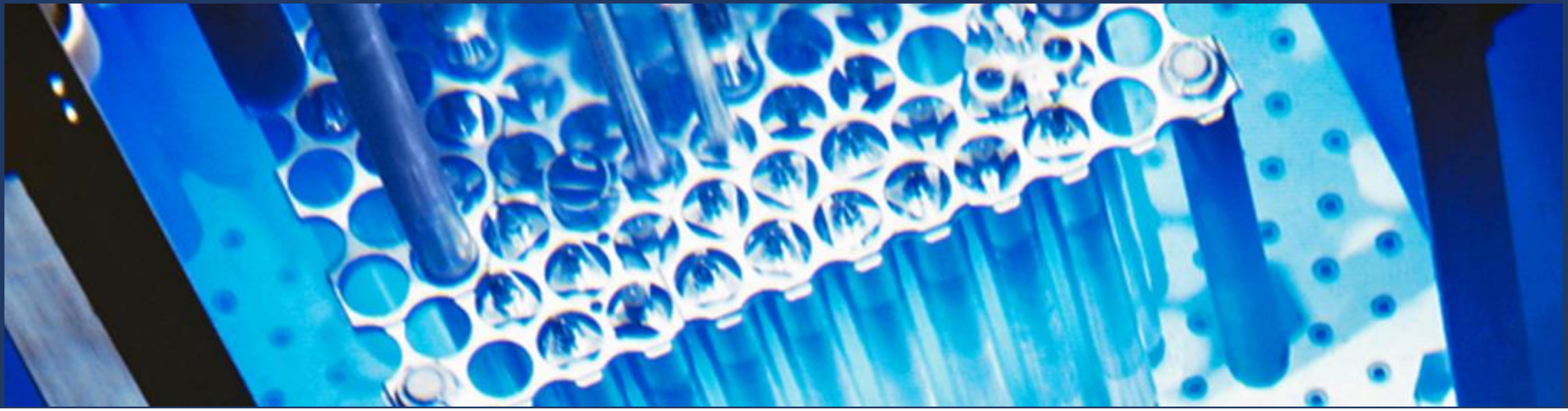

Development of a New Neutron Imaging Facility for Radiation Science and Engineering at the Penn State University

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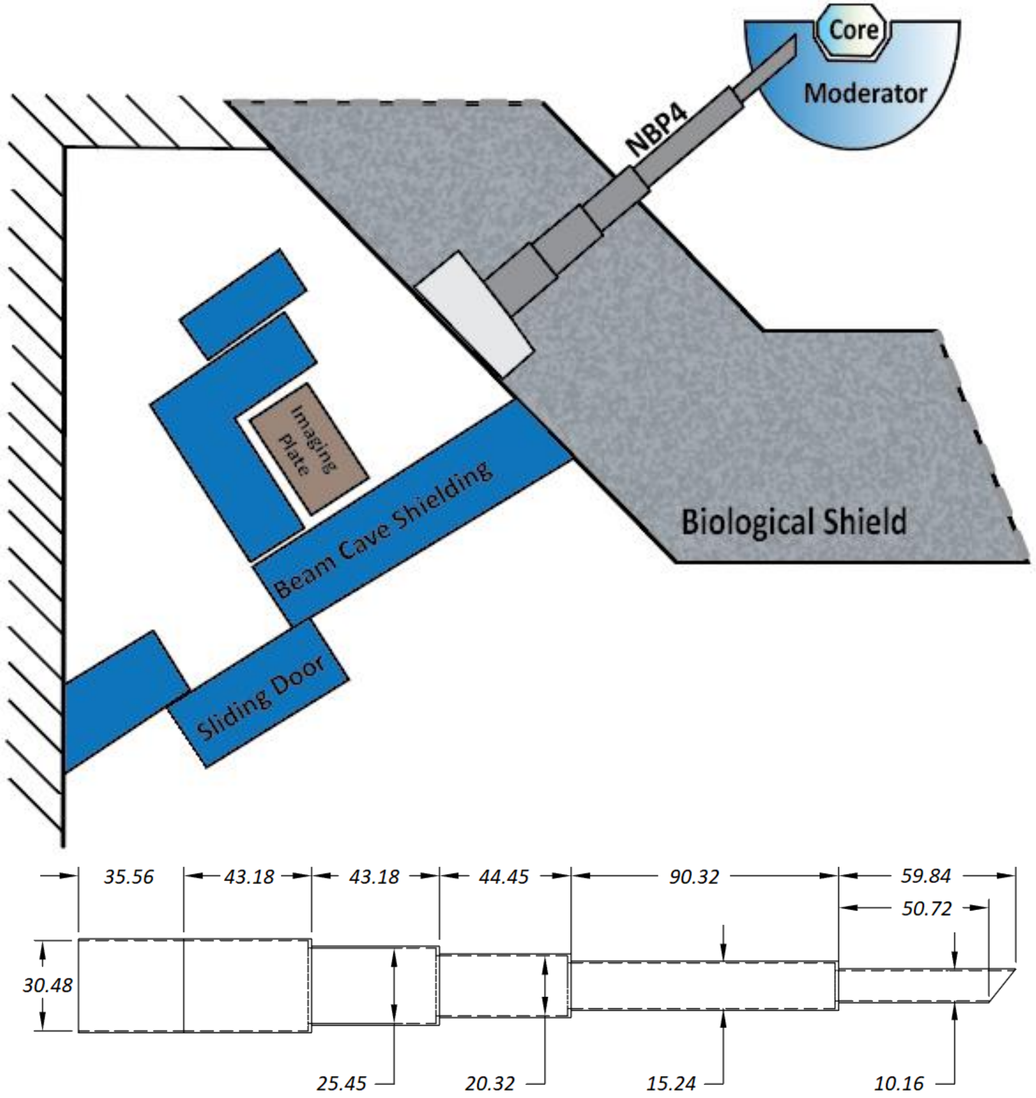
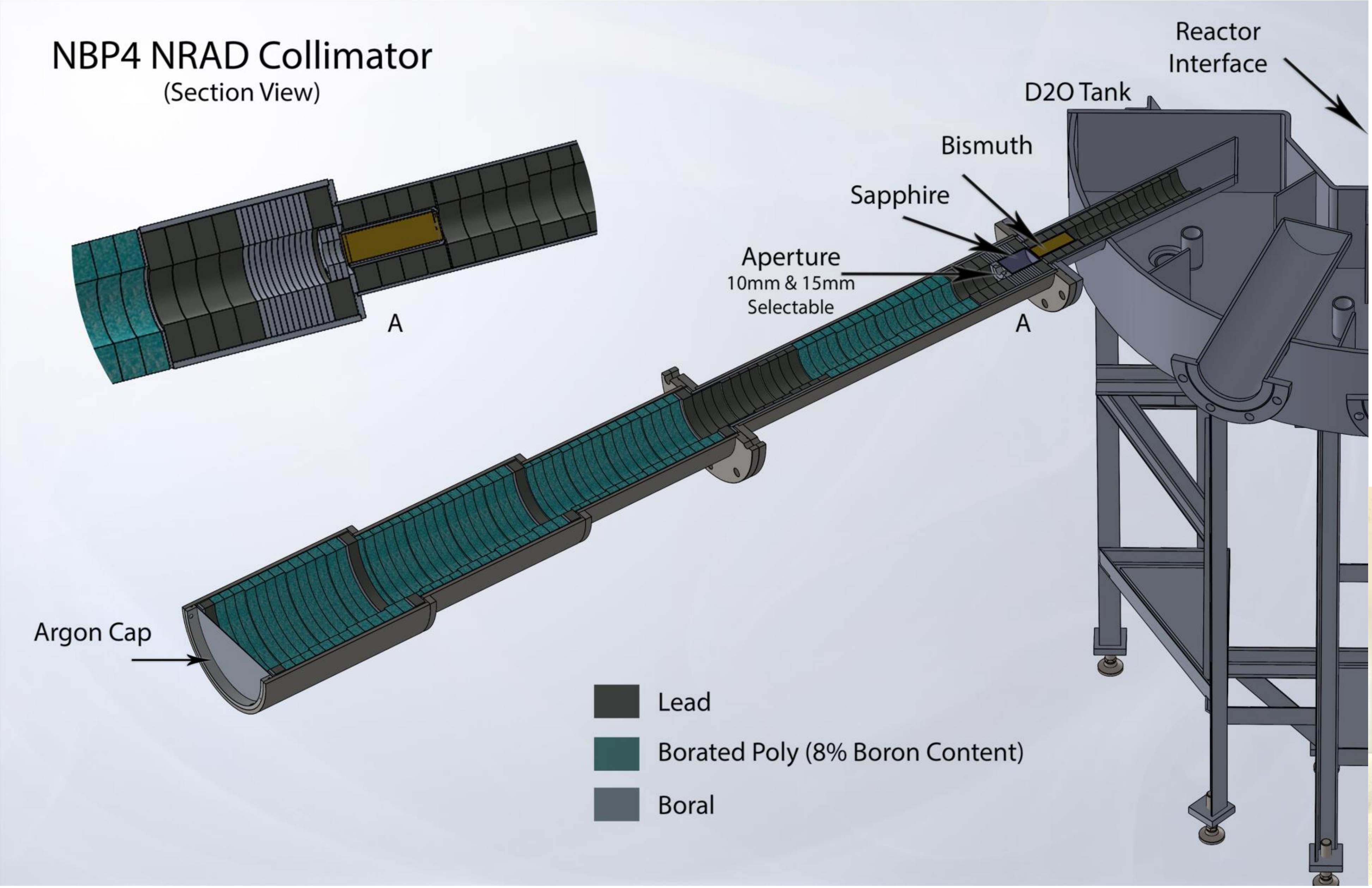
Introduction

