

Oak Ridge Subcritical Assembly Final Design and Current Progress

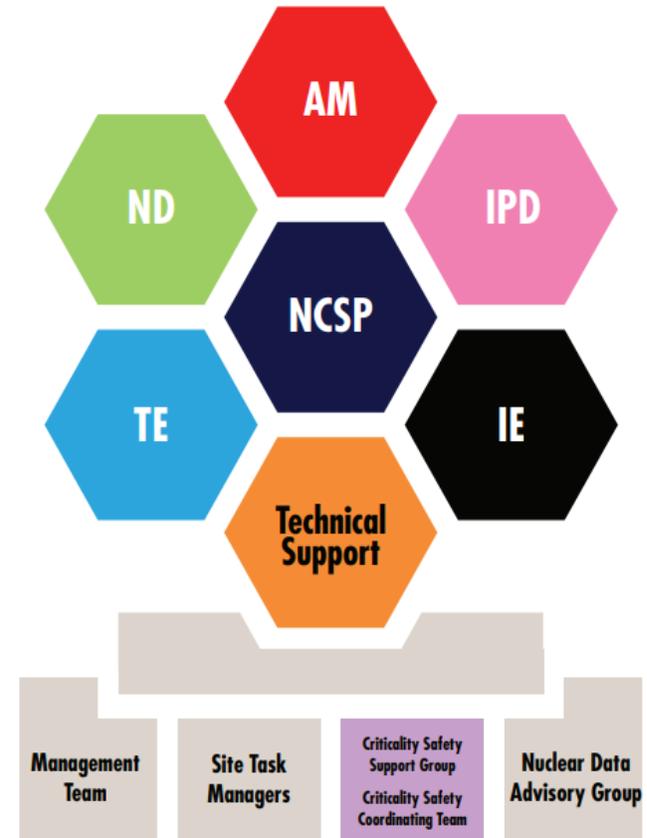
2023 Annual NCSP Technical Program
Review

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Bowen

ORNL is managed by UT-Battelle LLC for the US Department of Energy

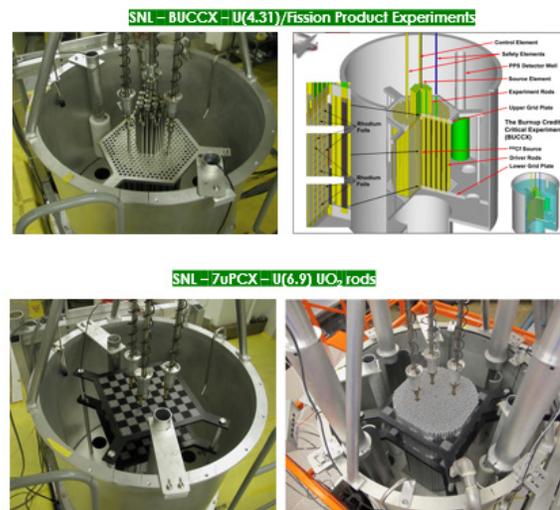
DOE Nuclear Criticality Safety Program

- The US Department of Energy (DOE) Nuclear Criticality Safety Program (NCSP) is chartered with maintaining the technical infrastructure necessary to ensure safe, efficient operations from a criticality perspective.
 - Part of the NCSP mission is to provide Training and Education (TE)
 - This includes sustainable, cost-effective, hands-on training in the behavior of fissionable material systems including those at near critical conditions

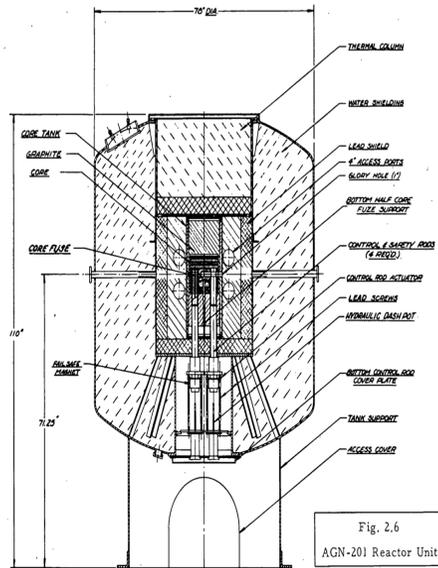


NCSP Training and Education

- Two courses implemented are the 1-week Manager's Course and 2-Week Criticality Safety Engineer Course
 - Courses are offered at Sandia National Lab or Nevada Test Site
- NCSP needs a backup training location with more flexibility
 - COVID-19 and facility incidents have created a backlog of students
 - Needs to add additional flexibility for students that are foreign nationals or uncleared
 - Needs more diversity in geographical location



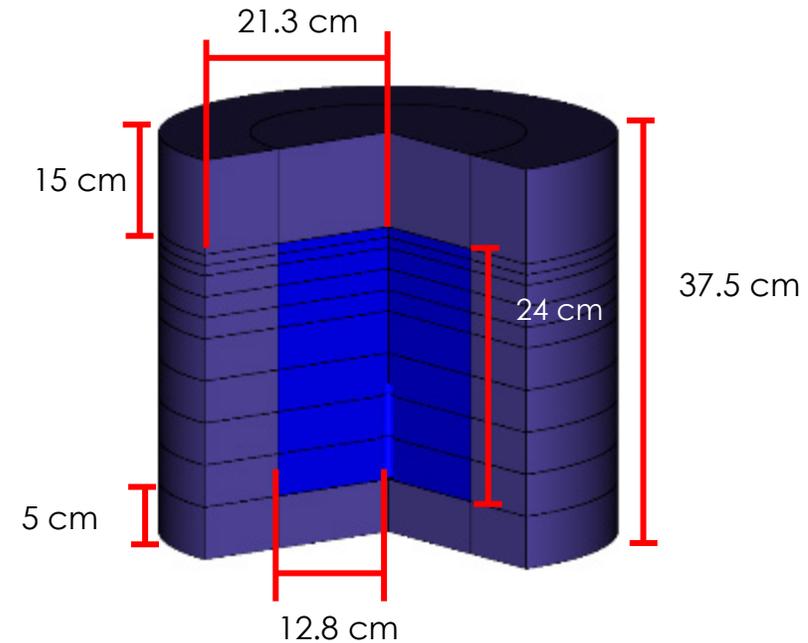
AGN-201M Fuel for Subcritical Assembly



- Fuel from several assemblies are currently stored at Y-12
 - Nearby and able to customize configuration to our needs
- 19.5 wt% ^{235}U UO_2 powder matrixed in polyethylene
 - Solid material and easy to physically manage
 - Material is Cat. IV and Attractiveness E: Security Requirements are manageable.
- Total ^{235}U mass can be under the single-parameter subcritical limit while maximizing neutron multiplication
 - Criticality not credible. Ability to operate in \leq Cat. 3 Facility
 - Enough multiplication to demonstrate criticality safety to students
- The properties of this fuel allow easy management in a secure, safe, and regulatory manner.

