NETS 2025

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Design Methodology of a Pressurized Irradiation Test Apparatus for Stirling Convertor Organics in the Fission Surface Power (FSP) Project

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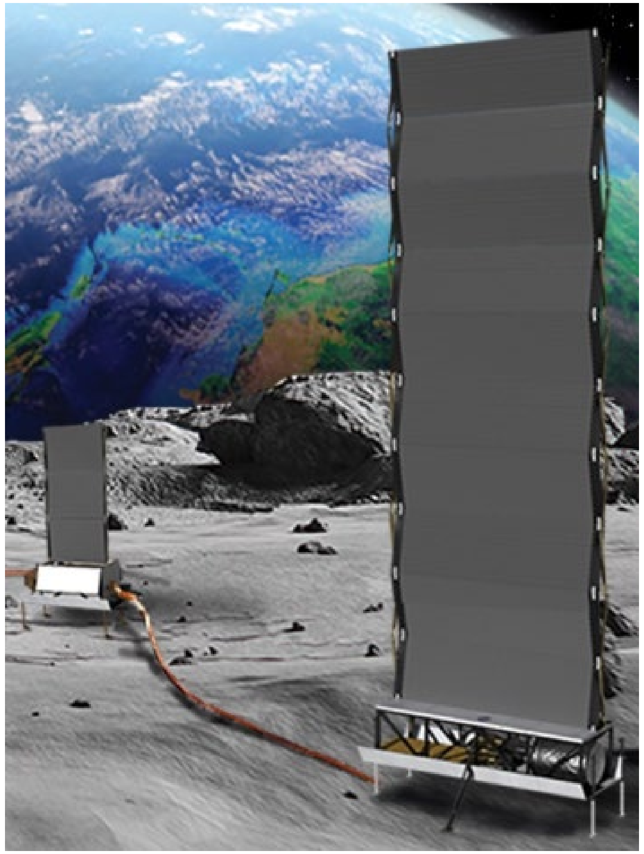
Fission Surface Powder (FSP) Project Overview

- NASA & DOE are developing a 40 kWe fission reactor technology demonstration to be deployed on the lunar surface in the early 2030s for future Mars missions.
- FSP phase 1 design requirements included:
  - Radiation exposure to be limited to 5 rem per year above lunar background 1 km away from the reactor
- NASA Glenn Research Center (GRC) is home of the FSP project and is the leading institution overseeing FSP technology maturation and risk reduction efforts [1].

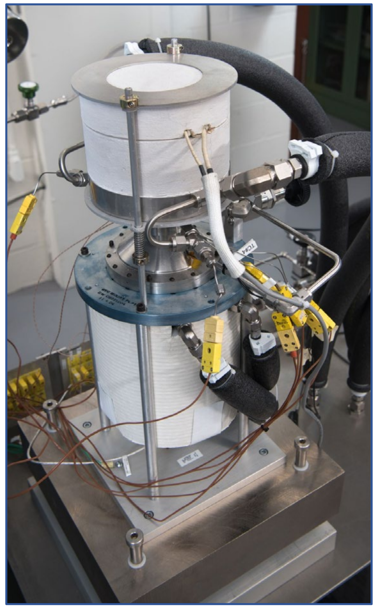


FSP Concept Art

Motivation

Stirling Engine Organics

- Stirling engines have long been studied to provide a means of converting nuclear thermal energy to electrical power due to their high efficiency [2]
- Polymer/organic based materials have been observed to degrade in radiation
  - cross-linking, scissioning, & outgassing [3]
- Outgassing produced by other organic components can cause greater damage necessitating synergetic testing

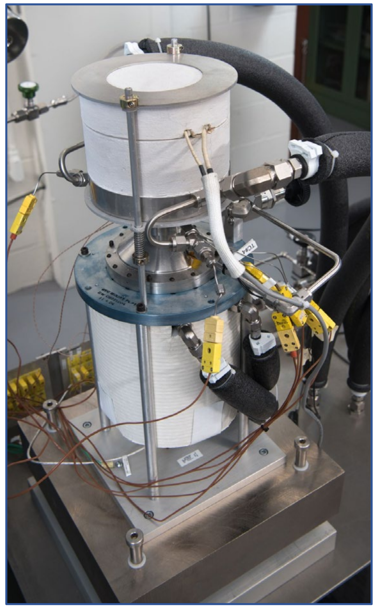


Stirling engine test at GRC [4]

O-ring radiation damage [5]

Motivation Continued

- The organic components of Stirling engines need to be studied under FSP induced radiation conditions.
  - i.e. dry lubricants, O-rings, wire insulation, etc.
- Previous studies have obtained conflicting conclusions [6] [7].
- Can a pressure vessel be designed to survive prolonged temperatures, pressure, and irradiation?

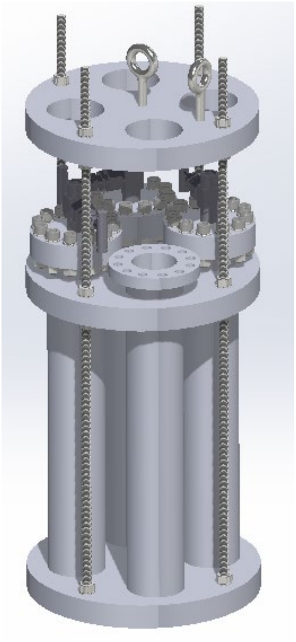


Stirling engine test at GRC [5]

O-ring radiation damage [4]

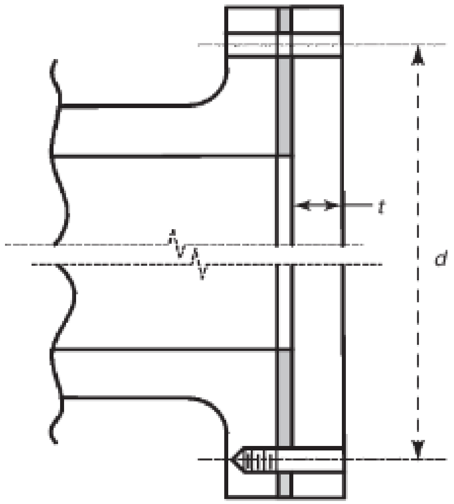
Objective: Design a Heated Pressure Vessel for Irradiation that Minimizes Cost and Activation

Task 1



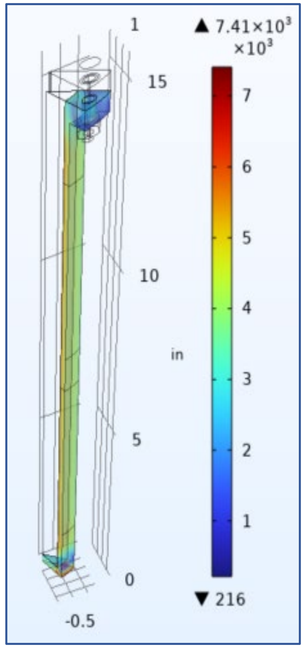
CAD Design

Task 2



ASME Structural Calculations

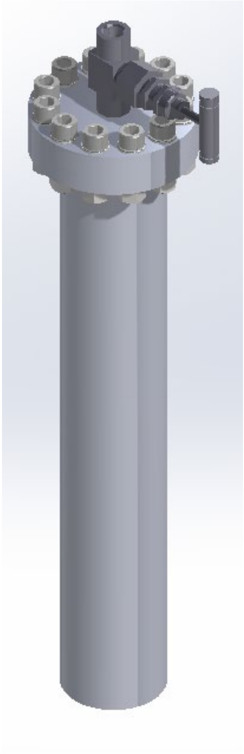
Task 3



Thermo-Mechanical Modeling

- Introduction
  - FSP background & issue
  - Stirling Organics
  - Objective of this project
  - Overview of tasks (design, calcs, MCNP)
- Design Methodology
  - Design parameters
  - Design analysis
- Results and Discussion
  - Design analysis results
  - MCNP results
  - Lessons learned
- Next Steps

Test Conditions Were Selected Based on Modeled FSP Conditions

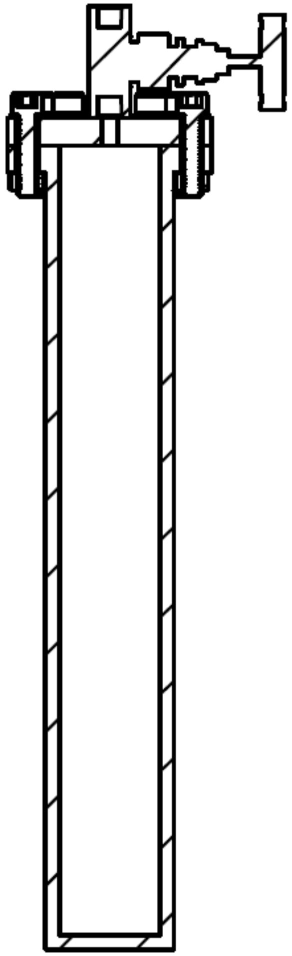


Stirling Organic Pressure Vessel Conditions [8]

Vessel	Temperature [°C]	Max Time [mo]	Pres [psig]	Expected neutron fluence [n/cm^2]	Target gamma dose [krad]	TCs
1	100	12	600	2E16	2.2E4	5
2	130	12	600	2E16	2.2E4	5
3	160	12	600	2E16	2.2E4	5
Open	N/A	N/A	N/A	2E16	2.2E4	0
Control	Ambient	12	600	0	0	5

Material Selection Must Consider Neutron Activation

- Material considerations
  - Neutron flux induces radioactivity (activation) in materials
  - Depending on the material, the activation can be long lived or short lived
  - This restricts the use of common structural materials such as steel
  - Aluminum is preferred, titanium is acceptable
- Activated test structures are difficult to preform post irradiation examination (PIE)