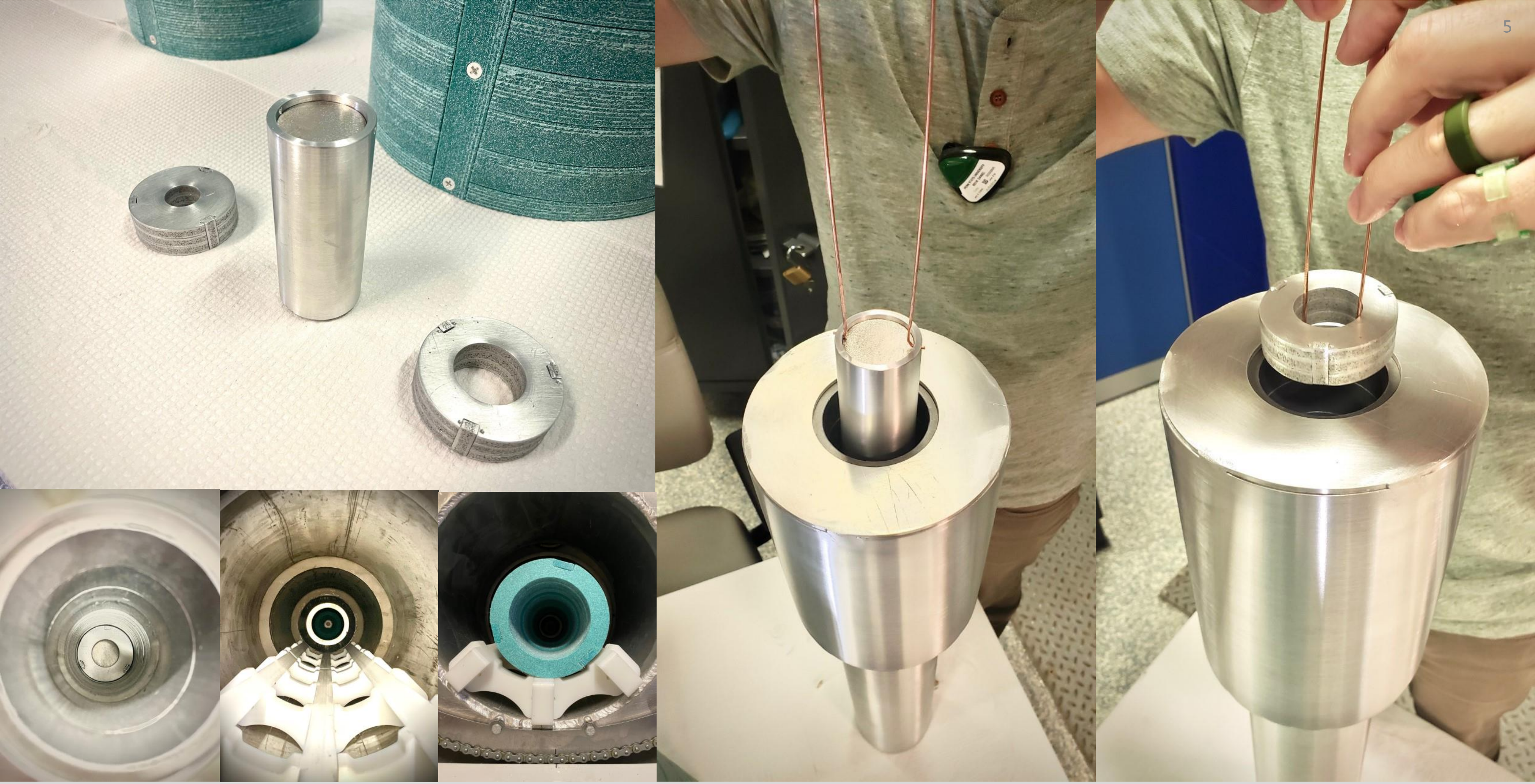
- Neutron imaging is a powerful tool in the field of non-destructive testing that utilizes the unique attenuation properties of neutrons
- The Radiation Science and Engineering Center (RSEC) has had a neutron imaging facility for the last several decades
- The RSEC new Neutron Imaging Facility (NIF) have Bismuth filter and collimators with variable apertures and will utilize state-of-the-art equipment and software for conventional neutron radiography and tomography



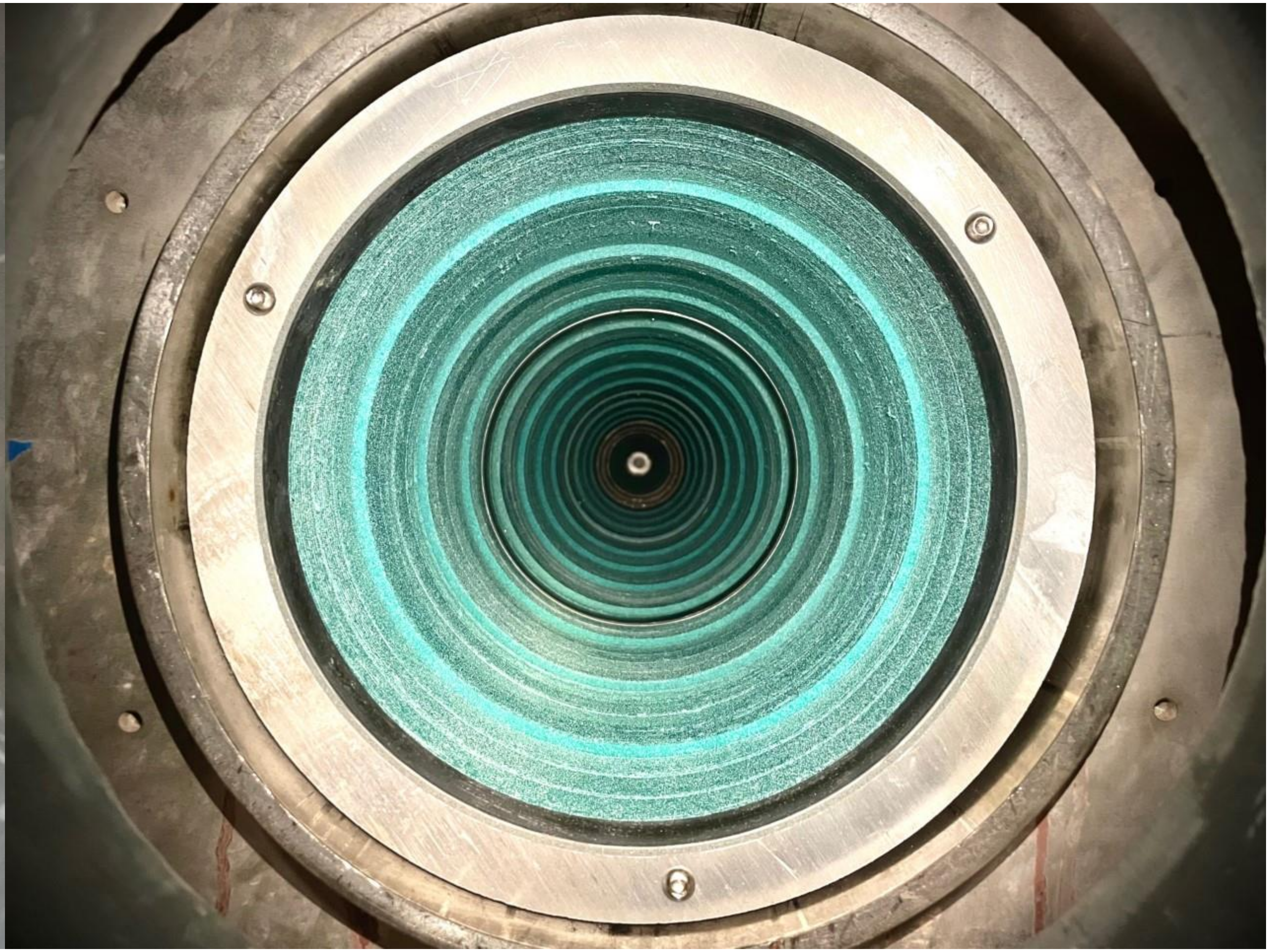
RSEC NIF layout and NBP4 (dimensions are in centimeters)