ORSA Conceptual Design

- Graphite Reflector (purple) at 2.3 g/cc
 - Total mass 105 kg (231 lbs)
- Poly fuel plates (blue)
- Stacking Configuration (Bottom – Top)
 - 2 4-cm disks with support cutout
 - 1 4-cm disk with partial support cutout
 - 1 4-cm disk with only control rod cutout
 - 3 2-cm disks
 - 2 1-cm disks
- Not shown: Al rod placed in core support cutout



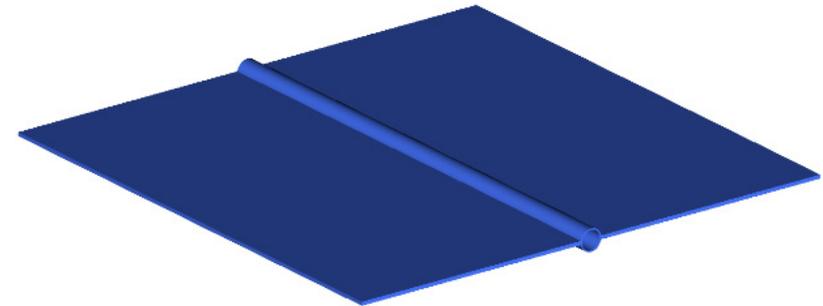
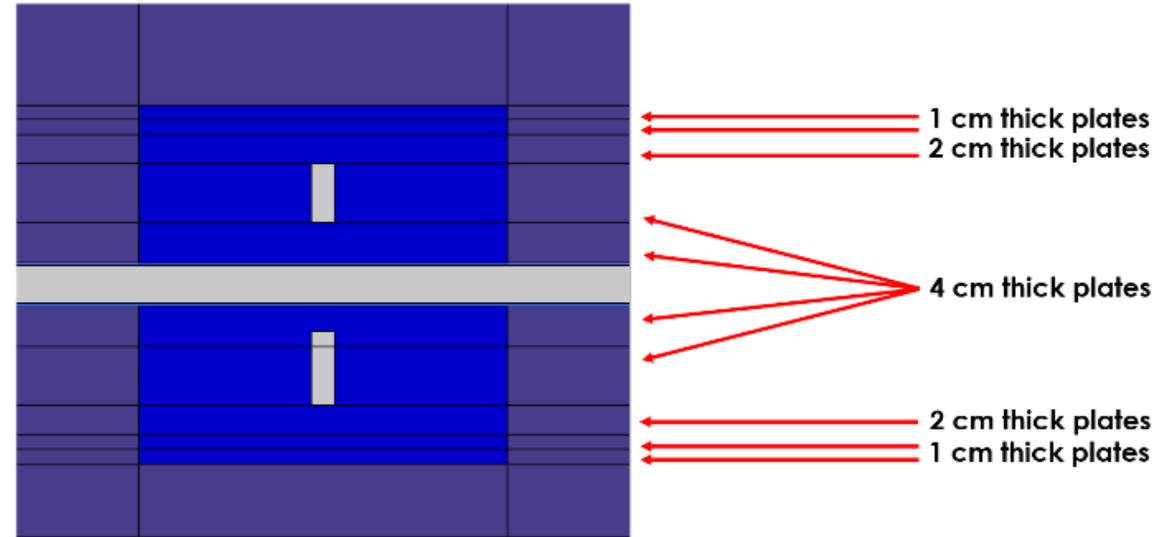
$$m_{\text{U-235}} = 620.29 \text{ grams}$$
$$k_{\text{eff}} \sim 0.94723$$

Image Reference:

Bowen, Douglas, Holcomb, Andrew and Hart, Shane. Feasibility Study for a Subcritical Assembly at the Oak Ridge National Laboratory, ORNL/TM-2020-1598. Oak Ridge, TN, August 2020.

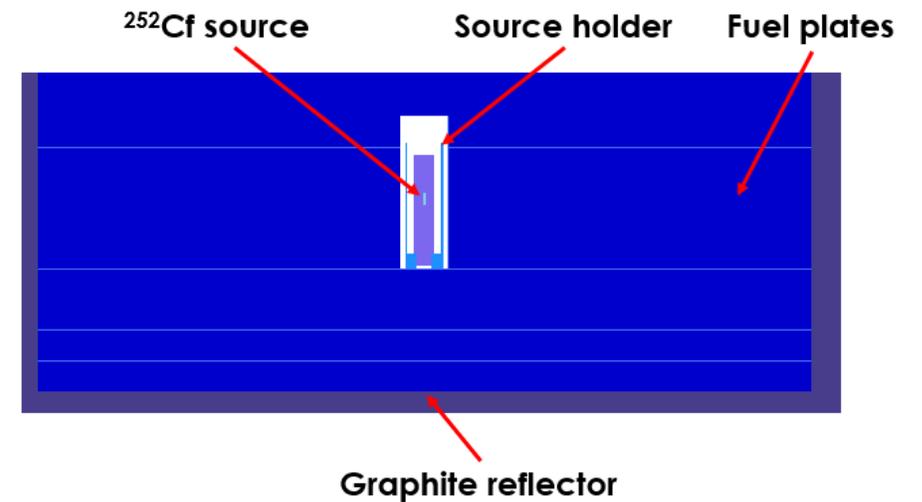
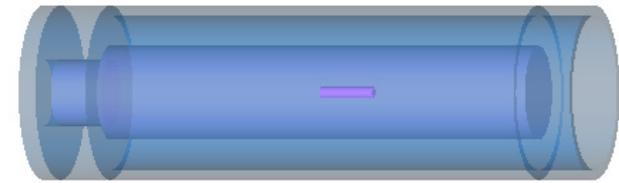
ORSA Design Changes

- Changes made
 - Removed Al Rod
 - Change Disk Layout
 - 2 4-cm disk with glory hole cutout
 - 2 4-cm disk with control rod cutout
 - 4 1-cm disk
 - 2 1-cm disk
 - Added Baffle Plate
 - Considered for detector placement
 - Considered for other measurement types (e.g., material worth and source jerk experiment)



ORSA Design Changes

- Changes made
 - Removed Al Rod
 - Change Disk Layout
 - Added Baffle Plate
 - Added Neutron Source
 - ^{252}Cf Source