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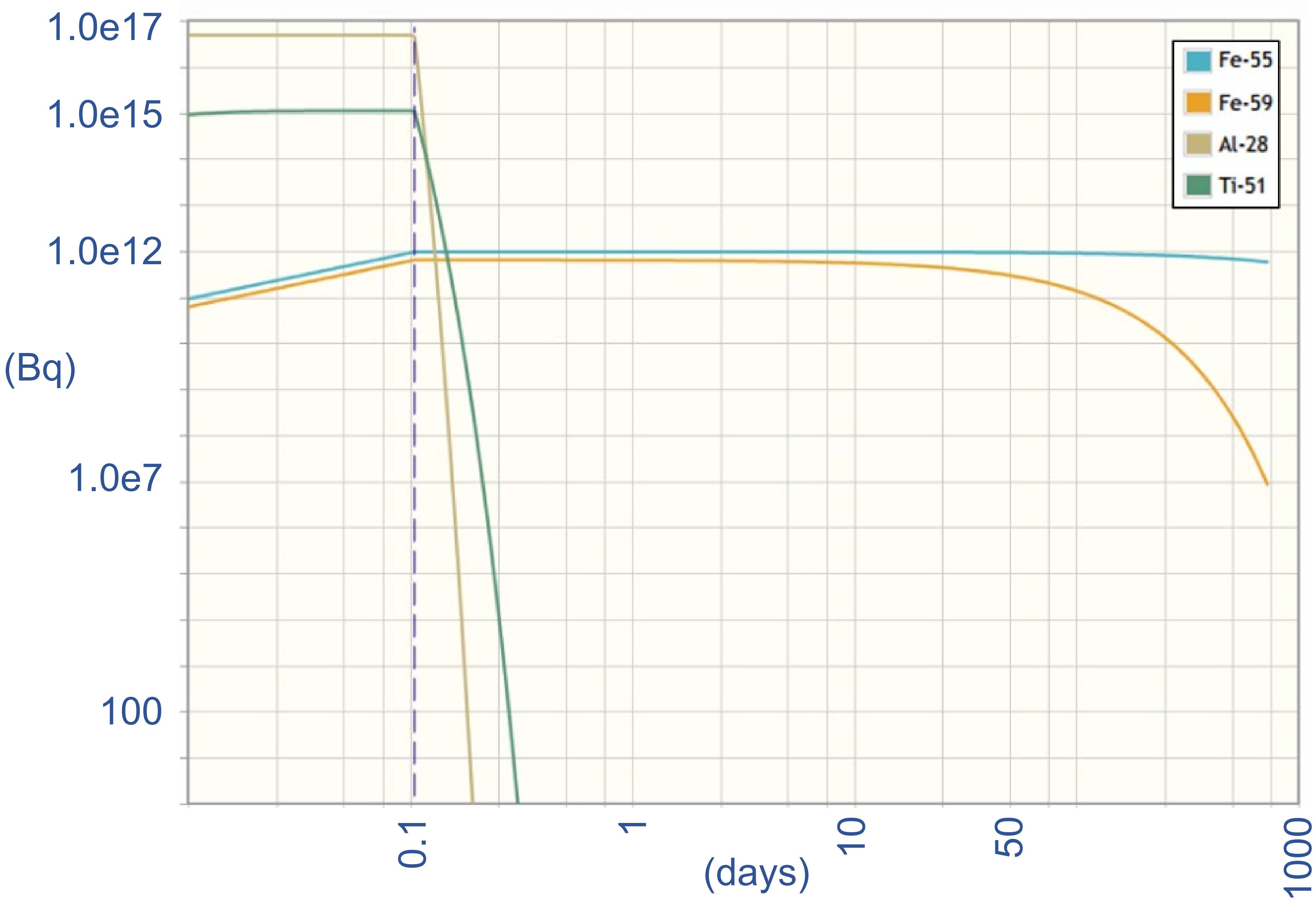
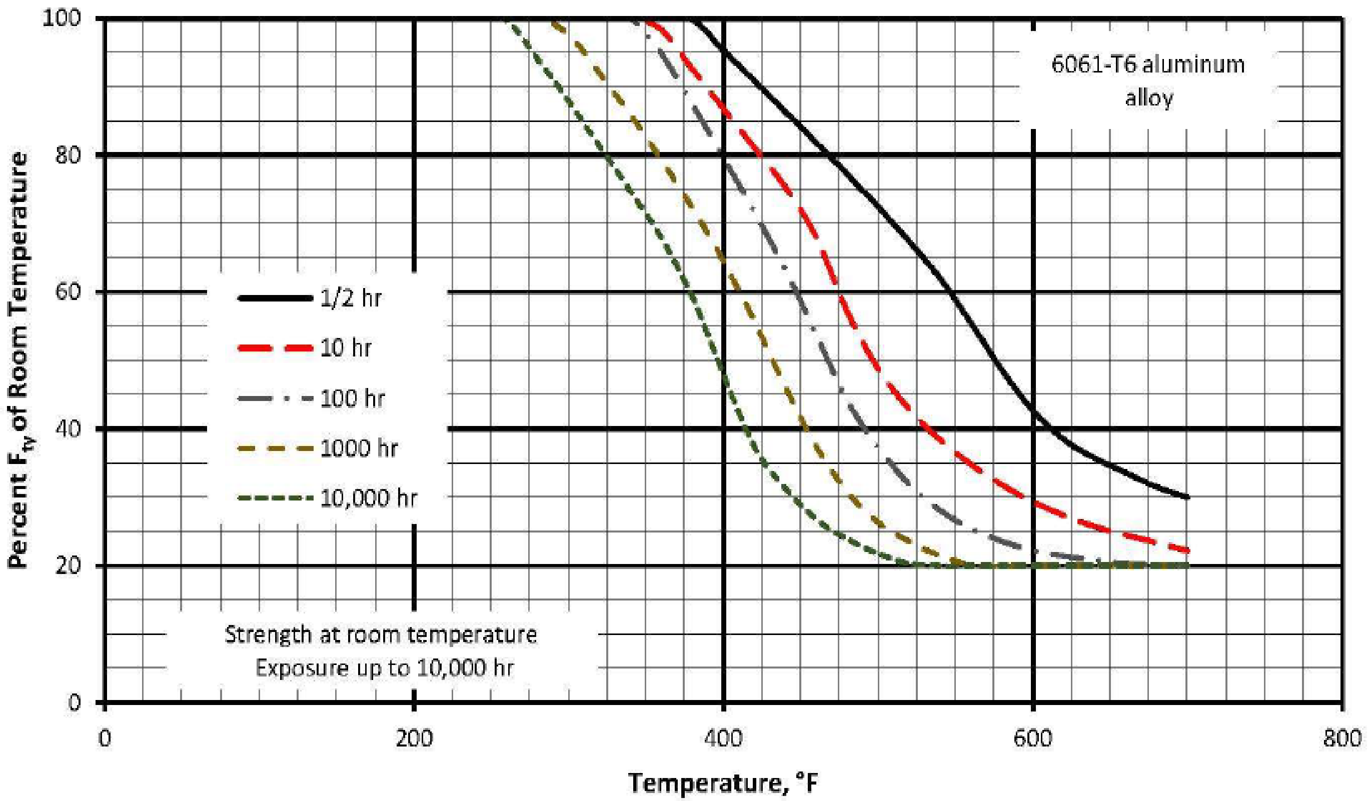
Activation Activity of Iron, Aluminum, and Titanium Over Two Years [9]



Material Selection Must Consider Temperature Degradation of Mechanical Properties

- Temperature dependent material properties were taken from MMPDS-2023
- Materials ideal from an activation standpoint can rapidly drop in mechanical strength at elevated temperatures

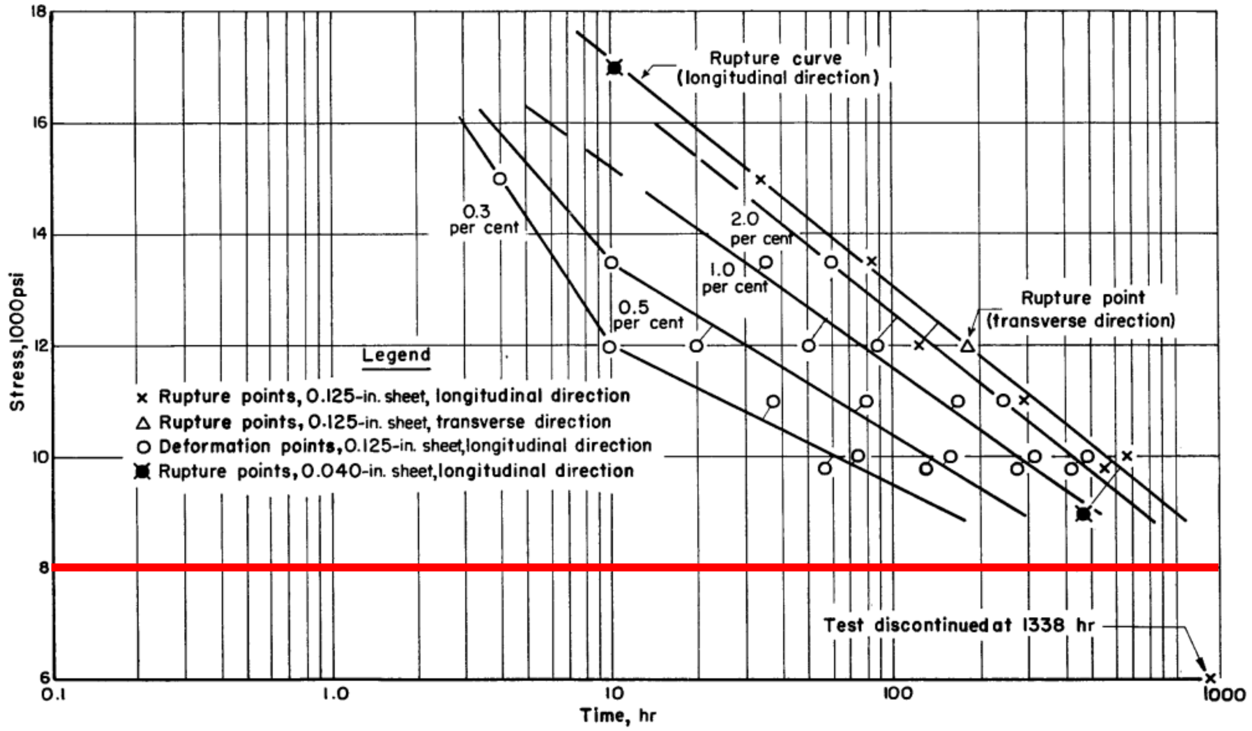


The effect of temperature on the tensile yield strength of 6061-T6 aluminum alloy. Note the rapid drop at 200 °C/400 °F [10]