RSEC Neutron Imaging Facility (RSEC – NIF)


NBP4 NRAD Collimator
(Section View)
Reactor Interface
D2O Tank
Bismuth
Sapphire
Aperture
10mm & 15mm Selectable
A
A
Argon Cap
Lead
Borated Poly (8% Boron Content)
Boral

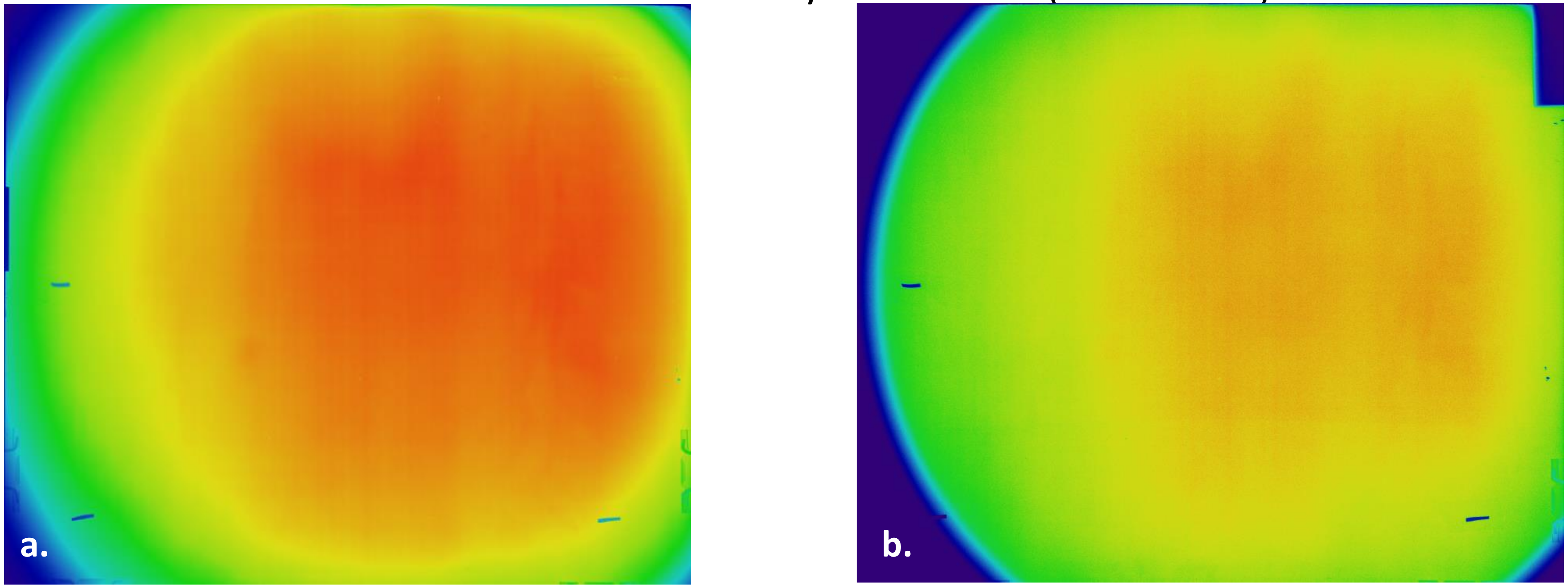


NBP4 in Open Beam vs. Collimators-installed configurations



Characterization of the RSEC-NIF beam

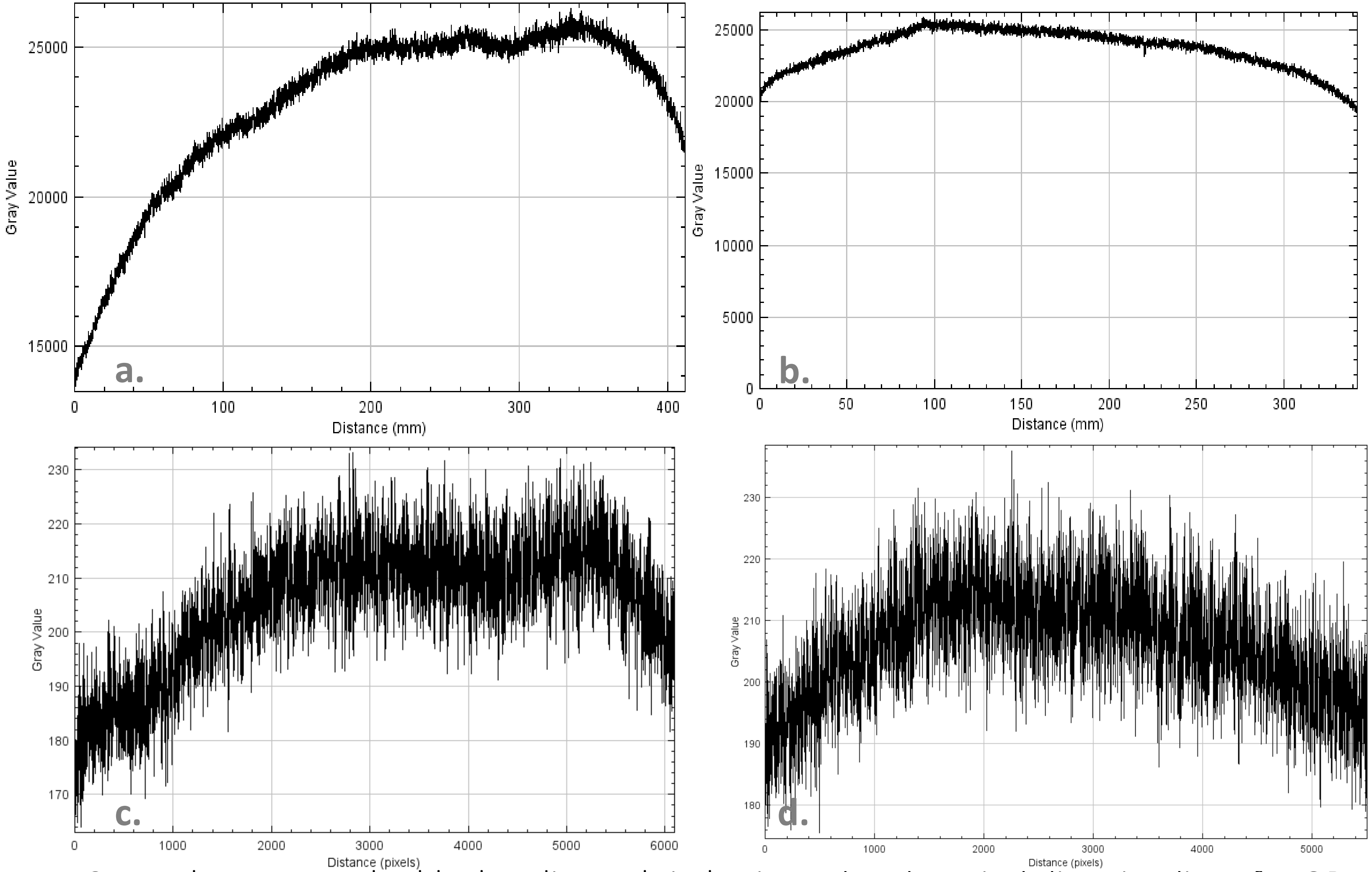
- GE CRxFlex system and IPU phosphor imaging plates were used for radiographs
- ***ImageJ*** image processing and analysis program has been used to access the resulting images with densiometric analysis
- The characterization started from the beam uniformity assessment (ASTM E545) of NBP4