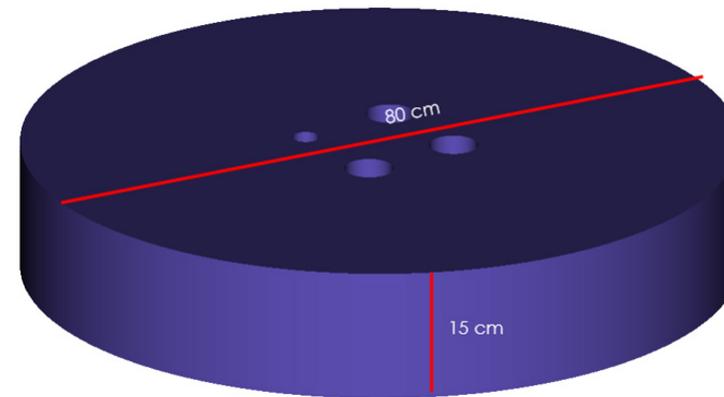
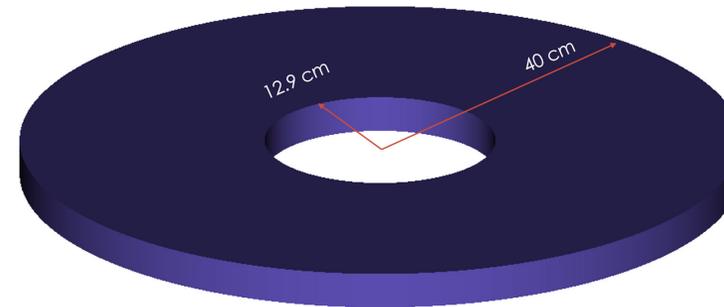
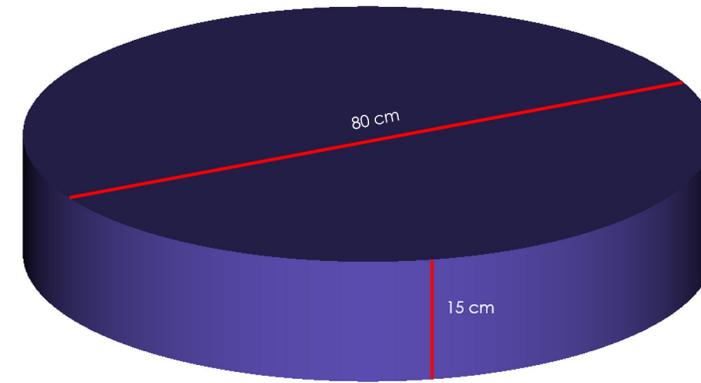
ORSA Design Changes

- Changes made
 - Removed Al Rod
 - Change Disk Layout
 - Added Baffle Plate
 - Added Neutron Source
 - Encasing Fuel Plates
 - Went with epoxy sealing of sources
 - ORNL has demonstrated this practice with metal sources
 - UNM personnel use a similar practice
 - Considered aluminum cladding
 - Gaps and risk with welding/crimping too risky



ORSA Design Changes

- Changes made
 - Removed Al Rod
 - Change Disk Layout
 - Added Baffle Plate
 - Added Neutron Source
 - Encasing Fuel Plates
 - Adjustments to Graphite
 - Applied realistic density of 1.75 g/cc
 - Increase of reflection needed
 - Baffle plate separation
 - Encasing of fuel
 - Reflector Mass
 - Top/Bottom - 132 kg each
 - Annular disk - 7.9 kg/cm-thick
 - **Total Reflector mass - 452.2 kg**



ORSA Design Changes

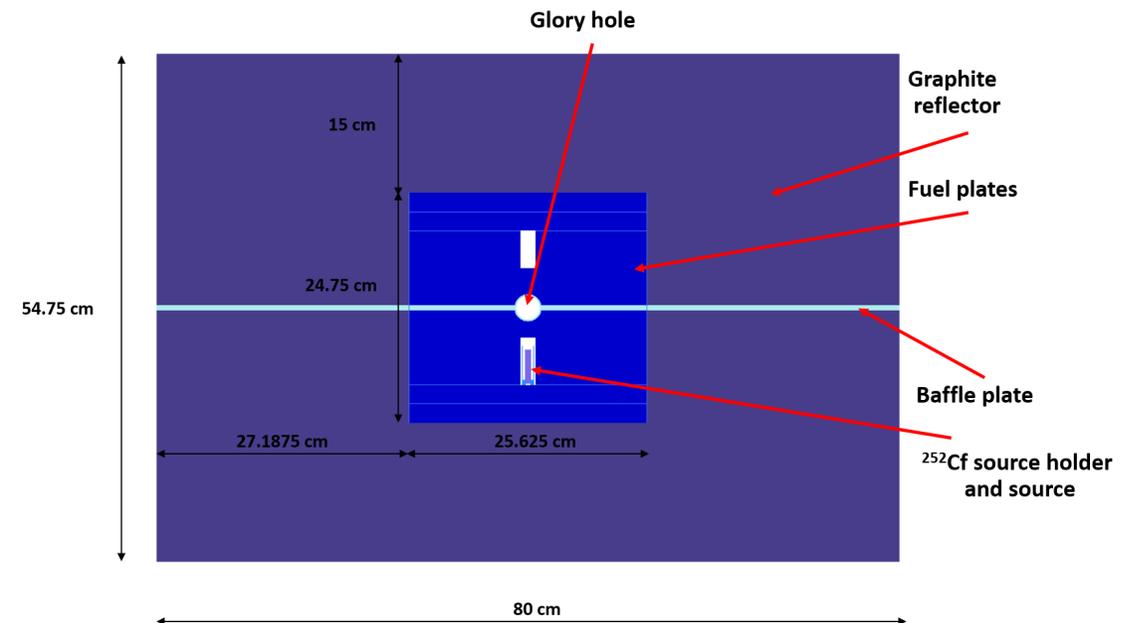
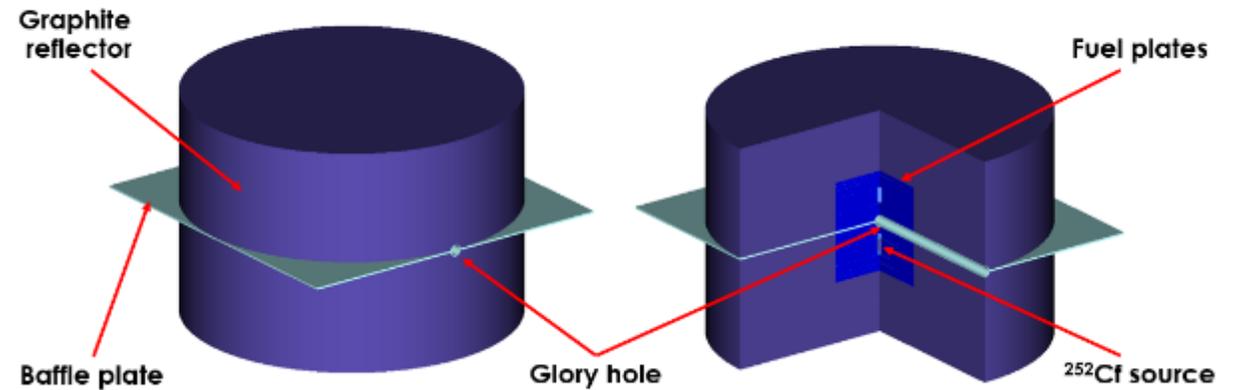
- Changes made
 - Removed Al Rod
 - Change Disk Layout
 - Added Baffle Plate
 - Added Neutron Source
 - Encasing Fuel Plates
 - Adjustments to Graphite
 - Adjustment to Fuel Plate Composition
 - Most reactors were built in the '50s
 - Fuel Plates were made per reactor and will be unique
 - ORNL/TM-2019/1410 evaluates UNM reactor disks with multiple measurement techniques (mass spec and NDA)
 - Used average values for all plates
 - Will need to analyze received disks