References Show Acceptable Creep Resistance

Aluminum 6061 T6

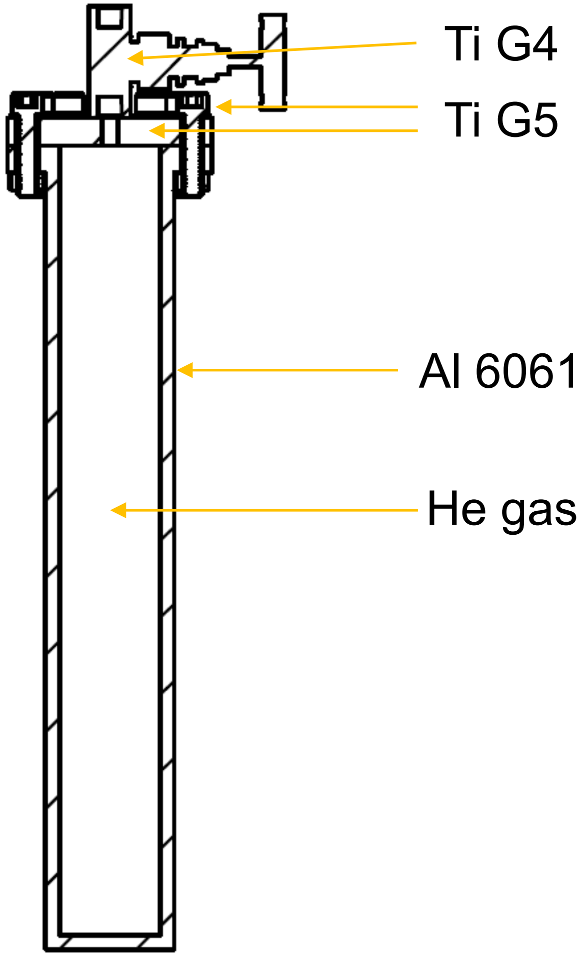
- Pressure vessels may be kept at temperature for up to 12 months
- Creep properties are a concern
- Two sources were checked
  - Both verified design
  - Further analysis merited
- G5 titanium has good creep properties up to 300 °C [11]



Design curves for 6061-T6 Aluminum alloy sheet tested at 450 °F
https://apps.dtic.mil/sti/pdfs/ADA396840.pdf (Pg. 9, Fig. 1)

Material Selection

Component	Material
Pressure Vessel Body	6061 aluminum
Bolts (x12)	Grade 5 titanium
Flange	Grade 5 titanium
Valve	Grade 4 titanium
Basket	G10, aluminum rods, steel eyebolts

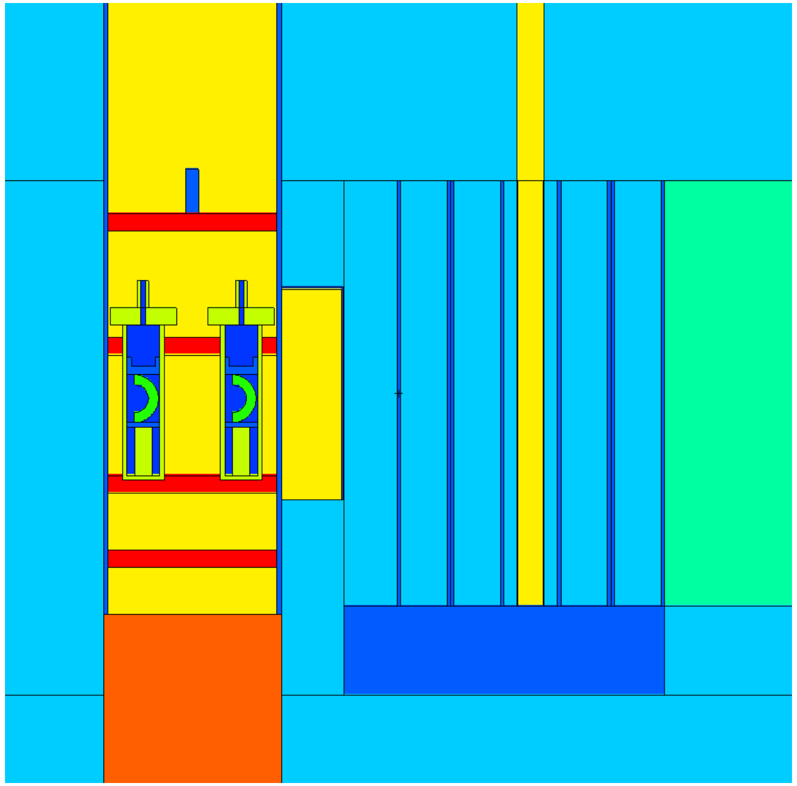


Modeling Supported by Mechanical Calculations Were Used to Justify the Design

- Structural Calculations
  - The bolts were designed via joint calculations from Shigley's Mechanical design and NASA's EFAST design tool [12].
  - The flange was designed in accordance with ASME BPVC Section VIII-1 UG-34 and Section VIII-2 4.6.
  - The structural calculations for the pressure vessel body were done similarly utilizing ASME BPVC Section VIII-2 and ASME B31.3.
- COMSOL Multiphysics® 6.2 was used to model the pressure vessel structural and thermal loads.

Modeling to Verify Sample Dose and Activation Levels

- Monte Carlo Neutral Particle (MCNP) analysis was conducted to determine if the target neutron and gamma fluences could be met with a research reactor.
- SCALE/ORIGEN model was created to determine when the experiment could be handled and shipped following the irradiation.



MCNP model of the basket and four pressure vessels in a research reactor (side view)

- Introduction
  - FSP background & issue
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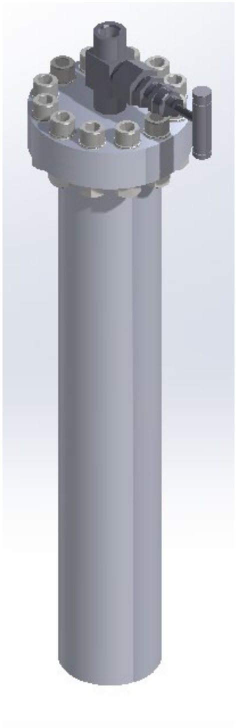
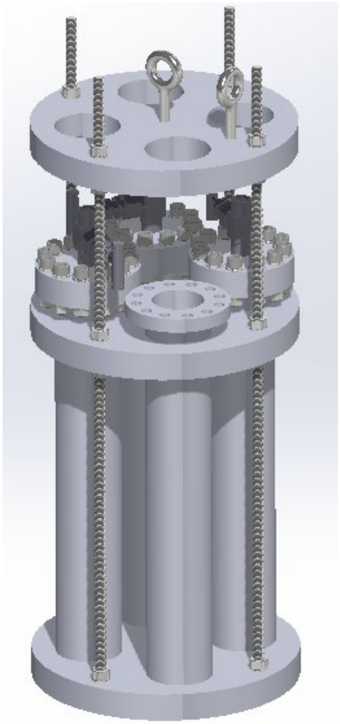
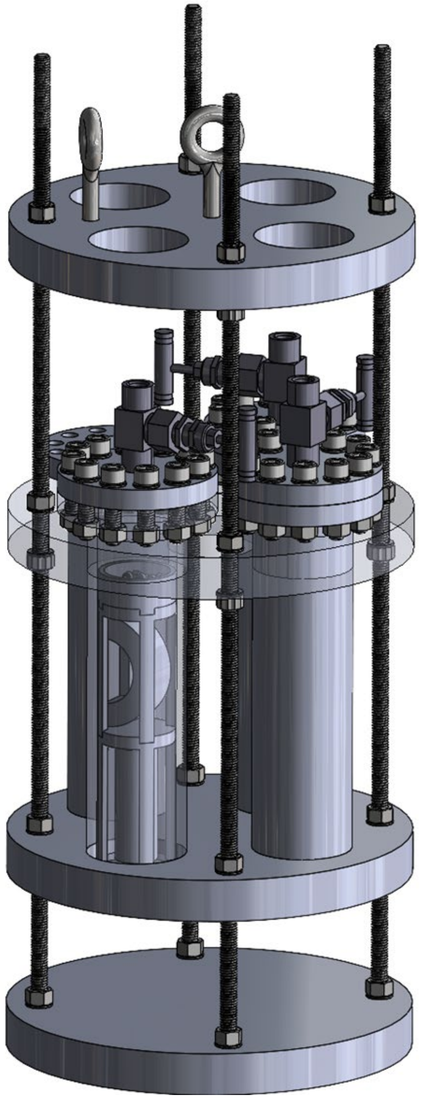
Design Iteration #1



Helium Pressure Vessel
[4X] & Open Vessel [1X]



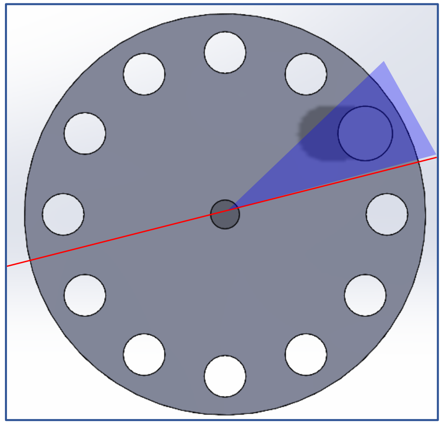
Pressure Vessel Basket
[1X]



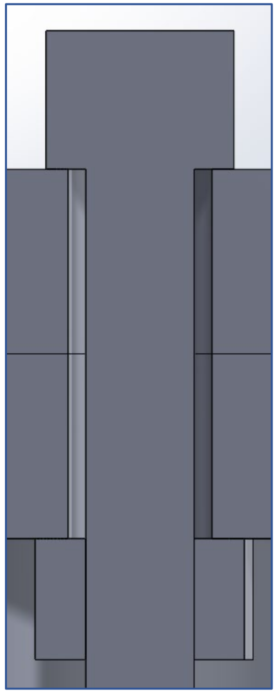
COMSOL Model Setup

- COMSOL Assumptions
  - 1/12th symmetry used
  - Simplified geometry
  - Assumption that density & Poisson's ratio unchanged over temperature
  - Air is 20°C
  - Pressure is double nominal value

