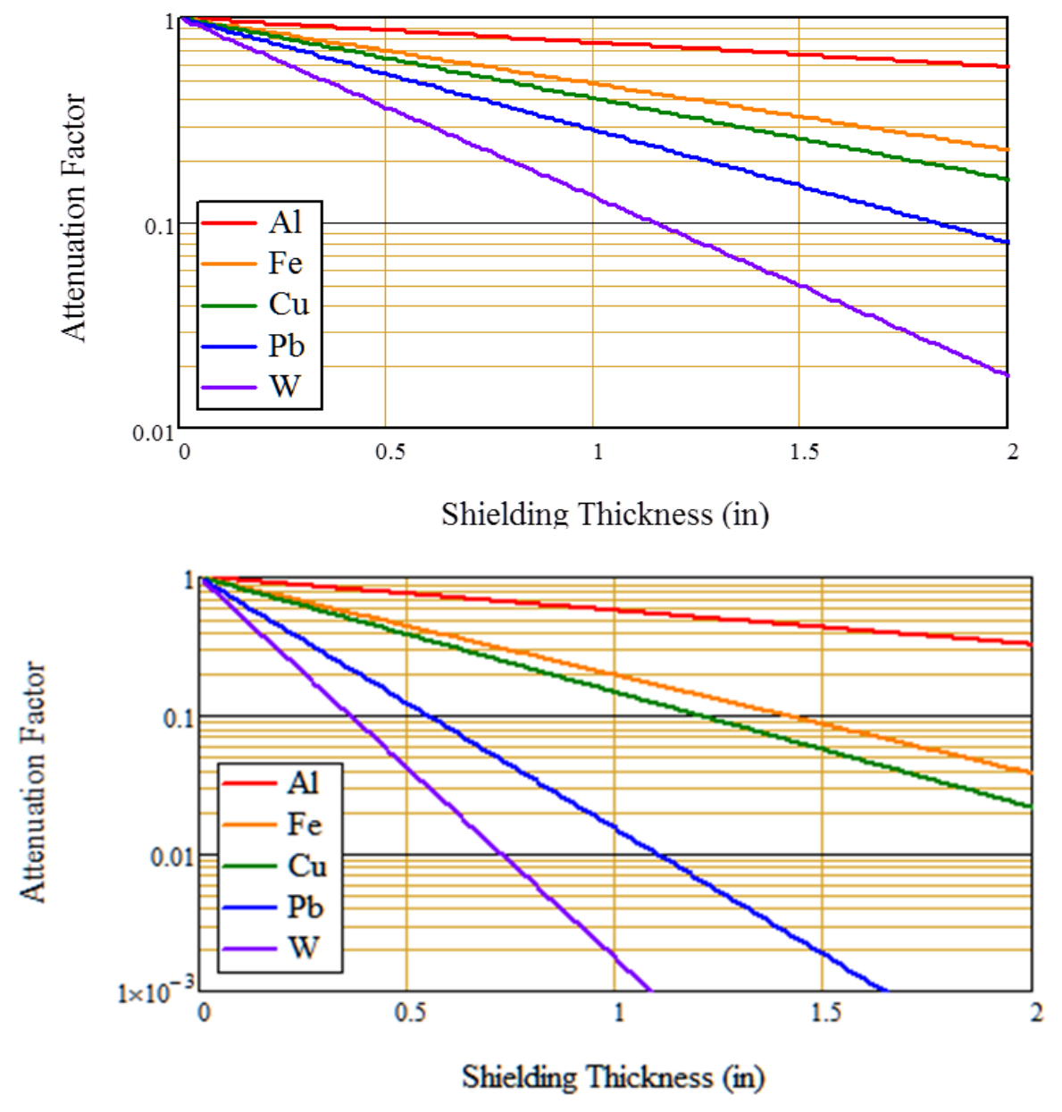


Figure 7 X-ray attenuation for relevant shielding materials for 2.5 MeV (top) and 2.5 MeV (bottom).