The resulting image of the beam profile for the open beam (a.) and collimator-filter-installed (b.) configurations (ImageJ filter has been used for better visual illustration)

Characterization of the RSEC-NIF beam

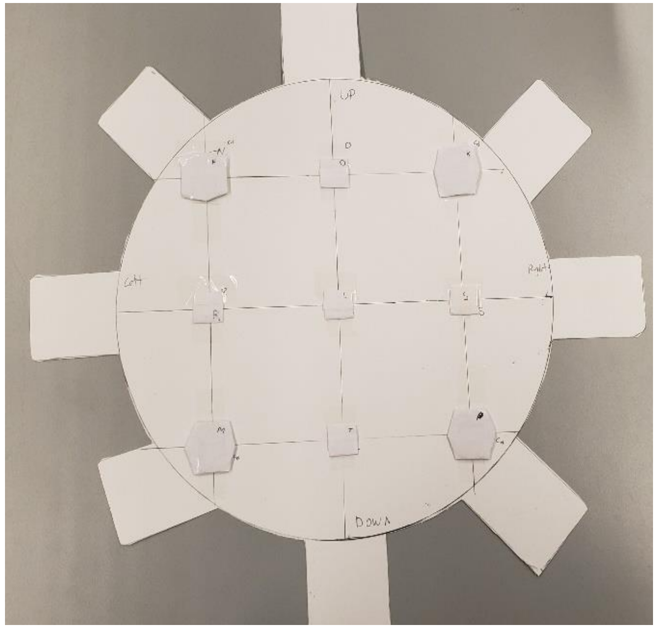
- Asymmetric neutron flux profile can be seen from gray values for the horizontal and vertical lines across the beam exit surface
- Deviation across the entire image for the OB is ~40% and in the middle section, it is ~ 13%
- Thus, for the OB the results are greater than 5% meaning that <u>the flux profile is Not Uniform</u>
- Possible cause: the beam's longitudinal axis is not aligned with the core
- For collimators-installed configuration, deviation across the entire image is ~24% and for the middle section ~ 10%
- The results are still greater than 5%, but <u>More Uniform</u>
- Possible cause: degraded IPU plate

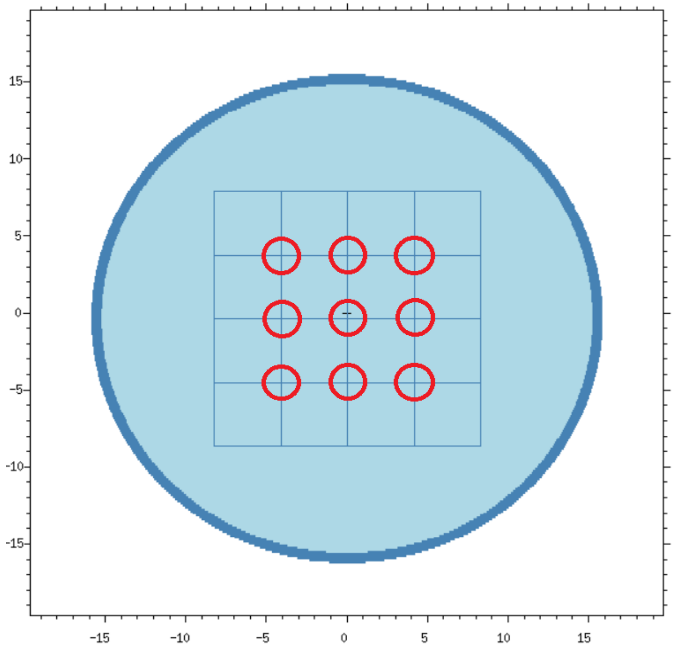


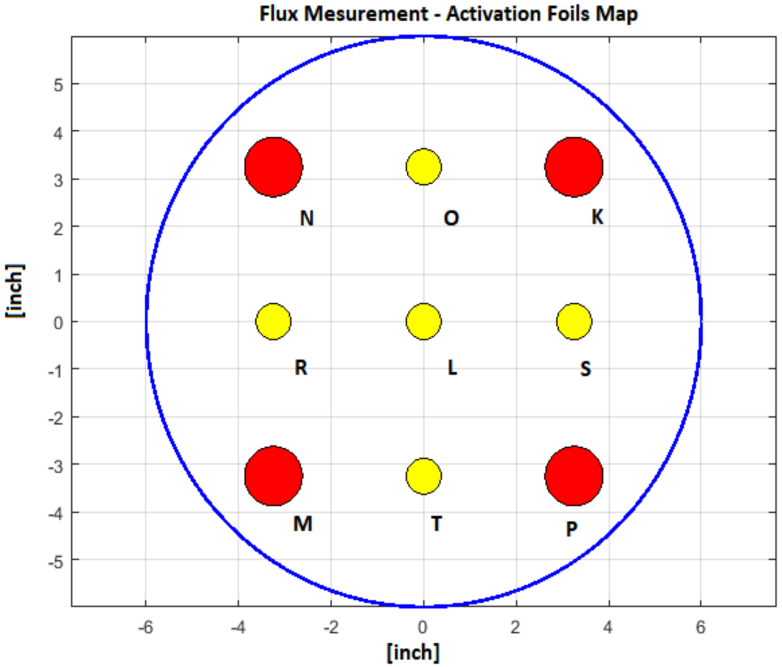
Gray values across the blank radiograph in horizontal and vertical direction lines for OB (a., b.) and collimator-filter-installed (c., d.) configurations

Neutron Flux Measurements at the exit of NBP4

- Thermal neutron flux values were obtained through gold foil activation at the central area of the beam exit surface



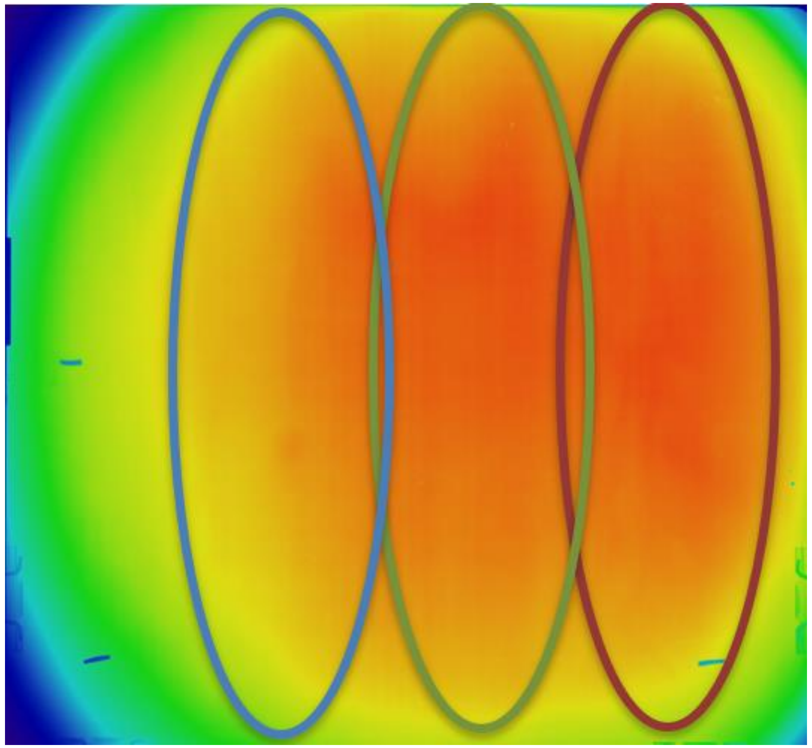




Pasteboard sample holder on the left and the activation foils map as a mesh tally at the end surface (12”-in-diemeter shutter section) of the NBP4. Red circles indicate Cd-covered foils; and the yellow are bare foils.