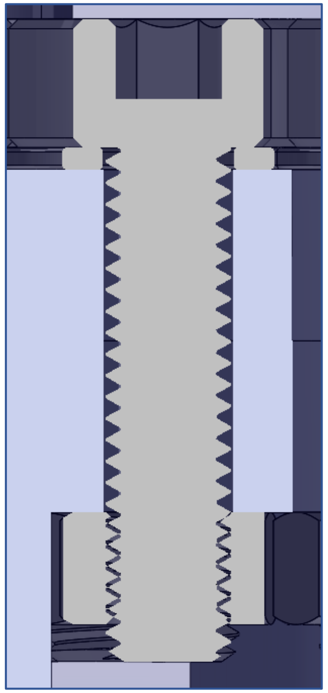
Description	Value
Bolt Preload	900 lbf
Max Temperature	473 K
Room Temperature	293 K
Pressure	1200 psi [8.3 MPa]



Symmetry



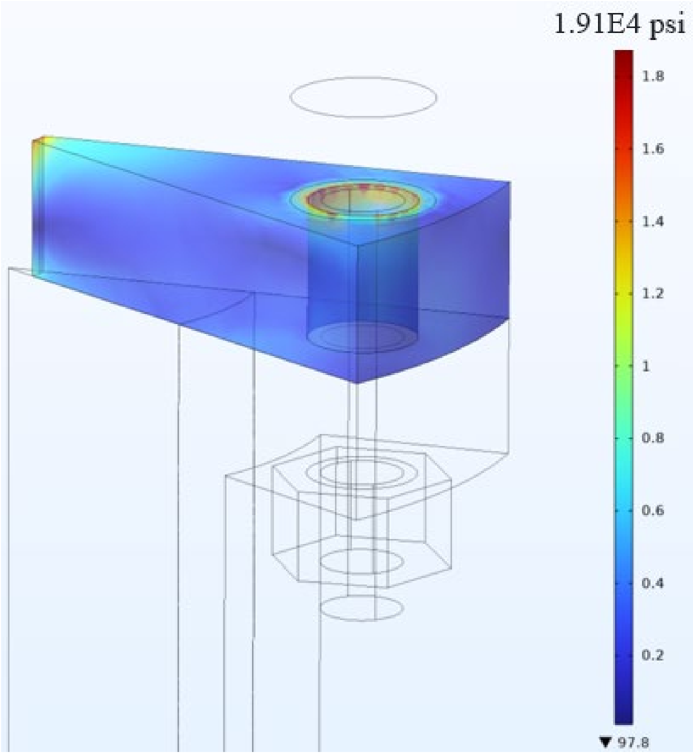
Simplified Geo.



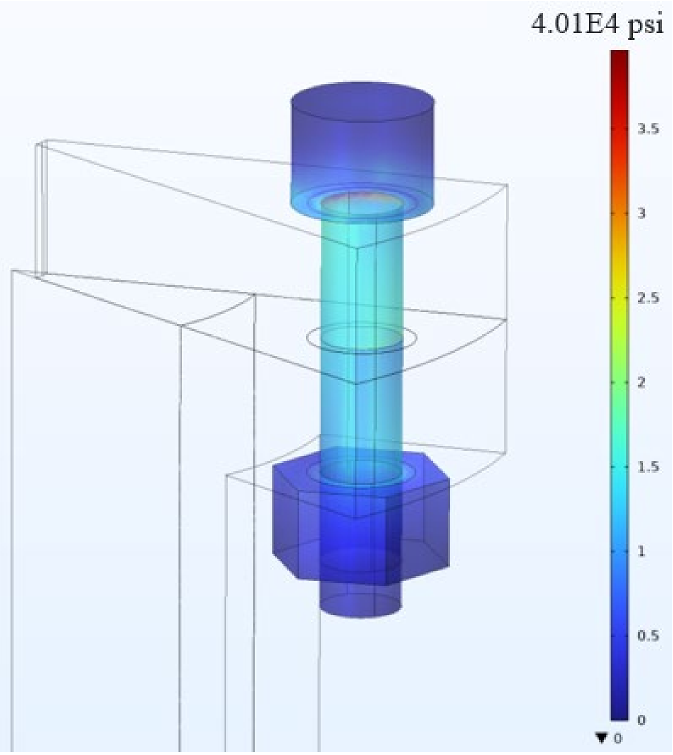
Model Geo.

COMSOL Model Below 2/3 of the Yield Stress

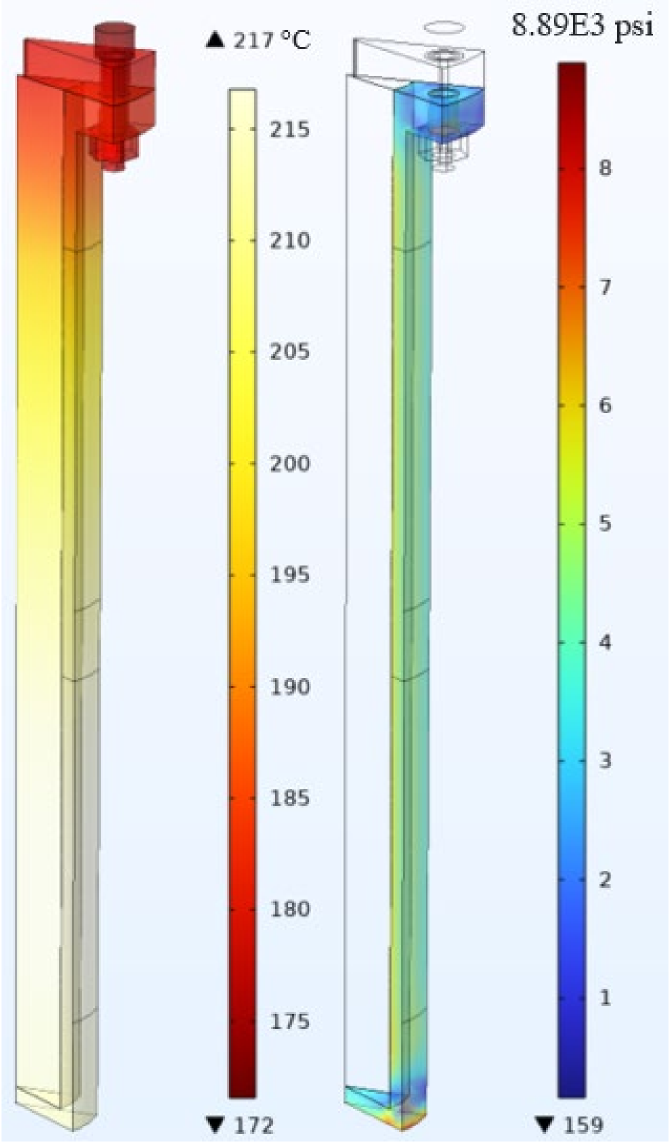
	Yield Stress at 200 °C (ksi)	COMSOL Stress at 200 °C (ksi)
Flange	75	19
Bolt	75	40
Body	18	8.9



Titanium Flange



G5 Titanium Bolt



6061 Vessel Body

Structural Calculations and COMSOL Analysis Were Found to be in Overall Agreement

- Limiting factor:
  - Body – wall thickness
  - Flange – thickness
  - Bolts – gasket preload
- Safety Factor Comparison
  - Calculation gives a required thickness vs. the COMSOL compared Von Mises stress to a yield criterion.
- Both methods justify the design

Structural Calculation Safety Factors

Component	Calculated	Model
Body	3.28	2.42
Flange	1.53	4.68
Bolts	1.50	1.87

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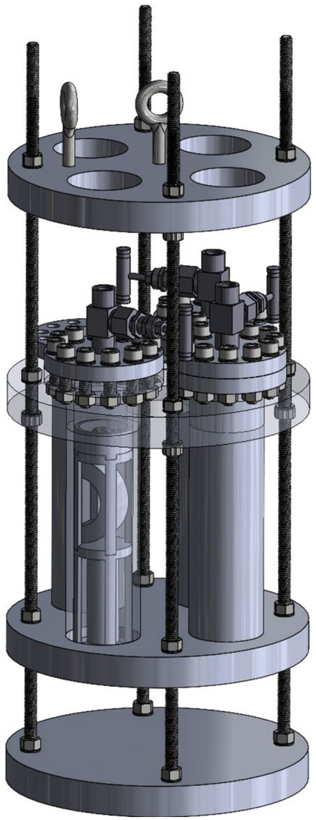
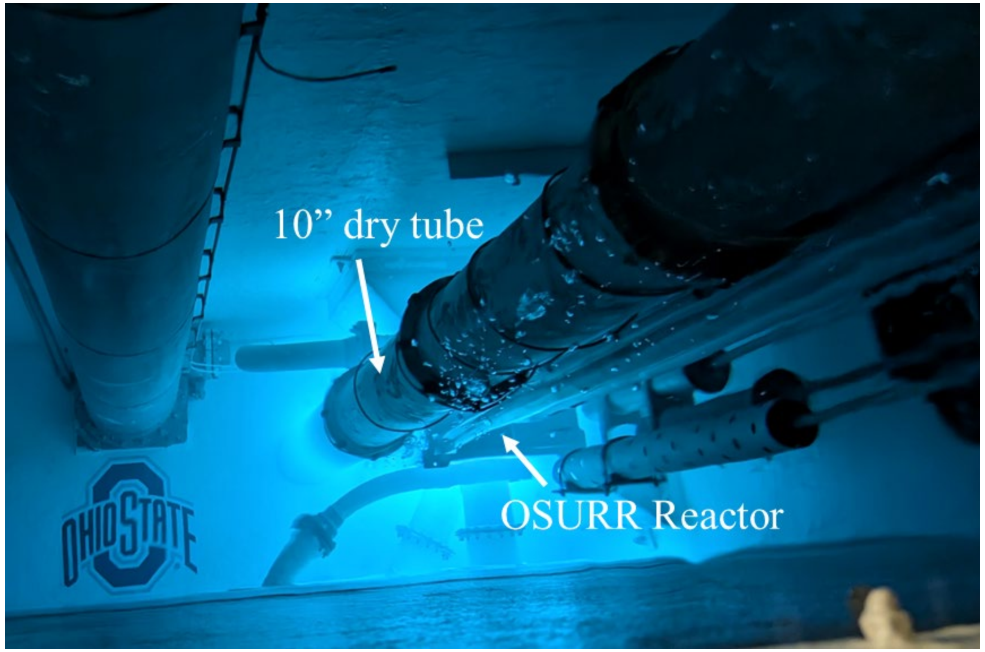
Limitations of the Analysis

- Adding additional creep behavior could improve COMSOL model fidelity
- Gasket design needs to be confirmed and the analysis updated
- Future iterations will use welding instead of a bolted flange
  - Welding has a pressure containment advantage over gaskets. Trade-off is ease of access.