Attenuation depends on the thickness and density a material.

$$I(x) = I_0\, e^{-\alpha x} = I_0\, e^{-\frac{x}{L}}$$

$$L = \frac{1}{\mu\rho}$$

μ – mass attenuation coefficient
α – linear attenuation coefficient
ρ – density
x – thickness
I – intensity of radiation
L – scattering length

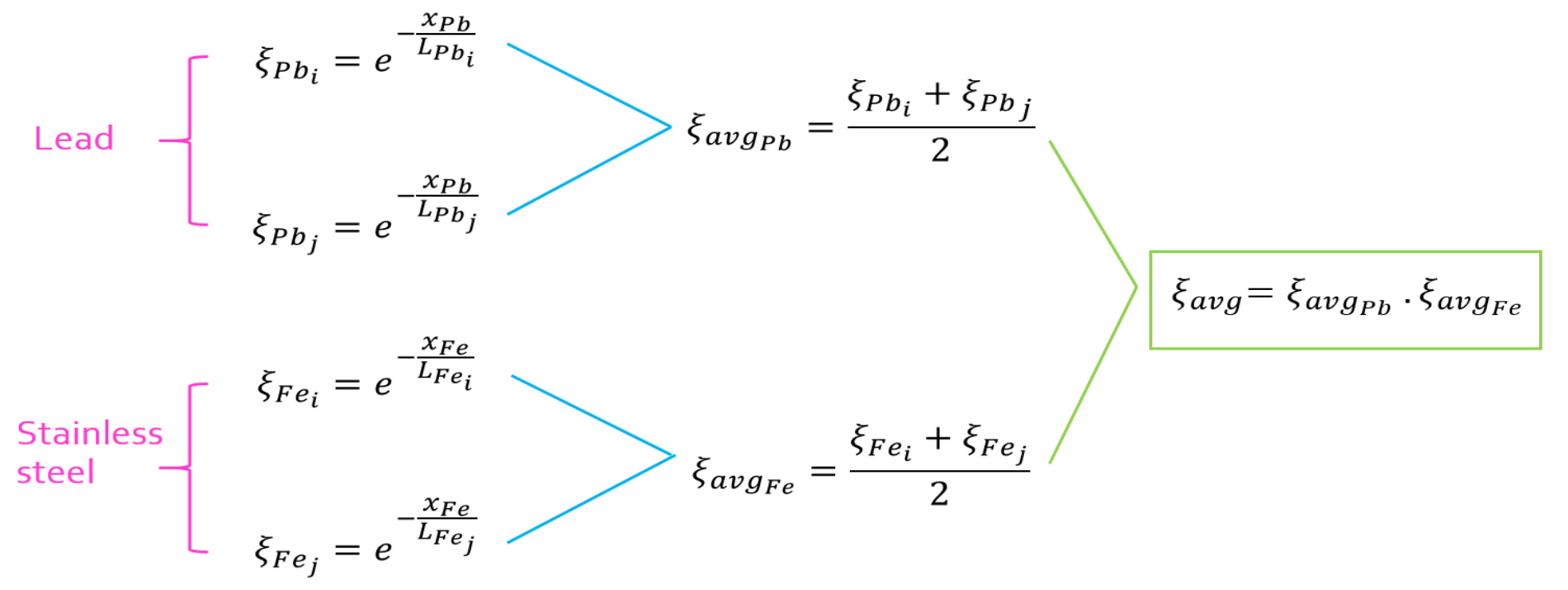
MATERIAL	$\mu\ \left(\frac{cm^2}{g}\right)$	$\rho\ \left(\frac{g}{cm^2}\right)$	$L\ (cm)$
Pb	0.14	11.8	0.61
Cu	0.085	8.9	1.3
Al	0.082	2.7	4.5
W	0.13	19.25	0.4
Fe	0.082	7.87	1.5

MATERIAL	$\mu\ \left(\frac{cm^2}{g}\right)$	$\rho\ \left(\frac{g}{cm^2}\right)$	$L\ (cm)$
Pb	0.042	11.8	2.0
Cu	0.040	8.9	2.8
Al	0.040	2.7	9.3
W	0.041	19.25	1.3
Fe	0.037	7.87	3.4

Figure 6 Scattering lengths for 0.5 MeV (top) and 2.5 MeV (bottom) electron energies of Sr-90 source.