Reference Report for Material Composition	Δk from # 5 (pcm)
#1 ORNL/TM-2019/1410 Table 8-1 plate 20497 with corrected H and C (2019)	-1493
#2 ORNL TM Table 8-1 average of all plates with corrected H and C (2022)	-1068
#3 Idaho State University M.S. Thesis (2012)	-244
#4 BWXT report (2007)	-1573
#5 ORSA Conceptual Design (2020)	0

ORSA Design Changes

- Changes made
 - Removed Al Rod
 - Change Disk Layout
 - Added Baffle Plate
 - Added Neutron Source
 - Encasing Fuel Plates
 - Adjustments to Graphite
 - Adjustment to Fuel Plate Composition

Total ^{235}U mass ~ 617.2 g
 $k_{\text{eff}} = 0.95024 \pm 0.0003$



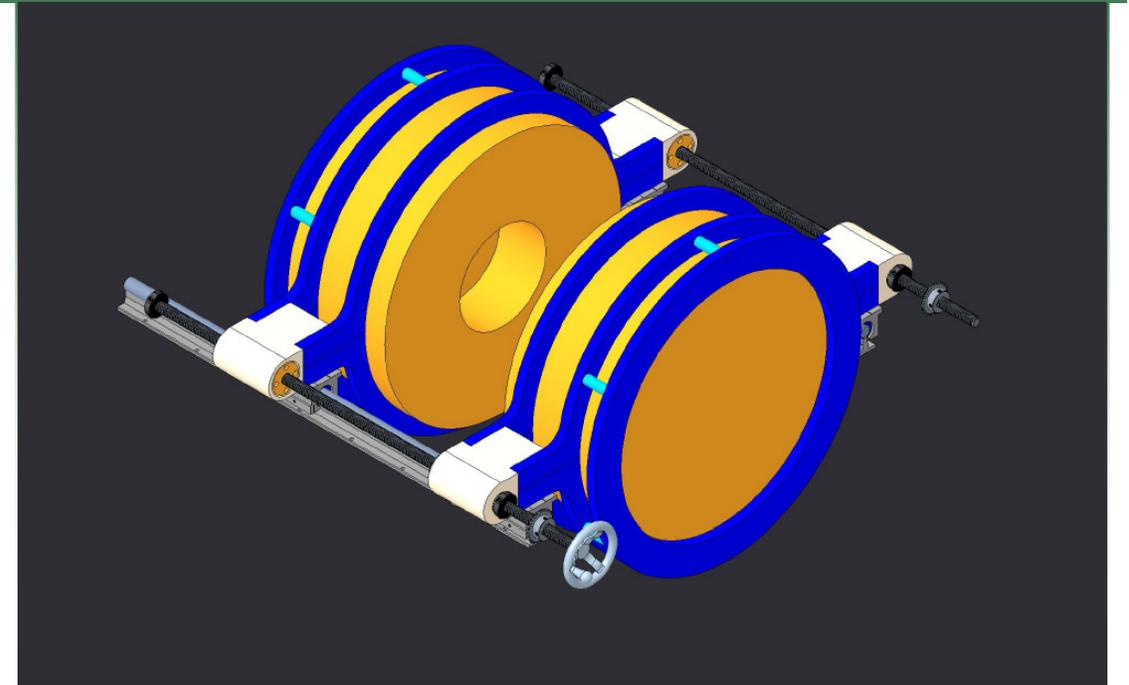
Assembly Design Concepts

Vertical Split Assembly



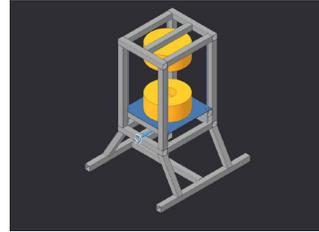
Base: 62" x 72"
Height: 90"

Horizontal Split Assembly



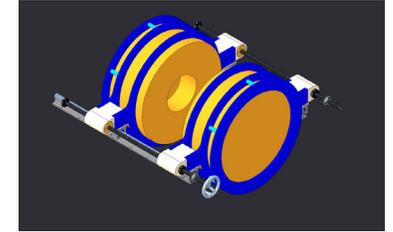
Base: 49" x 60.4"
Height: Standard Table Height

Assembly Design Concepts



Vertical Split

- Advantages
 - Typical design of current critical assemblies
 - Non-reflector measurements are trivial
- Disadvantages
 - Top portion is heavy and requires support
 - Students may have to use a ladder for assembly
 - Adding reflectors to the top portion when fuel is split



Horizontal Split

- Advantages
 - Design can be installed on a table
 - Ergonomically better for students
- Disadvantages
 - Design challenges with stacking fuel plates without reflectors
 - Design challenges for keeping fuel plates in reflectors