Neutronics Modeling Setup

- Irradiation Goals
  - Neutron Fluence: 2E16 n/cm2
  - Gamma Dose: 22 Mrad
- 3 Pressure cylinders with different organics will be irradiated in 4 titanium pipes (G10 Basket)
- Irradiation will occur in 10” OD dry tube facility

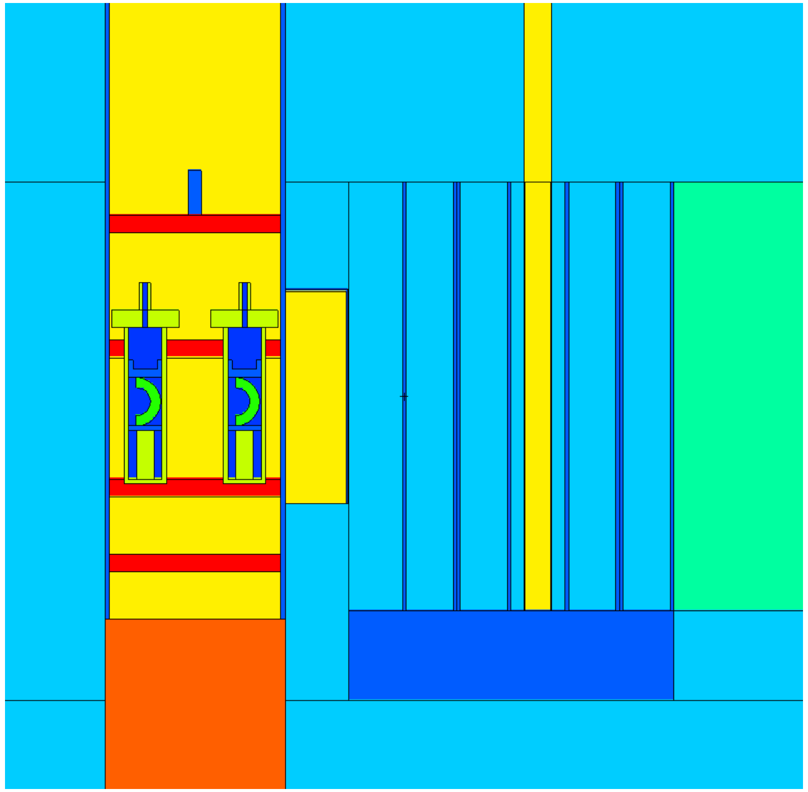


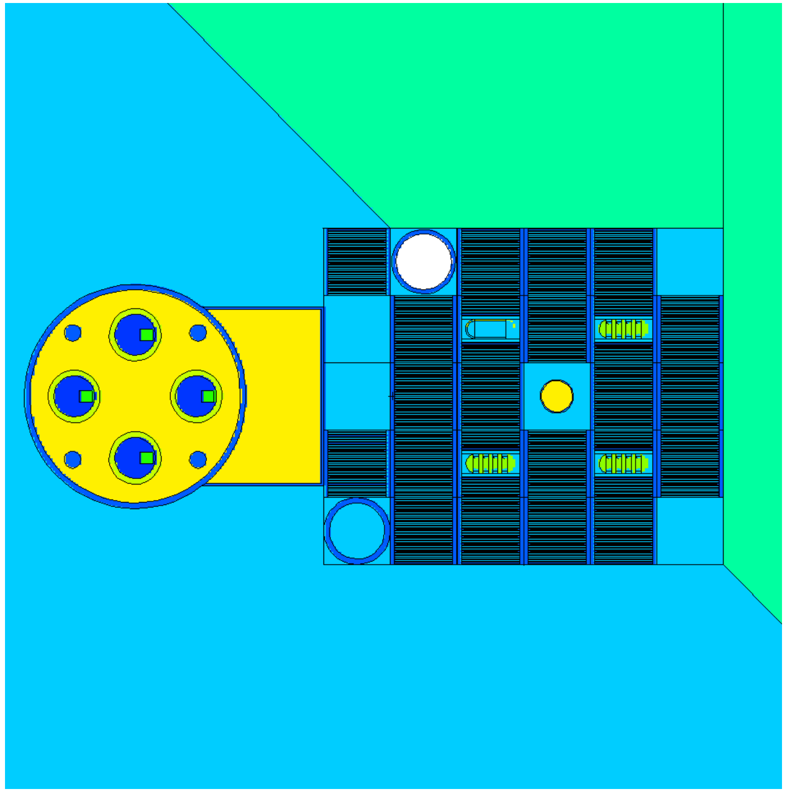


Ohio State University research reactor (OSURR)

MCNP Analysis - Models

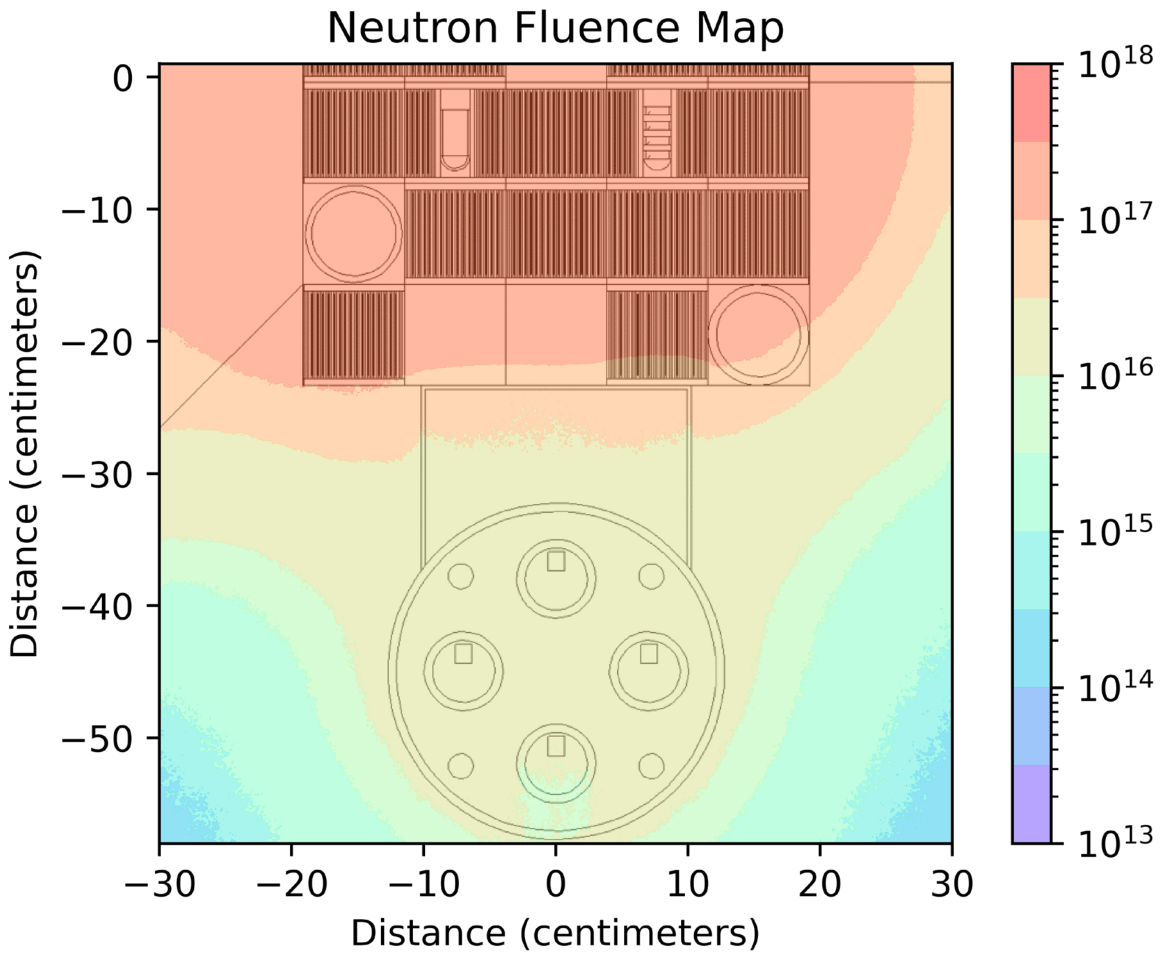
- The neutron fluence and spectrum calculated by MCNP on the materials was sent to ORIGEN to determine neutron activation
- ORIGEN was run to determine the radioisotopes created in the experiment and their resulting gamma dose at 1 meter away