With these predicted scattering lengths, the attenuation factor ξ was calculated through each shielding material. The attenuation factor simply represents the percent of radiation that gets through the material.

$$\xi = \frac{I(x)}{I_0} = e^{-\frac{x}{L}}$$



$$\xi_{Pb_i} = e^{-\frac{x_{Pb}}{L_{Pb_i}}} \qquad \xi_{Pb_j} = e^{-\frac{x_{Pb}}{L_{Pb_j}}} \qquad \xi_{avg_{Pb}} = \frac{\xi_{Pb_i} + \xi_{Pb_j}}{2}$$

$$\xi_{Fe_i} = e^{-\frac{x_{Fe}}{L_{Fe_i}}} \qquad \xi_{Fe_j} = e^{-\frac{x_{Fe}}{L_{Fe_j}}} \qquad \xi_{avg_{Fe}} = \frac{\xi_{Fe_i} + \xi_{Fe_j}}{2}$$

$$\boxed{\xi_{avg} = \xi_{avg_{Pb}} \cdot \xi_{avg_{Fe}}}$$

Results

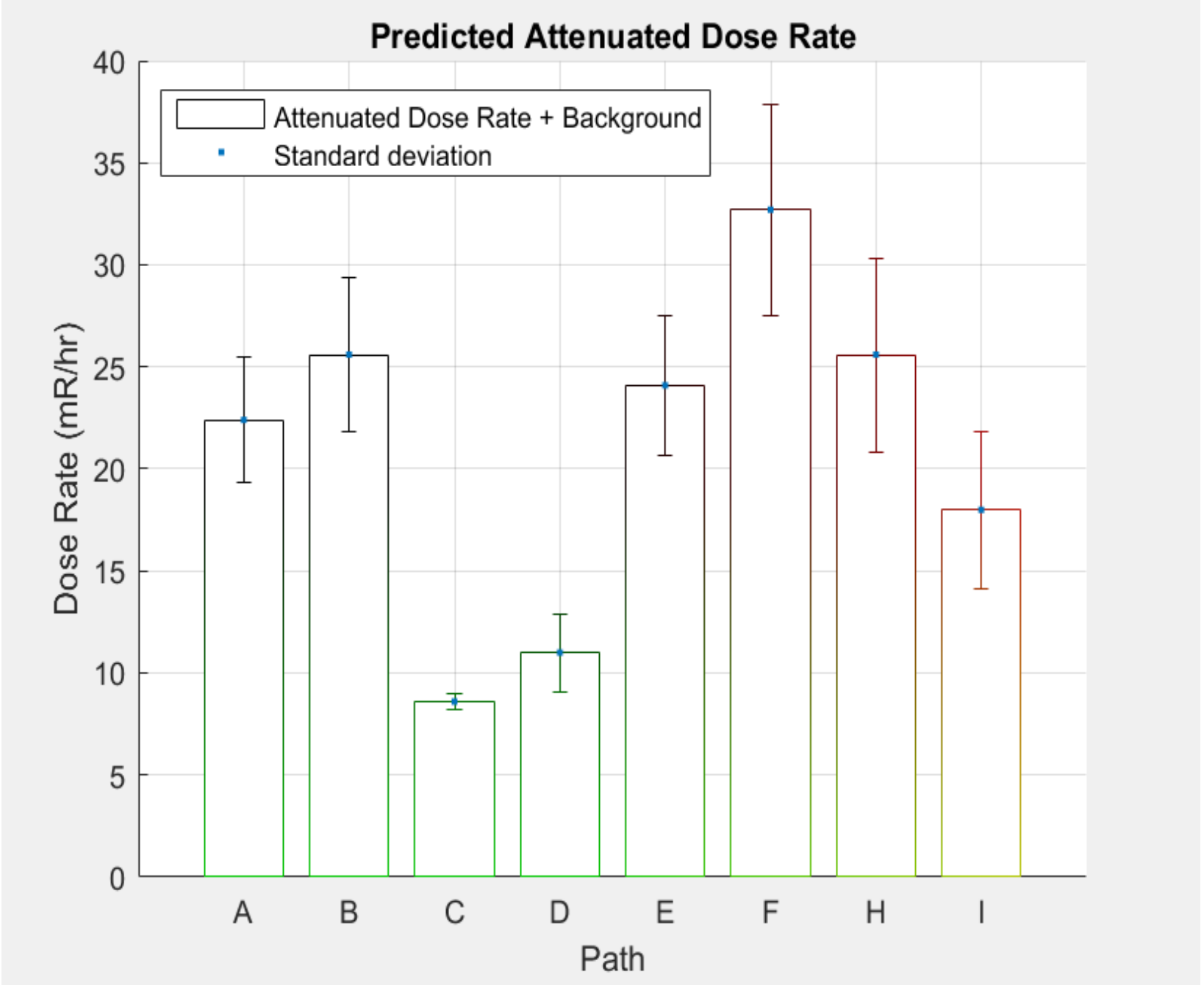


Figure 8 Predicted attenuated dose rates along paths described in Figure 4

	Exposure Position	Storage Position
Path	Preliminary dose rate (d) (mR/hr)	Attenuated dose rate (D) (mR/hr)
A	81.0 ± 0.05	15.4 ± 3.09
B	98.0 ± 0.05	18.6 ± 3.75
C	1.7 ± 0.05	1.3 ± 0.38
C'	2.2 ± 0.05	1.6 ± 0.49
D	6.5 ± 0.05	4.0 ± 1.89
D'	0.17 ± 0.05	0.1 ± 0.066
E	90.0 ± 0.05	17.1 ± 3.44
F	135.0 ± 0.05	25.7 ± 5.16
G	822000.0 ± 0.05	-
H	116.0 ± 0.05	18.6 ± 4.75
I	105.0 ± 0.05	11 ± 3.86

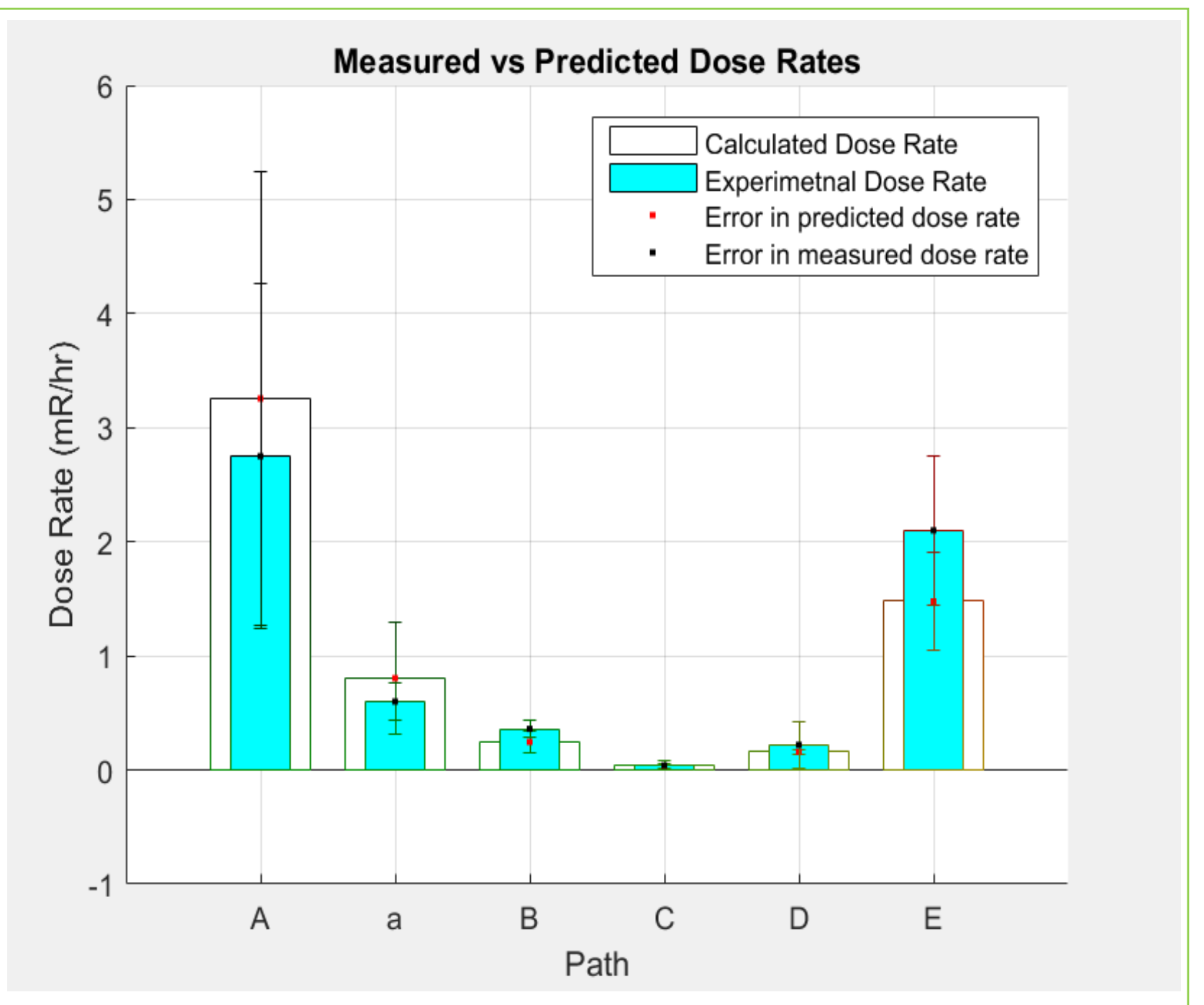


Figure 9 Predicted attenuated dose rates plotted against actual measured values along certain paths