Approach to Critical with Subcritical Systems

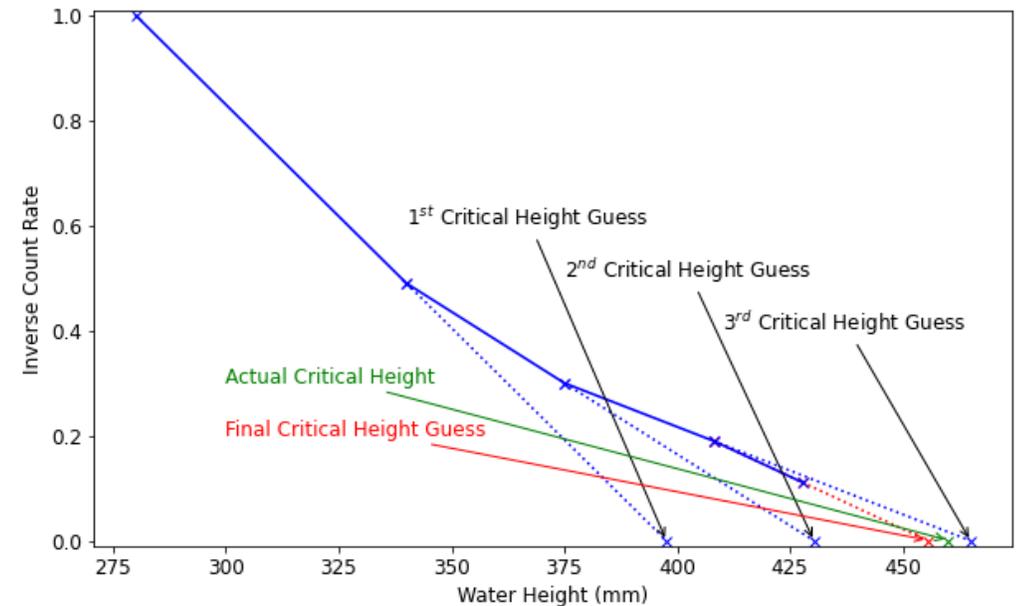
- Approach to critical will use the reciprocal multiplication method
- While a system is subcritical
 - Adding fuel to a steady-state neutron source will amplify the source to a new steady-state flux
 - The amplification (M) is related to k_{eff}

$$M = \frac{1}{1 - k}$$

- k_{eff} of 0.95 is a factor 20 multiplication
- As the system approaches critical, the inverse of the multiplication approaches zero

$$\text{As } k \rightarrow 1, \frac{1}{M} \rightarrow 0$$

1/M measurements performed during Hands-On Training at SNL with SPR/CRX Critical Facility

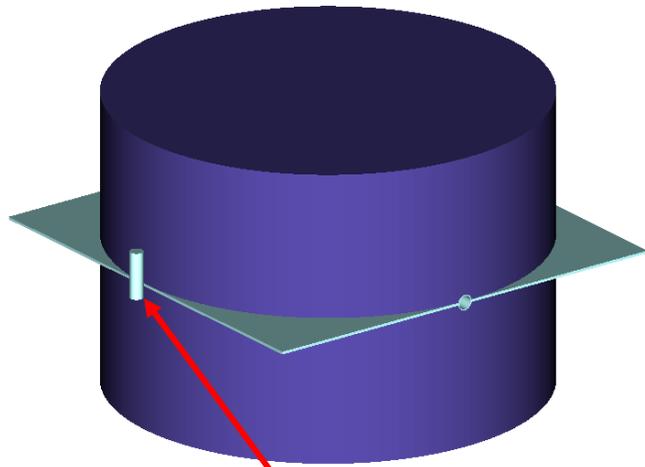
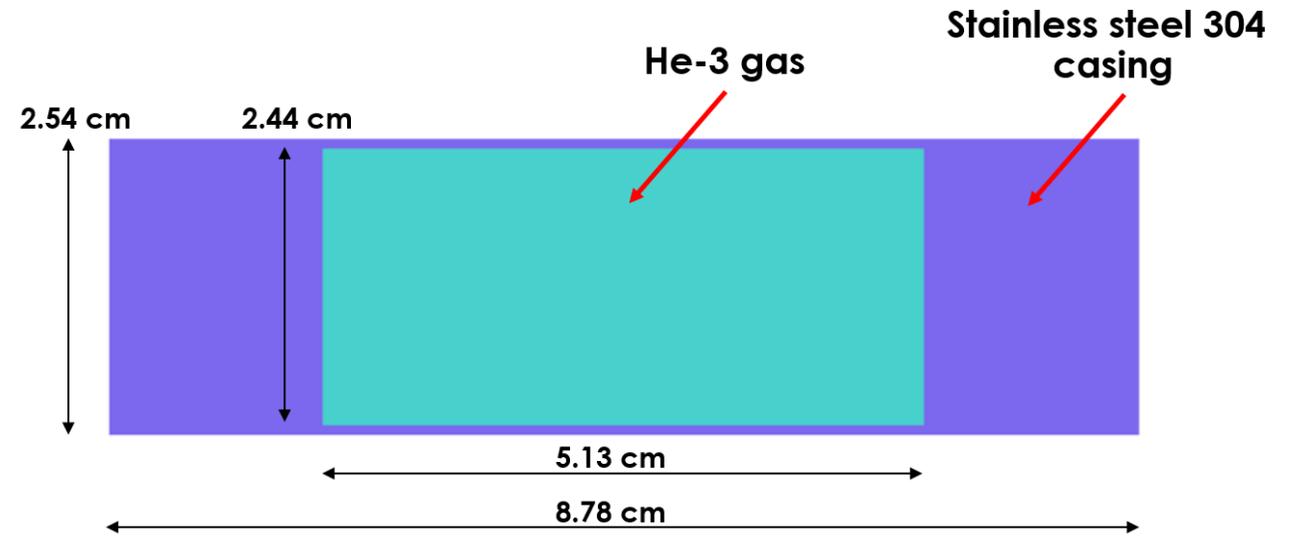


Hands-On Experiments

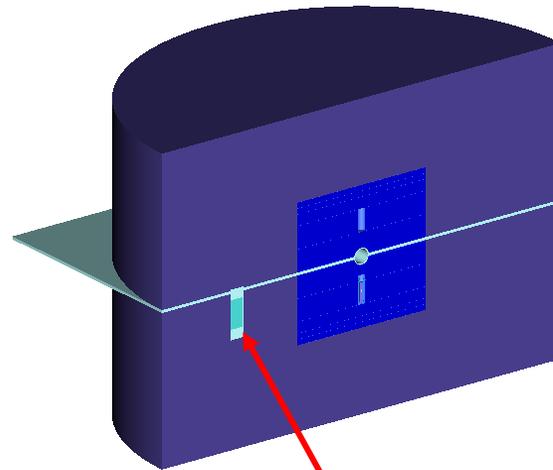
- Hands-on Experiments will use the Reciprocal Multiplication Method
- Students will perform 4 experiments
 - Experiment 1: Mass and Reflection
 - Experiment 2: Interaction
 - Experiment 3: Moderation
 - Experiment 4: Absorption
- Simulated experiments with 3 detector Placements

Detector Evaluation

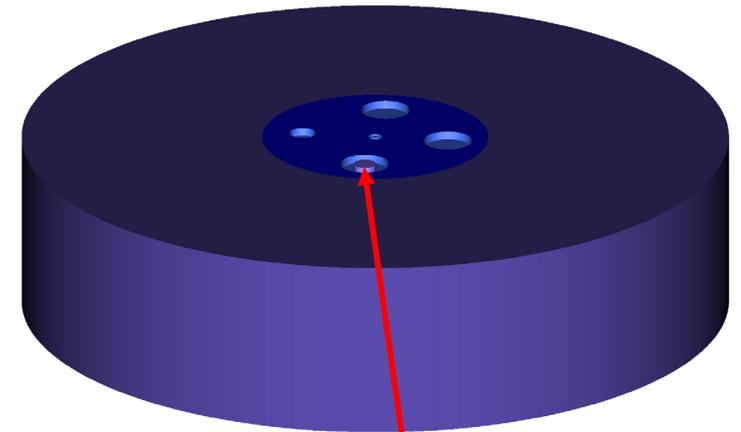
- Evaluated detector placement to ensure 1/M curve
- Models currently use ^3He detector