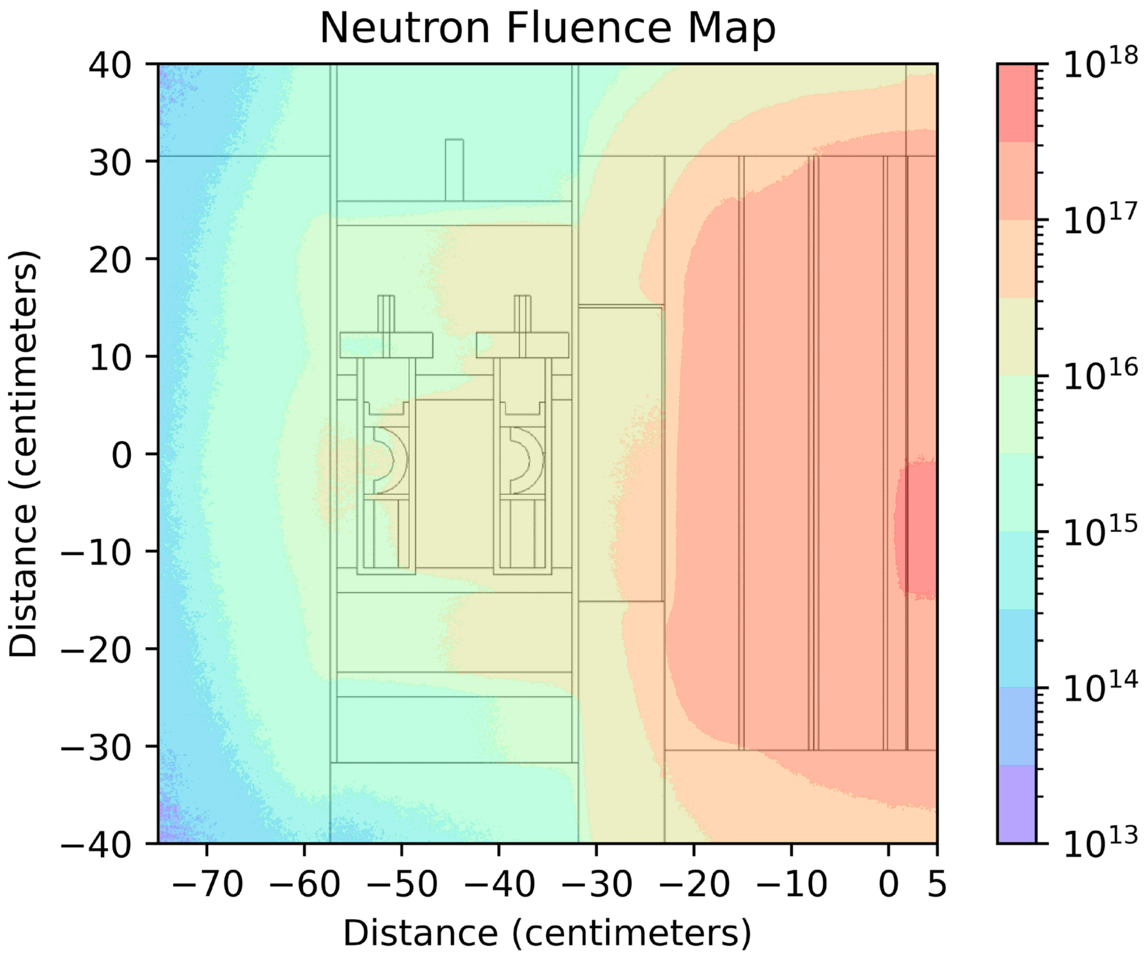




MCNP Analysis – Neutron Fluence

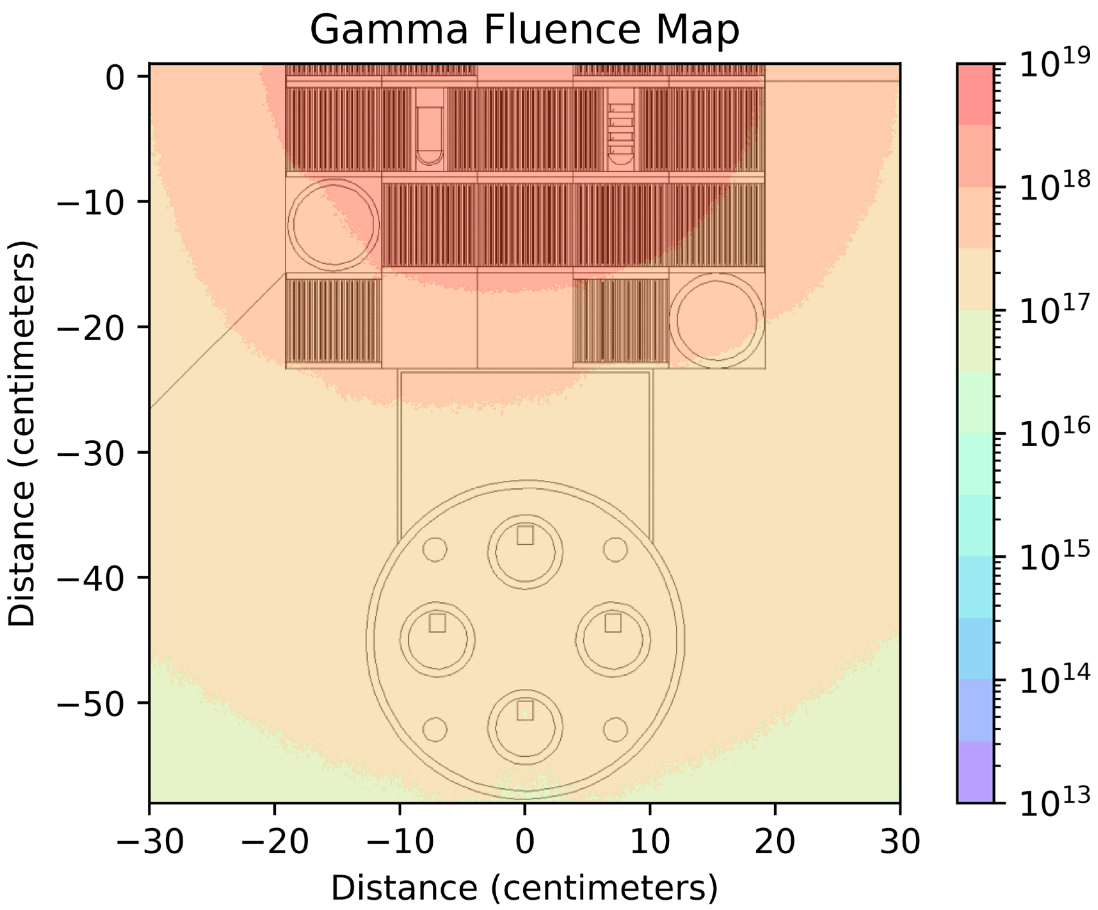
- Total neutron fluence map of the experiment (n/cm2)