Neutron Flux Measurements at the exit of NBP4

- For the OB configuration, the average thermal flux value across all 9 foil positions at the exit surface is 3.5E+08 for 1 MW power with ~4.9% associated uncertainty
- Inconsistency between the results of individual foils and the resulting image from the open beam indicates to the high intensity of gamma rays
- For collimators-filter-installed configuration, the average thermal flux is 5.4E+06 for 1 MW power with ~6.4% associated uncertainty



The resulting image for the open beam

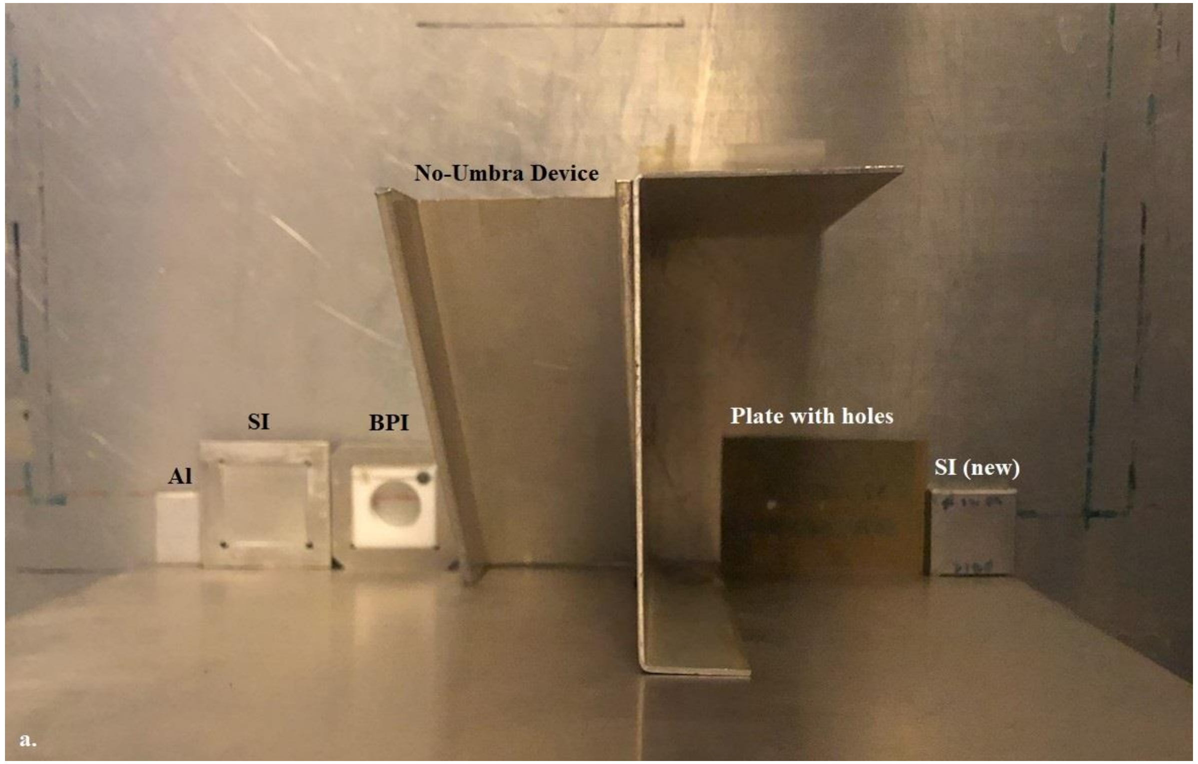
Experimental values for collimator-filter-installed configuration (1MW)		
-	5.172E+06	-
5.052E+06	5.89E+06	5.399E+06
-	4.916E+06	-

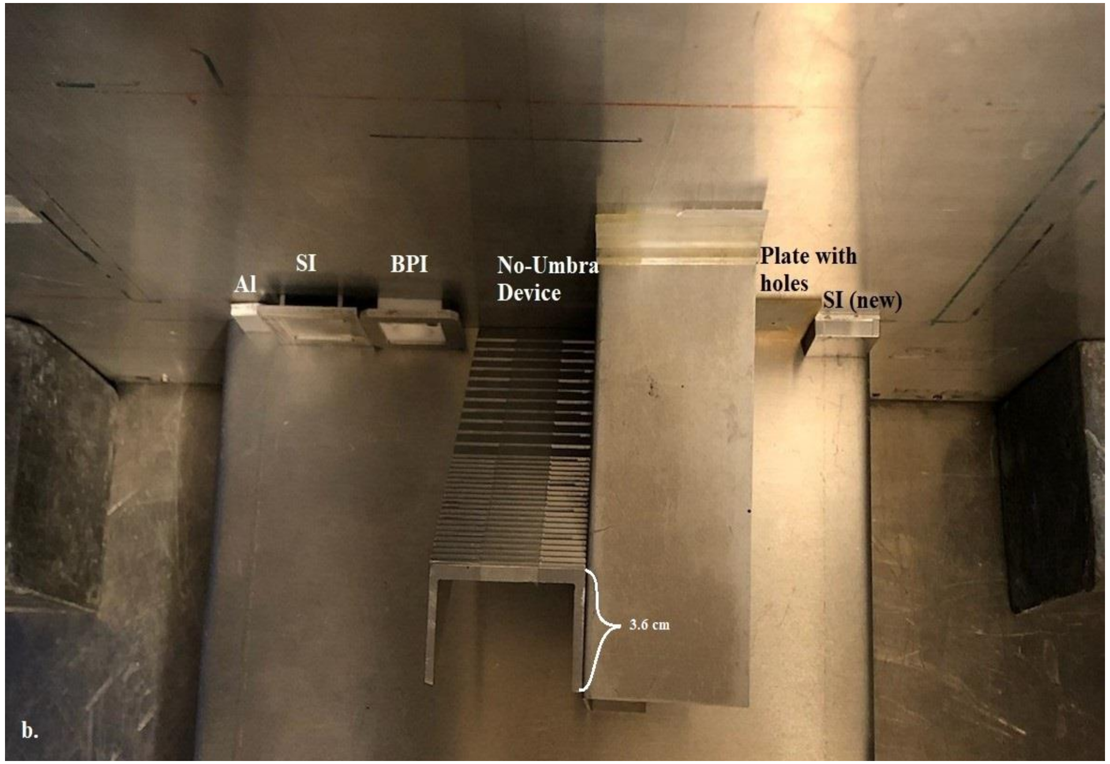
Experimental values for the OB configuration (1MW)		
3.51E+08	3.30E+08	3.62E+08
3.38E+08	3.54E+08	3.26E+08
3.71E+08	3.50E+08	3.81E+08