^3He detector 1



^3He detector 2

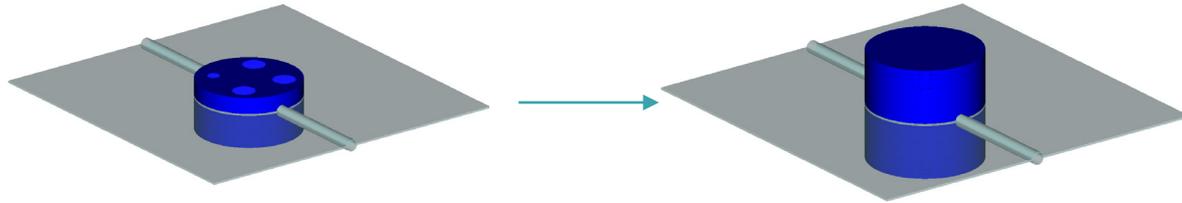


^3He detector 3

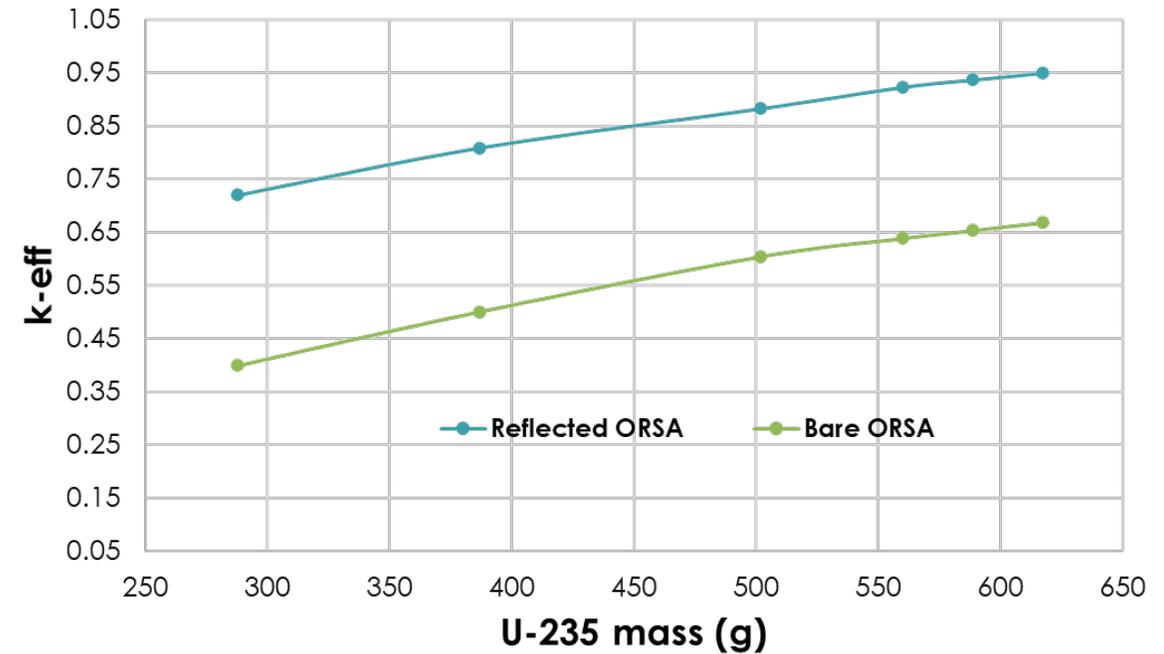
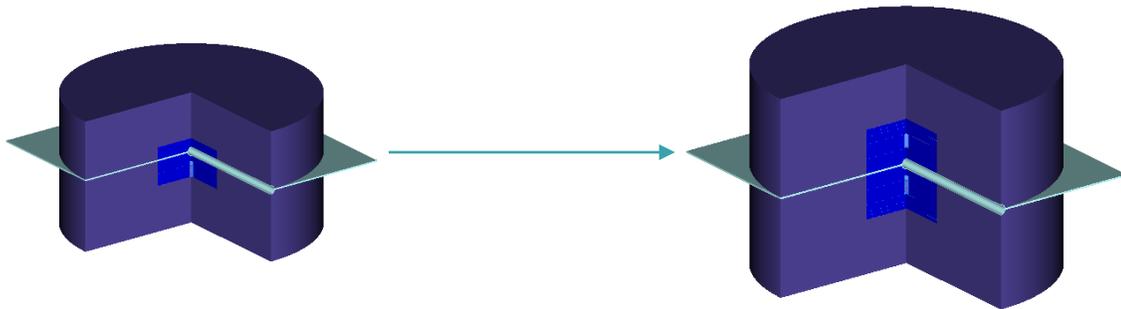
Hands-On Experiments

Experiment 1: Mass and Reflection

- Mass
 - Students start with 4 disks
 - No graphite reflection
 - Add until full stack