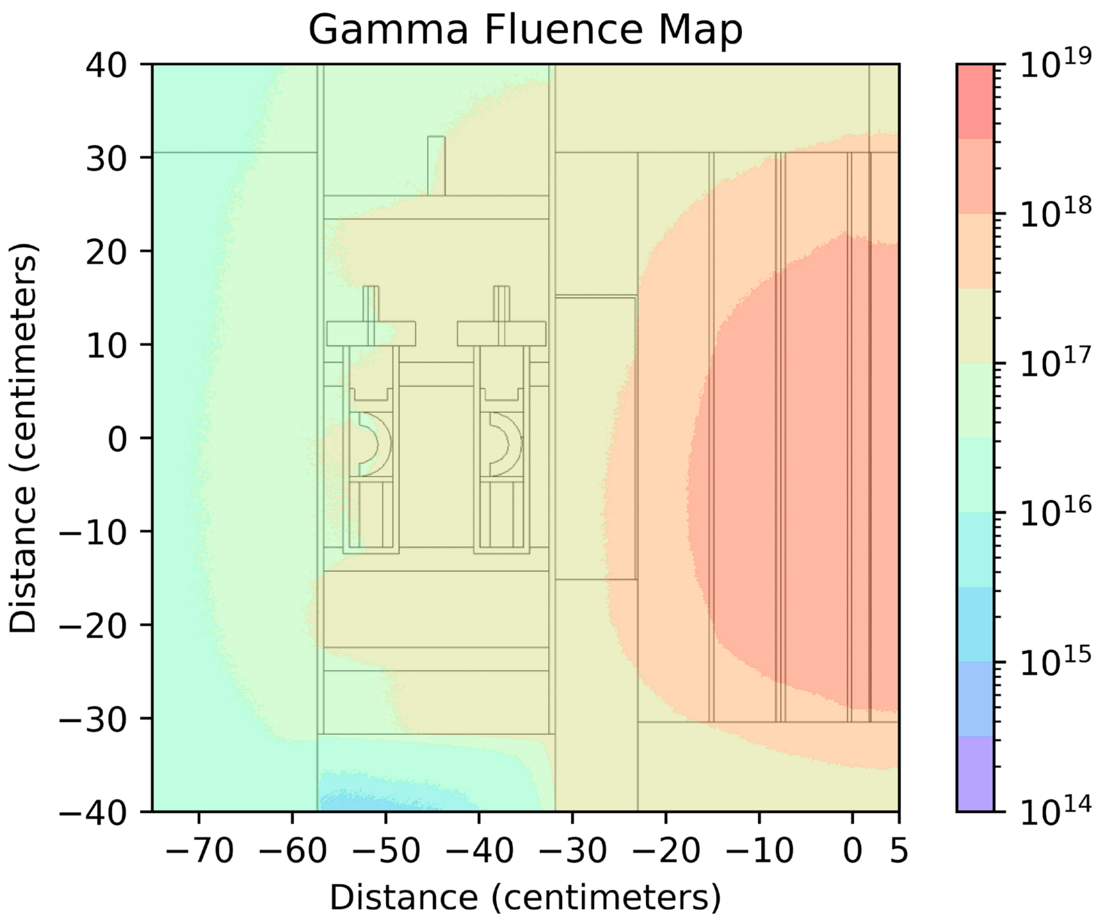




MCNP Analysis – Gamma Fluence

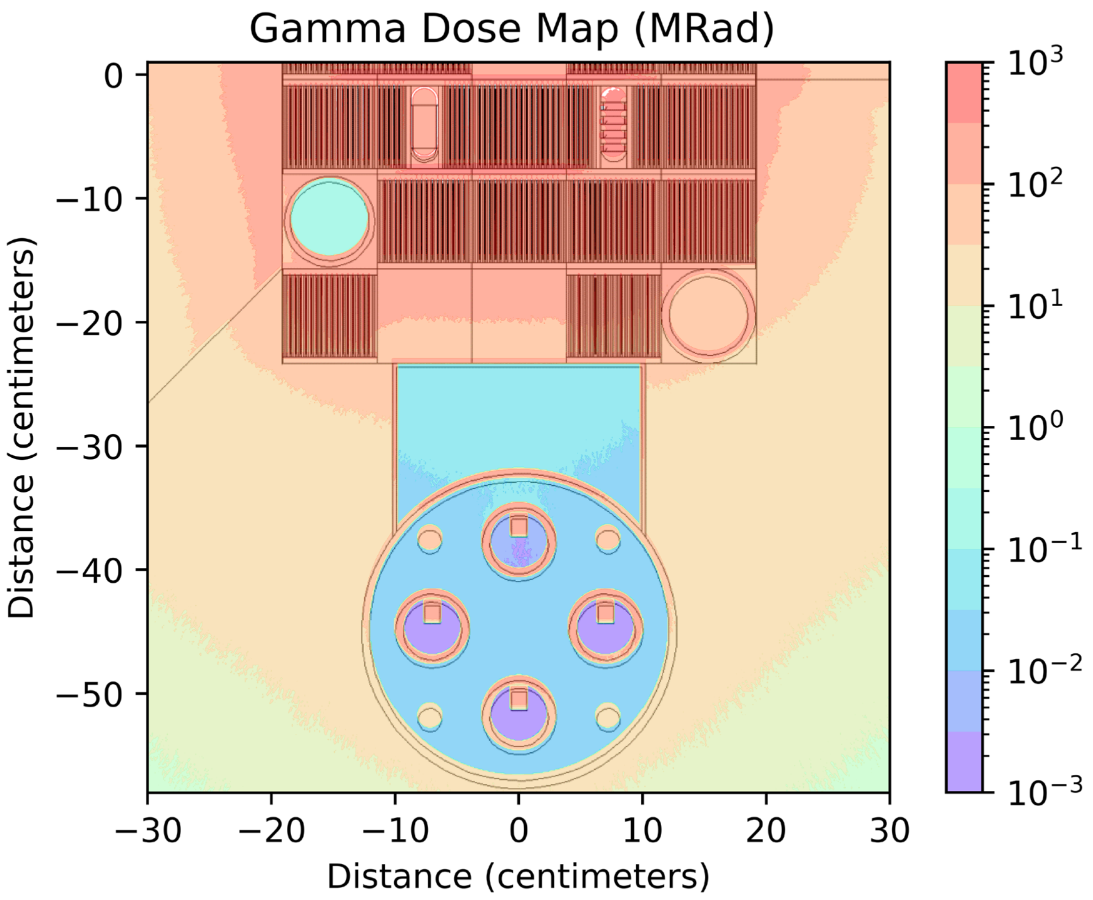
- Total gamma-ray fluence map of the experiment (γ/cm2)

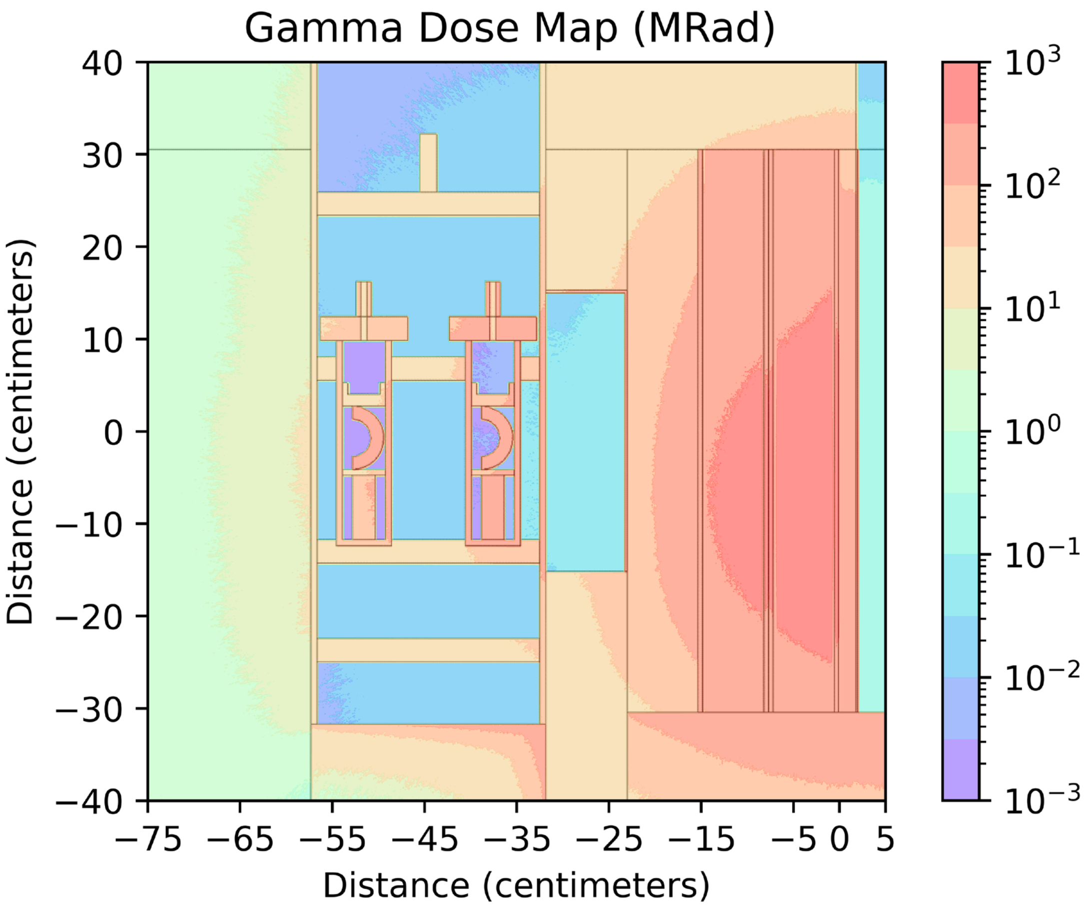




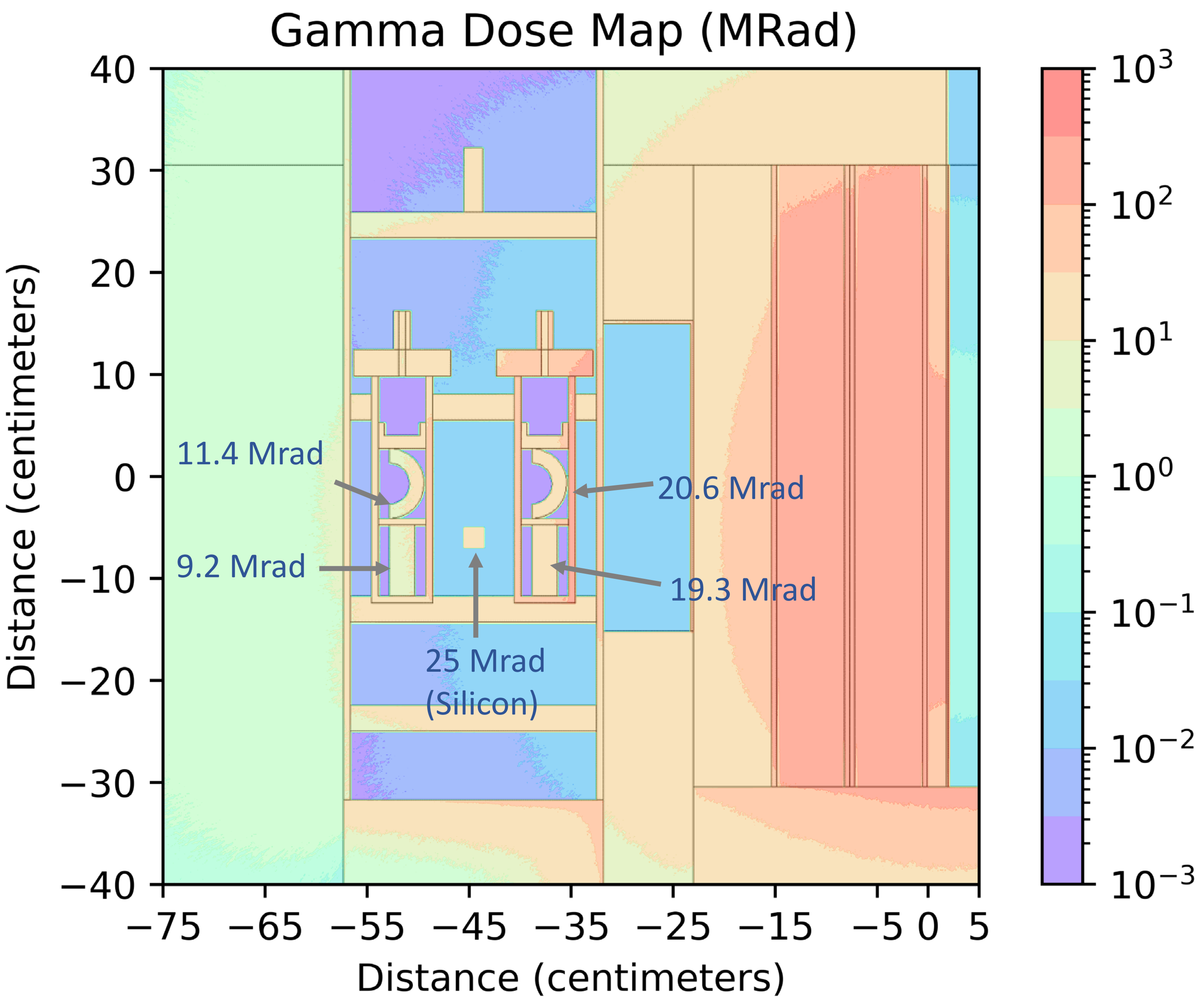
MCNP Analysis – Gamma Ray Dose

- Total gamma-ray dose map of the experiment (MRads)





MCNP Analysis – Gamma Ray Dose



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Titanium & Aluminum Vessels can be Removed in 5 Days & Shipped in 90 Days

Labeling requirements for radioactive shipping

	White	Yellow II	Yellow III
Dose at package surface	<0.5 mRem/hr	< 50 mRem/hr	< 200 mRem/hr
Dose at 1 meter	Negligible	< 1 mRem/hr	< 10 mRem/hr
FedEx Acceptable	Yes	Yes	No
Notes	Anyone can ship with proper tags	Anyone can ship with proper tags	High cost & lead time

[13] “Labeling.” NRC Web.