Beam Quality Indicators

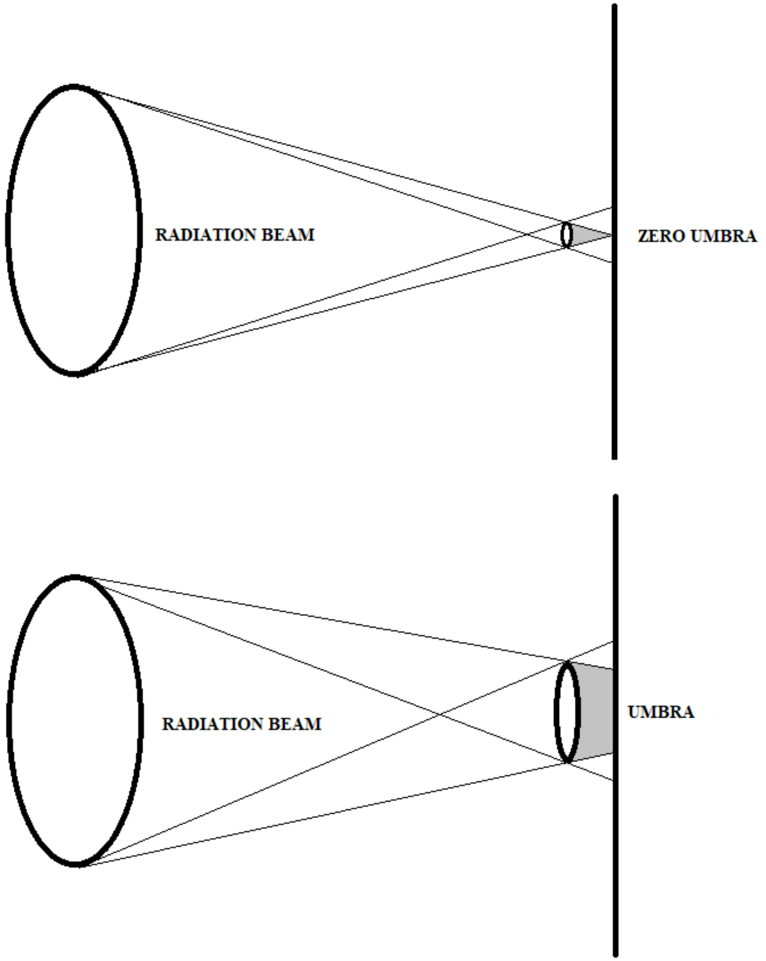
- ASTM E545 describes the process of designation of the quality level of a NR facility that includes the thermal neutron content and sensitivity level
- ASTM E803 describes empirical technique to find the effective collimation ratio based on analysis of image for the No-Umbra device

Experimental set-up of the characterization objects: front (a) and top (b) views





Effective Collimation Ratio

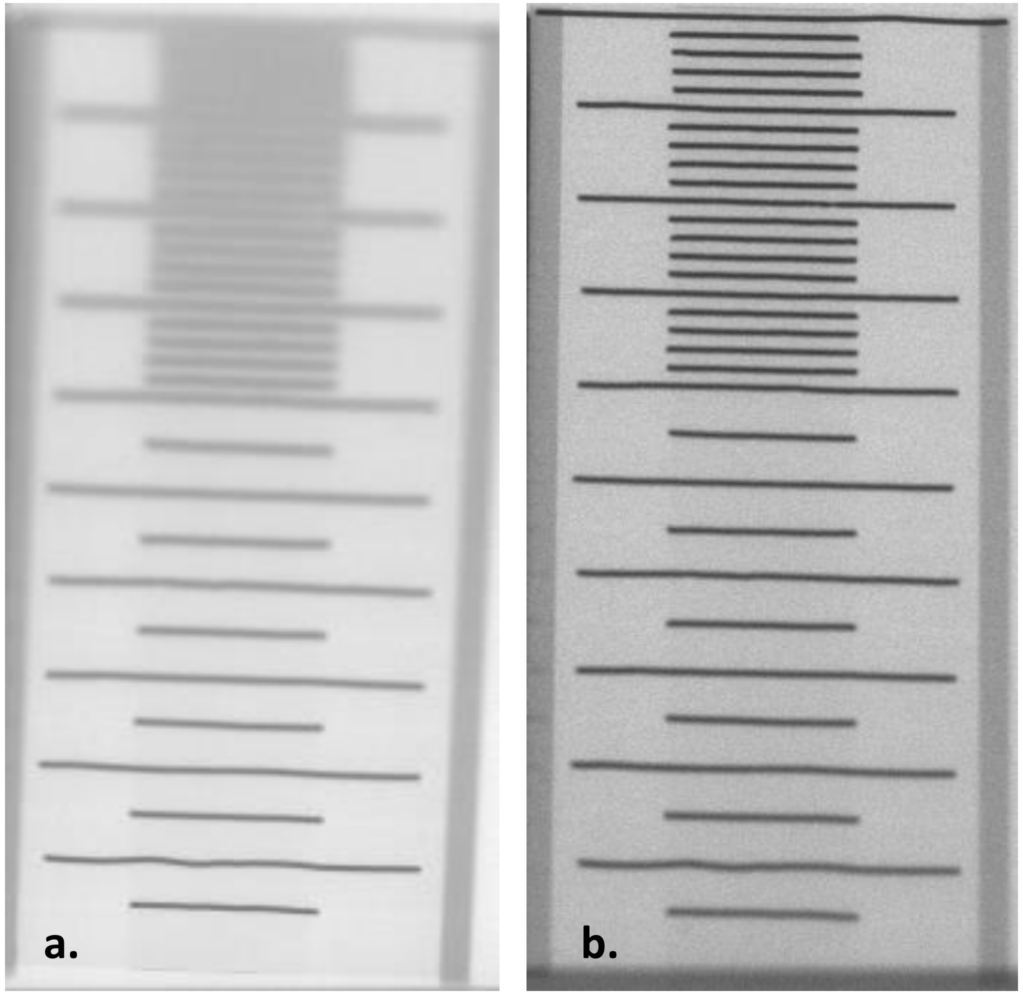


Conceptual representation of umbra shadow

- Collimation ratio (L/D) defines the spatial resolution
- The beam's geometry at RSEC is divergent with geometric L/D ratio of the open beam configuration equal to 46.25
- The effective collimation ratio accounts for scattering events within the beam reducing the L/D and can be calculated as:

$$\left(\frac{L}{D}\right)_{effective} = \frac{rod\ to\ image\ plate\ distance}{rod\ diameter}$$