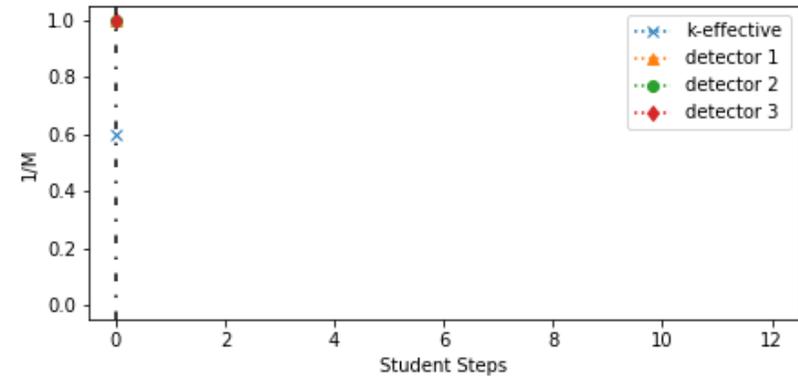
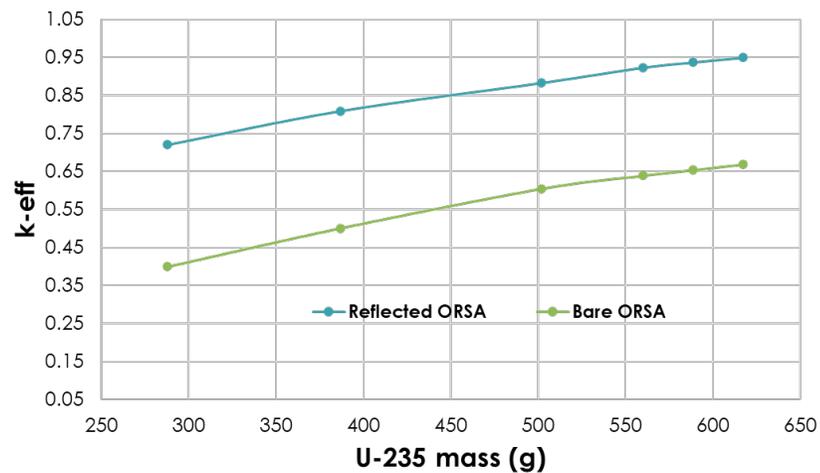
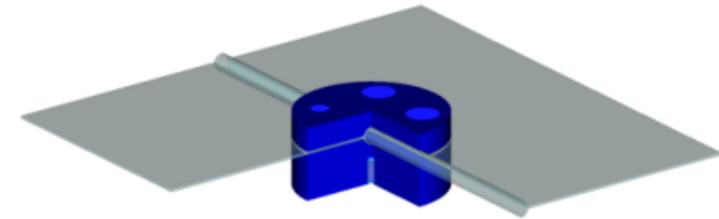
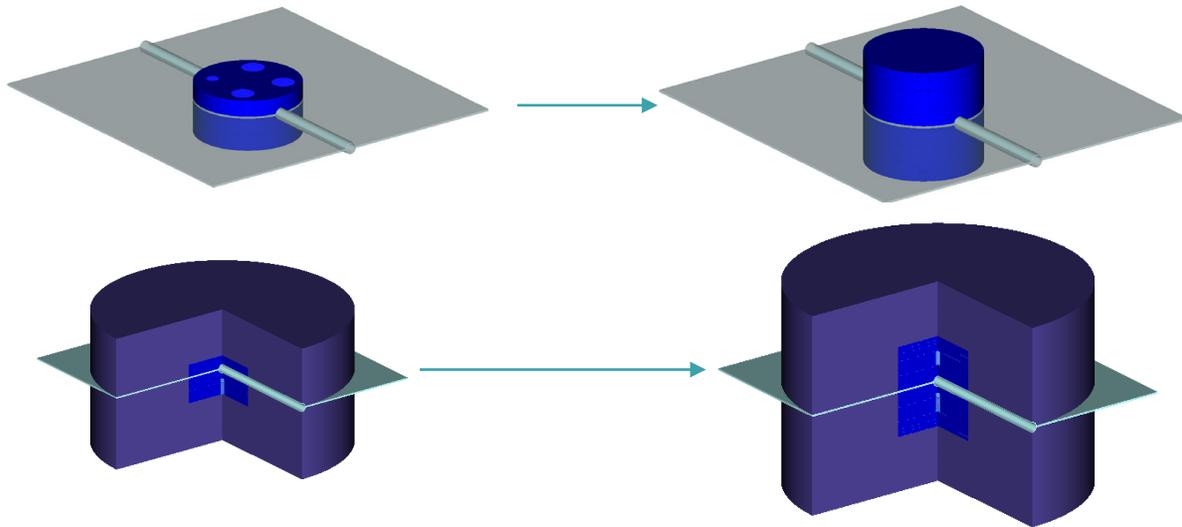


- Students will start over but with graphite reflector



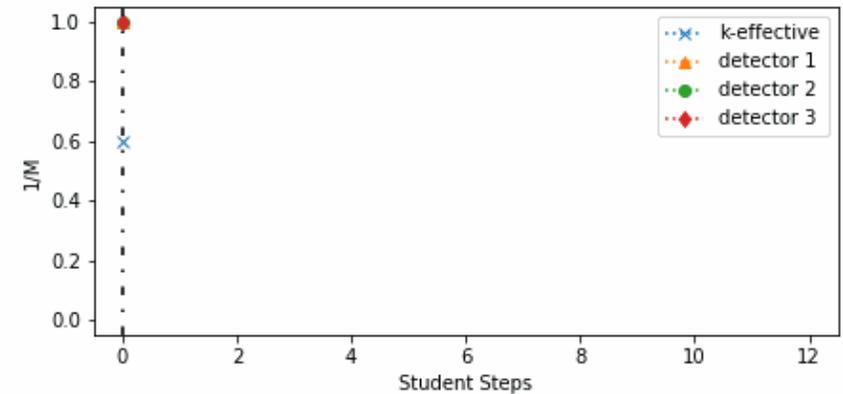
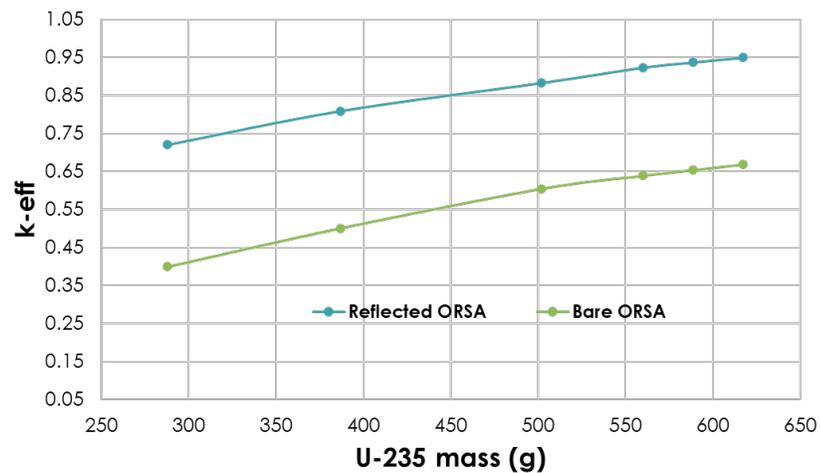
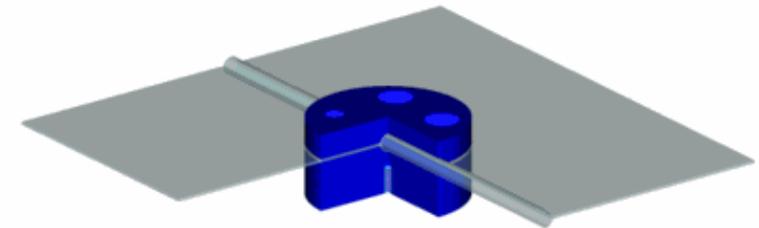
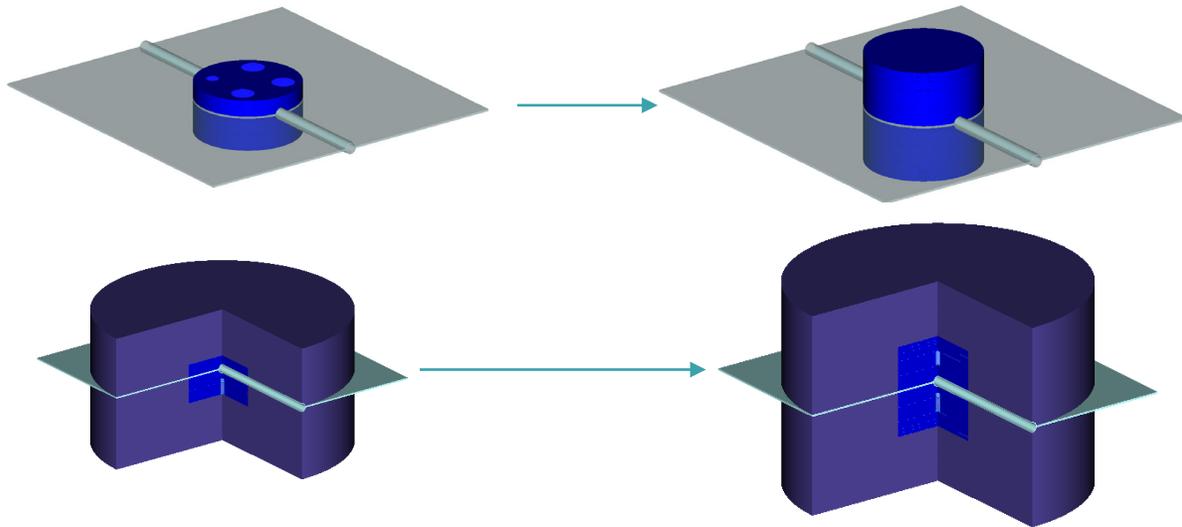
Hands-On Experiments