Titanium & Aluminum Vessels can be Removed in 5 Days & Shipped in 90 Days

Aluminum Body

Time after (days)	Dose (mrem/hr @ 1 meter)
0	428064
0.04	26141
0.5	7921
1	3941
2	1069
3	295
4	85
5	27.7
6	11.7
7	7.0
14	3.89
21	3.33
30	2.84
90	1.2
180	0.44
365	0.1
547.5	0.04
730	0.02

Titanium Body

Time after (days)	Dose (mrem/hr @ 1 meter)
0	490273
0.04	28528
0.5	8173
1	4020
2	1088
3	299.3
4	85.05
5	26.6
6	10.55
7	6.0
14	3.46
21	3.0
30	2.55
90	1.0
180	0.36
365	0.1
547.5	0.05
730	0.03

50 mrem/hr at 1 meter is when reactor staff remove experiment

Shipping usually occurs at Yellow II or <1 mrem/hr at 1 meter, this can be done with UPS, etc.

Top 6 Long Term Radioisotopes

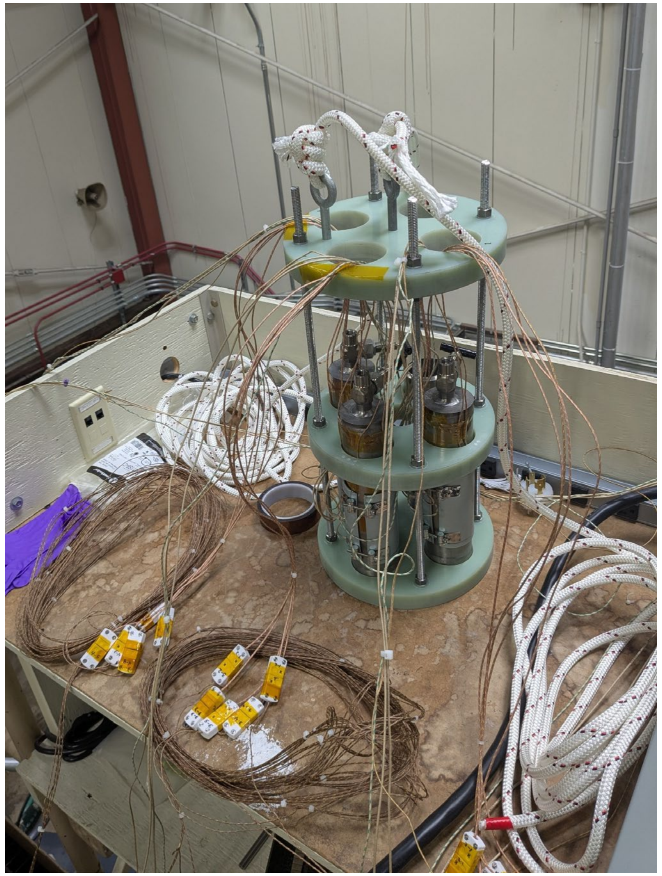
Isotopes	Source
Cr-51	chromium (heaters/thermocouples)
Sc-46	titanium (vessel)
Fe-59	iron (heaters, eyebolt)
Co-58	nickel (thermocouples/heaters)
Zn-65	zinc (aluminum 6061)
Mn-54	iron (heaters, eyebolt)

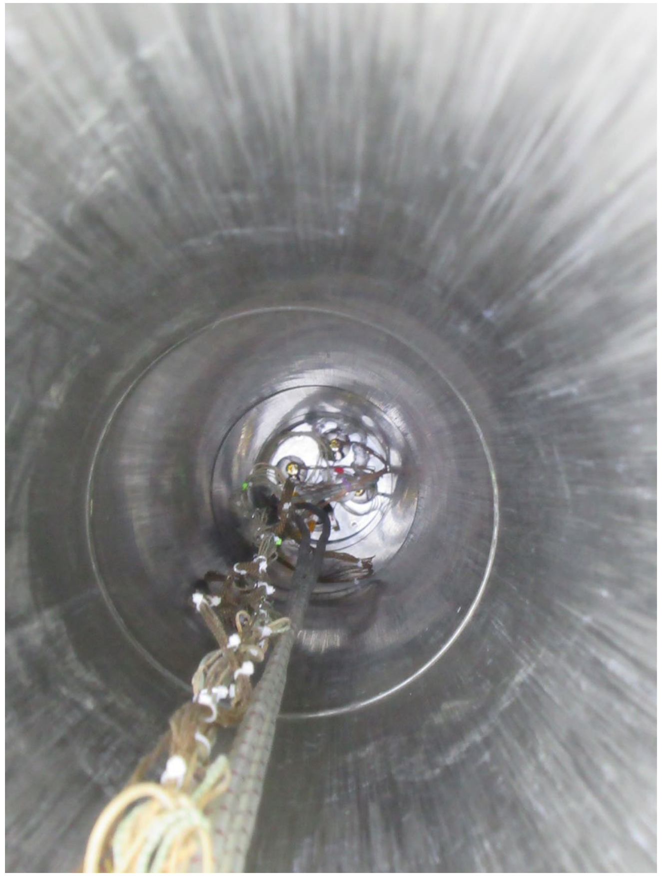
Key Takeaways

- In addition to standard mechanical design, radiation effects such as neutron activation must be taken into consideration.
- Aluminum is an excellent material for radiation considerations but its mechanical properties degrade significantly at higher temperatures.
- A research reactor can provide FSP relevant mix-radiation fluences.
- The activation of the testing apparatus is within 90 days to ship either titanium and aluminum pressure vessels.

Experiment Completed at OSURR April 2025

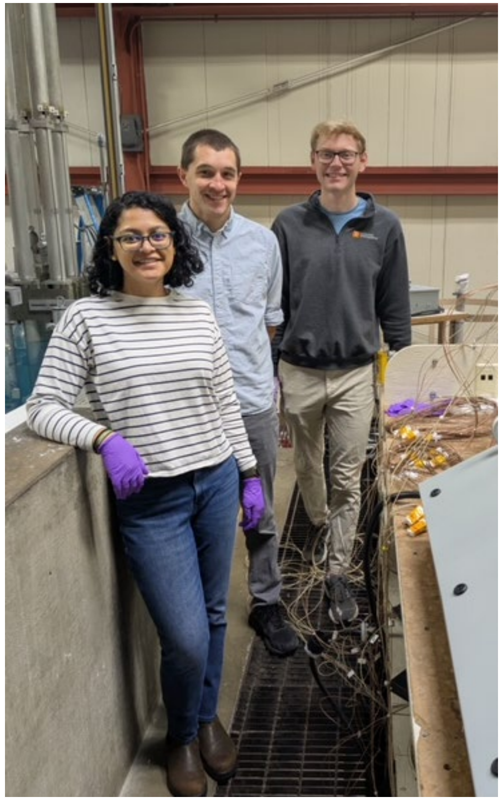
- Results are forthcoming





Acknowledgements

Special thanks to the FSP project team at NASA GRC for an incredible summer internship experience!



This presentation was inspired by the works of Mireles et al. [14] and Bowman et al. [15]

References

1. T. Steiner, R. Bruckner, And S. Wilson, “NASA’s Interest in Radiation Tolerance and Requirements of Candidate Technologies for Fission Surface Power and Further Relevance to Dynamic Radioisotope Power Systems,” Nuclear and Emerging Technologies for Space, Santa Fe, NM, 88-92, ANS (2024).
2. Schreiber, Jeffrey G. “Summary of Stirling Convertor Testing at NASA Glenn Research Center,” 2006.
3. Mireles, Omar R. “Experimental Demonstration Of Radiation Effects On The Performance Of A Stirling-alternator Convertor and Candidate Materials Evaluation,” (2010).
4. Stirling Convertor Sets 14-Year Continuous Operation Milestone - NASA. (2020). https://www.nasa.gov/centers-and-facilities/glenn/stirling-convertor-sets-14-year-continuous-operation-milestone/
5. Shin, E. Eugene. “Evaluation and Validation of Organic Materials for Advanced Stirling Convertors (ASCs): Overview.” 2015.
6. C. Bowman, S. Geng, J. Niedra, A. Savir, E. Shin, J. SUTTER, And L. Thieme, "Materials-of-Construction Radiation Sensitivity for a Fission Surface Power Convertor," in Space Nuclear Conference (2007).
7. E. Golliher, S. Pepper, "Organic materials ionizing radiation susceptibility for the Outer Planet/Solar Probe radioisotope power source," 35th Intersociety Energy Conversion Engineering Conference and Exhibit (IECEC), Las Vegas, NV, USA, 2000, pp. 1491-1496 vol.2, (2000).
8. Bowman, C. L., Shin, E. E., Mireles, O. R., Radel, R. F., & Qualls, A. L. “Radiation Specifications for Fission Power Conversion Component Materials.” (2011).
9. WISE Neutron Activation Calculator, https://wise-uranium.org/rnac.html.
10. "Metallic Materials Properties Development and Standardization (MMPDS) Handbook - 2023," Battelle Memorial Institute, Columbus, OH (2023).
11. Li, S., Deng, T., Zhang, Y., Liang, Y., Li, R., & Dong, T. (2021). Review on the Creep Resistance of High-Temperature Titanium Alloy. Transactions of the Indian Institute of Metals, 74(2), 215–222. https://doi.org/10.1007/s12666-020-02137-x
12. R. Budynas, J. Nisbeth, “Shigley's mechanical engineering design 10th edition,” New York: McGraw-Hill. (2015).
13. “Labeling.” NRC Web, www.nrc.gov/reading-rm/basic-ref/students/for-educators/labeling.html. (2020).
14. O. Mireles, E. Shin, C. Bowman “Post-Irradiation Evaluation of the Stirling Alternator Radiation Test Article,” San Diego, CA, June 13-17, 2010, ICAPP ANS (2010).
15. C. Bowman, E. Shin, O. Mireles, R. RADEL And A. Qualls, "Radiation Specifications for Fission Power Conversion Component Materials,” NASA/TM-2011-216996, NASA (2011).