Path	Direction	% Diff	Average % Diff
A	10 ± 3 cm above unshielded source housing	16.86	26.72
a	10 ± 3 cm above shielded source housing	29.07	
B	20 ± 5 cm below shielded source housing	37.63	
C	20 ± 5 cm toward pillow block	10.52	
D	15 ± 3 cm away from the housing end cap	31.58	
E	2 ± 1 cm outside of Pb shielding	34.68	

Error Analysis

The standard deviation for the predicted attenuated dose rate was calculated by adding error in quadrature as

$$\sigma D = \left[\sigma d^2 \left(\frac{\partial}{\partial d} D\right)^2 + \sigma L_{Fe_i}^2 \left(\frac{\partial}{\partial L_{Fe_i}} D\right)^2 + \sigma L_{Fe_j}^2 \left(\frac{\partial}{\partial L_{Fe_j}} D\right)^2 + \sigma L_{Pb_i}^2 \left(\frac{\partial}{\partial L_{Pb_i}} D\right)^2 \right.$$
$$\left. + \sigma L_{Pb_i}^2 \left(\frac{\partial}{\partial L_{Pb_i}} D\right)^2 + \sigma x_{Fe}^2 \left(\frac{\partial}{\partial x_{Fe}} D\right)^2 + \sigma x_{Pb}^2 \left(\frac{\partial}{\partial x_{Pb}} D\right)^2 \right]^{\frac{1}{2}}$$

The χ^2 value for the predicted attenuated dose rates against he actual measured values was calculated as

$$\chi^2 = \sum \left(\frac{(MD - CD)^2}{\sqrt{(\sigma_{CD})^2}} \right)$$

Where MD is the measured dose rates, σ_{MD} is the error in MD, and CD is the calculated dose rates. This calculation provides

$$\chi^2 = 10.03$$

Conclusion

A safe test system for simulating high energy electron flux was developed. In order to ensure legal and safe employee dose, predictions of dose rate through the Sr-90 source shielding were calculated. The χ^2 value is about the number of data points (Figure 9), which provides a good argument that the calculated dose are well correlated with the actual measured values. Predicted values were thus calculated correctly and reflect the actual dose rate. Dose rates escaping the tests chamber through the shielding are low enough to allow employees to safely work around the source for extended periods of time. Incorporation of the Sr-90 source has diversified the Space Survivability Test chamber by allowing simulation of high energy electron radiation akin to geostationary orbit.

[1] Alex Souvall, Greg Wilson, Katie Gamaunt, Ben Russon, Heather Tippets and JR Dennison, "Properties of Spacecraft Materials Exposed to Ionizing Radiation," *American Physical Society Four Corner Section Meeting,* Arizona State University, Tempe, AZ, October 16-17, 2015.
[2] Amberly Evans and JR Dennison, "*The Effects of Surface Modification on Spacecraft Charging Parameters*," IEEE Trans. on Plasma Sci., 40(2), 291-297 (2012). DOI: 10.1109/*TSP*.2011.2179676
[3] Greg Wilson, Ben Russon, Alex Souvall, Katie Gamaunt, Heather Tippets, Lisa Phillipps, JR Dennison, and James S. Dyer, *"Small Satellite Materials and Components Space Survivability Assessment with Space Environments Effects Test Facility,"* 30th Annual AIAA/USU Conference on Small Satellites, (Logan, UT, August 8-13, 2016).
[4] Robert H. Johnson, Lisa D. Montierth, JR Dennison, James S. Dyer, and Ethan Lindstrom, *"Small Scale Simulation Chamber for Space Environment Survivability Testing,"* IEEE Trans. on Plasma Sci., 41(12), 2013, 3453-3458. DOI: 10.1109/TPS.2013.2281399