Effective Collimation Ratio

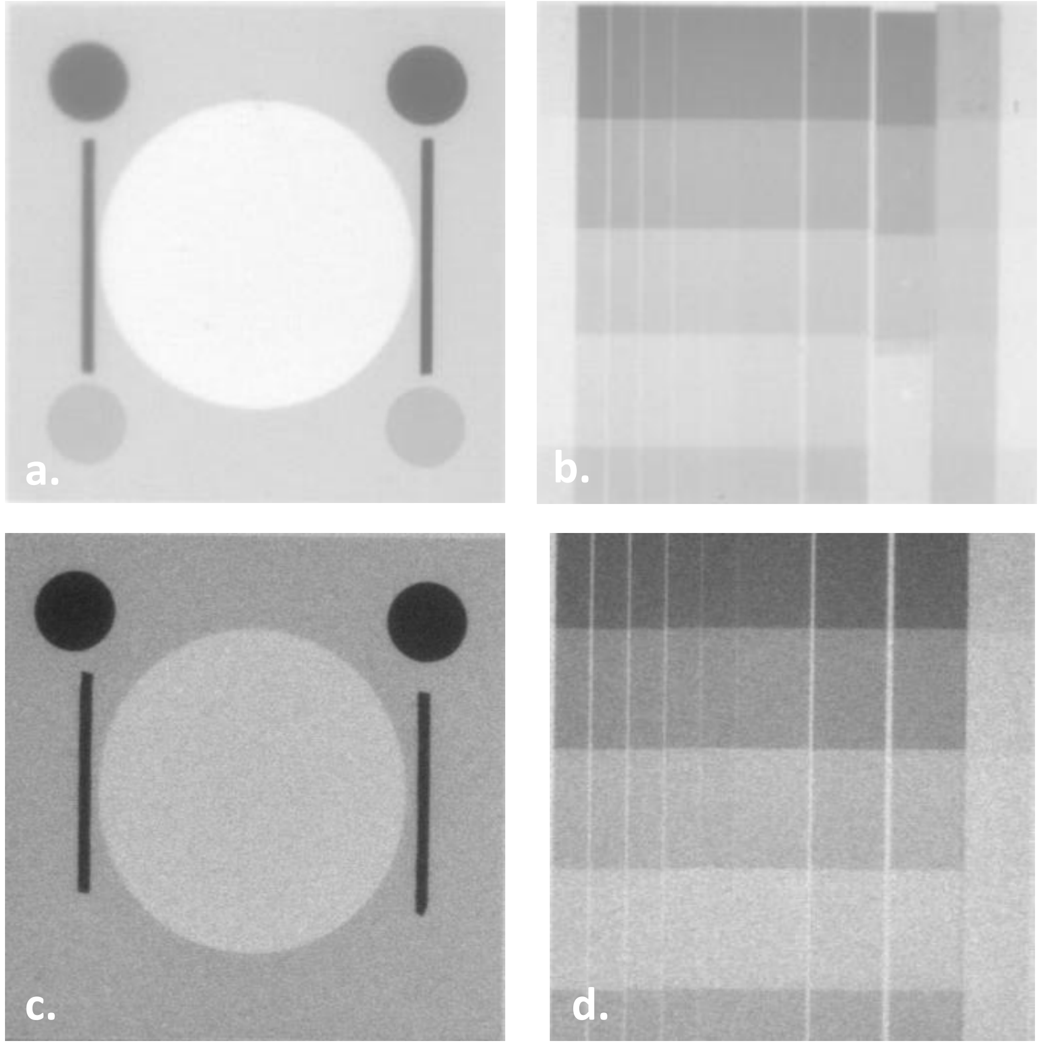


The resulting image for the NU-device for the OB (a.) and collimator-installed (b.) configurations

- For the OB configuration, the umbra shadow disappears after the 5th Cd rod from the bottom up
- Effective L/D ratio of the system for the OB is between 34.6 and 42.5, which is less than geometric value (46.3) that indicates to the existence of scattered neutron content
- For the collimator-filtered-installed configuration, the umbra shadow disappears after the 4th Cd rod from the bottom down
- The effective L/D ratio of the new system is between 107 and 115, which is less than geometric value (137) but more than 100 (initial objective)

Beam Quality: Beam Purity Indicator (BPI) & Sensitivity Indicator (SI)

- By ASTM E545, Beam Purity Indicator (BPI) and Sensitivity Indicator (SI) were used to analyze the quality
- Visual analysis of the BPI leads to following information;
  - ✓ If one of the Cd wires is significantly sharper than the other, the L/D ratio of the system is low and should be improved.
  - ✓ If lead disks lighter and distinguishable comparing to the surrounding polytetrafluoroethylene, there is high gamma content within the beam
- The SI is used to access the system based on the largest consecutive numbered visible hole (H) and the thinnest visible gap (G)



BPI and SI images for the OB (a., b.) and collimator-filter-installed configurations (c., d.)

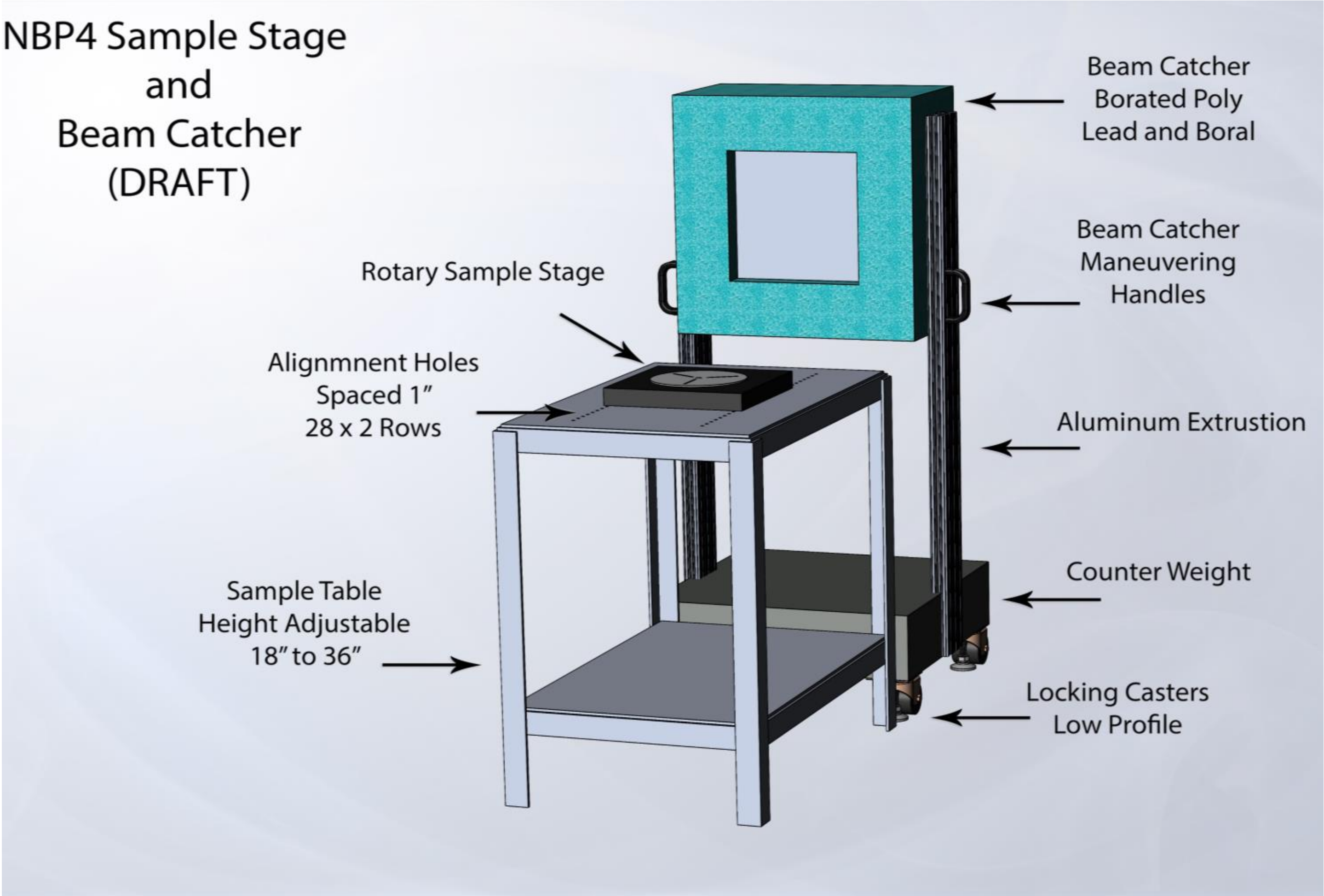
Beam Quality: Beam Purity Indicator (BPI) & Sensitivity Indicator (SI)

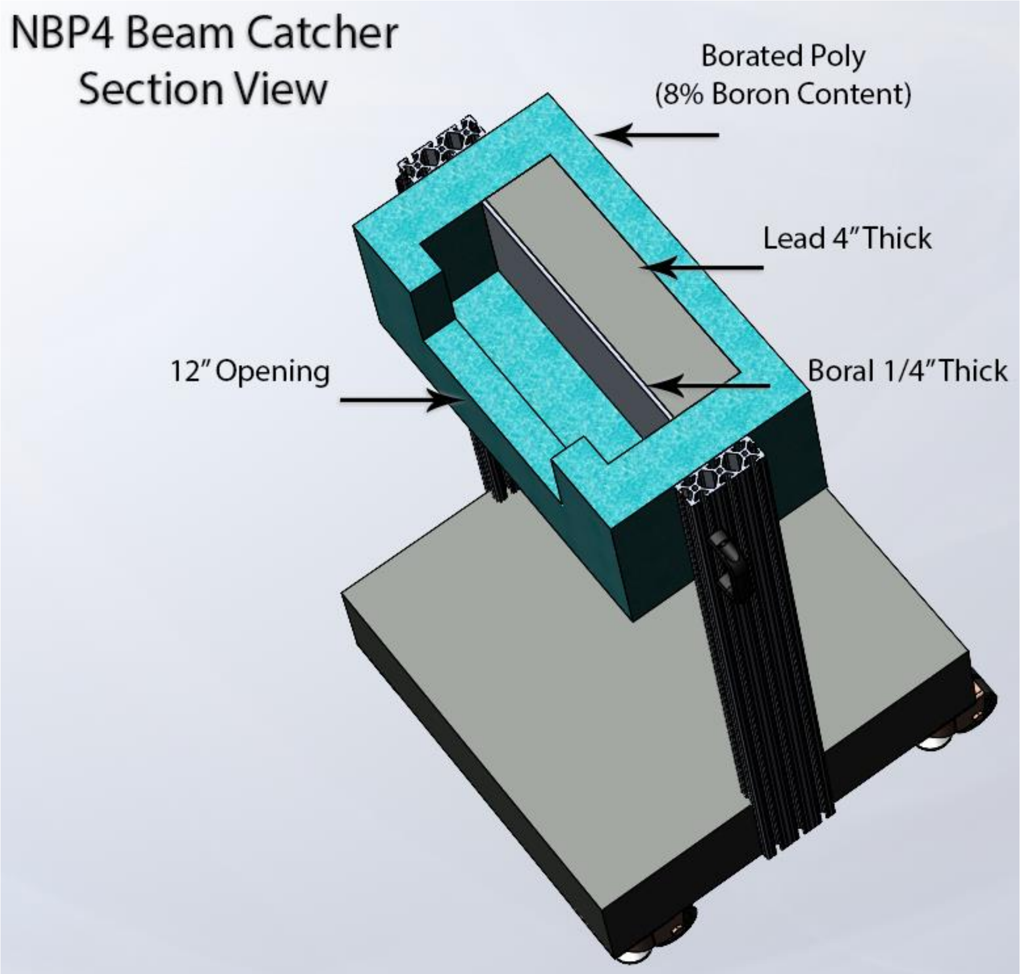
- Optical densiometric analysis performed on the SI and BPI image leads to following resulting information;
  - ✓The values for the H and G were determined to be equal to 4 and 6, respectively*.
  - ✓The thermal neutron content (NC) has been determined to be equal to more than 70.6
  - ✓The resulting values of NC, and G for the collimator-filter-installed system at RSEC corresponds to Category I by ASTM designation of quality*.

ASTM Neutron Radiograph Categories and initial RSEC results

	ASTM				RSEC			
Category	NC	H	G	S	NC	H	G	S
I	65	6	6	5	70.6	-	6	2.8
II	60	6	6	6	-	-	-	-
III	55	5	5	7	-	-	-	-
IV	50	4	5	8	-	4*	-	-
V	45	3	5	9	-	-	-	-

Upcoming Plans for RSEC – NIF





Upcoming Plans for RSEC – NIF

- Microplastics (MP) have become a global environmental concern that needs to be addressed
- There is no generally accepted size of MP; commonly the range is taken as 1 µm to 5 mm
- Typical method to find and analyze the microplastics in the soil involve destructive sample processing
- The Neutron Radiography and Tomography can be a viable solution to detect and analyze MPs in the soil in nondestructive manner
- Different approaches can be taken to differentiate the microplastics from other types of attenuating material (organic matter or/and minerals) – Neutron Imaging can be complementary technique

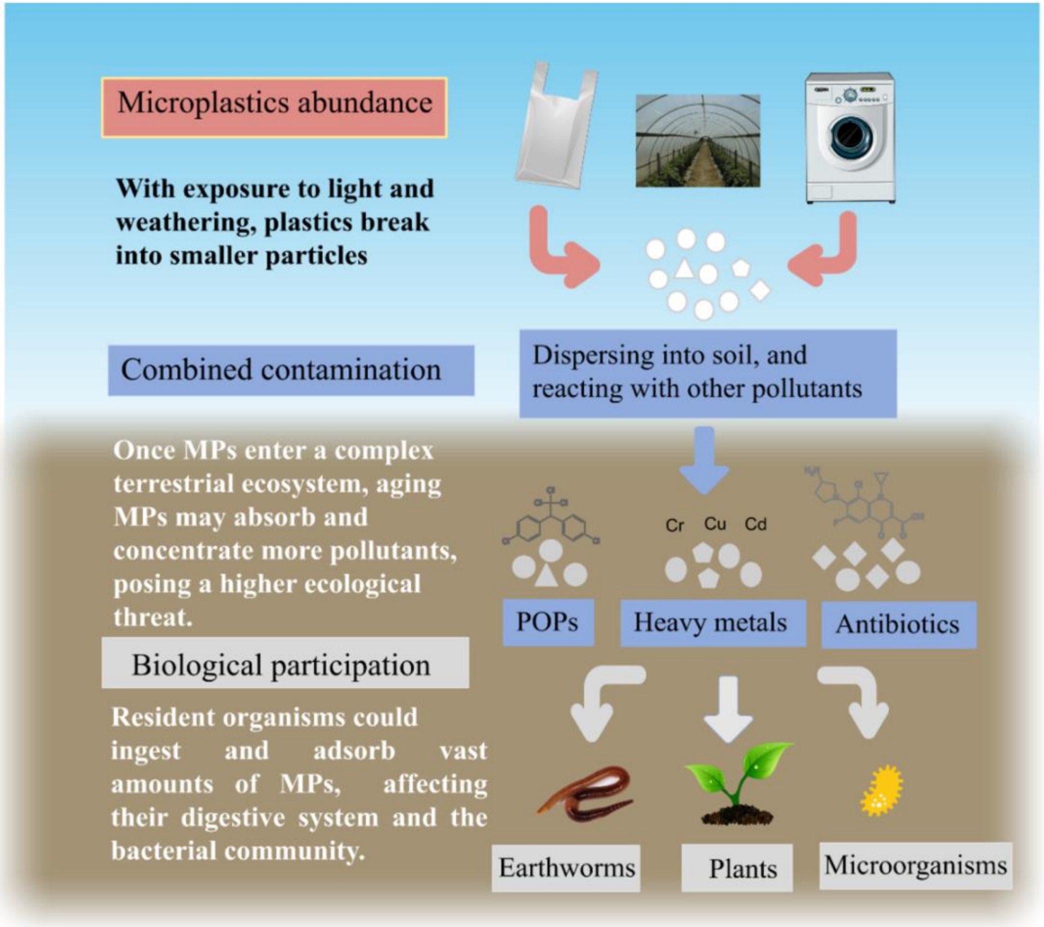


Figure from "Microplastics as contaminants in the soil environment: A mini-review", Jiao Wang, et al., Science of the Total Environment 691 (2019) 848–857

Conclusions and Upcoming Plans

● Gray value profile across exit surface image for the collimator-installed configuration of the beam resulted in $\sim 10 - 25\%$ deviation resulting in more uniform beam profile

● The effective L/D ratio of the system is now between 107 and 115 and can be improved up to 150 by adjusting either L or/and D

● The average thermal flux at the exit surface is equal to $5.4 * 10^6\ n\ cm^{-2} s^{-1}$ at 1 MW power with ~6.4% uncertainty

● The RSEC NIF currently can produce images of high quality, corresponding to Category I facility by ASTM designation of quality*.

● Upcoming plans for the RSEC NIF;

- ✓ Full declaration of the system as Category I by ASTM
- ✓ Design and manufacture of the Beam Catcher and adjustable Sample Table
- ✓ Development of Neutron Tomography Capabilities
- ✓ The neutron to gamma ratio of at least $10^5\ n\ cm^{-2}\ mrem^{-1}$
- ✓ Application of the system