Experiment 1: Mass and Reflection



Hands-On Experiments

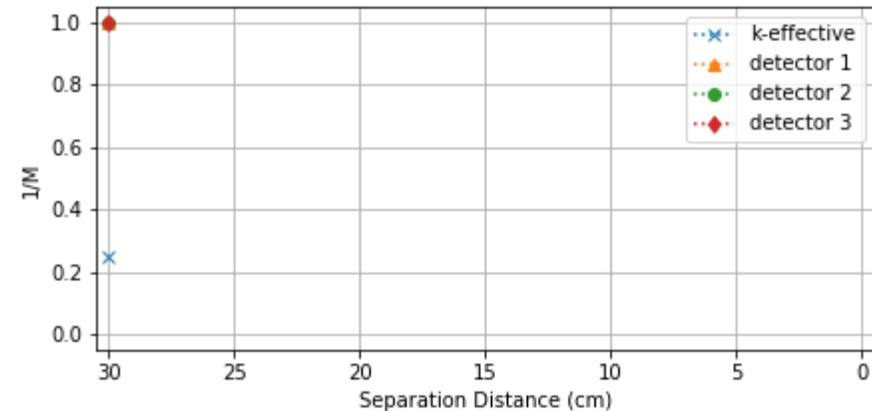
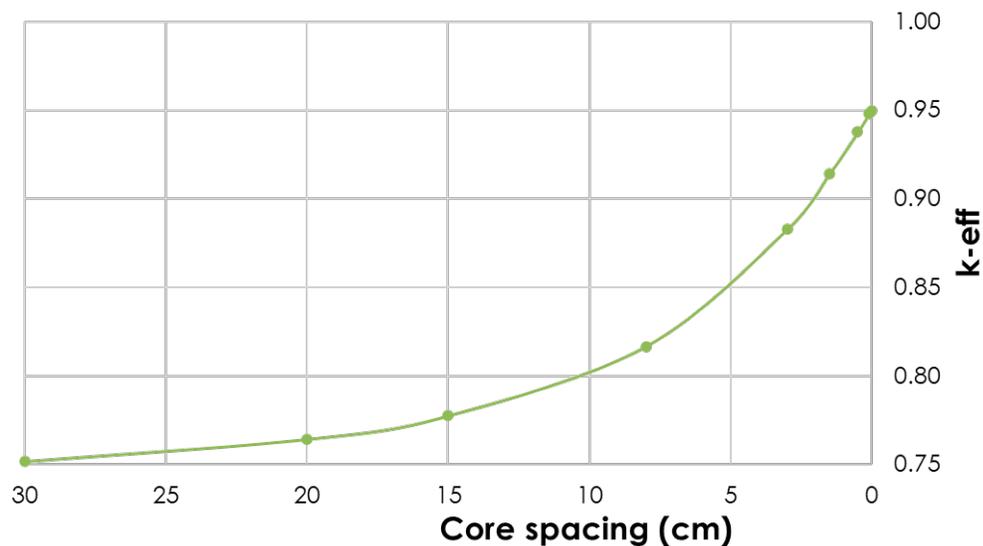
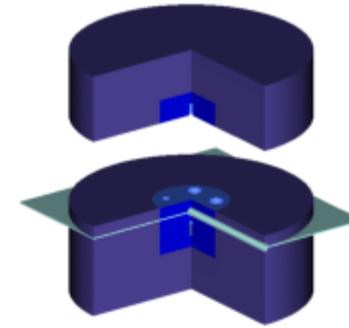
Experiment 1: Mass and Reflection



Hands-On Experiments

Experiment 2: Interaction

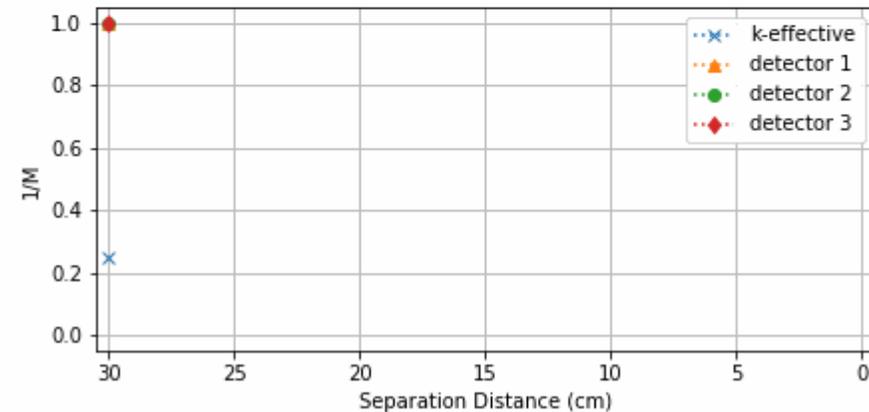
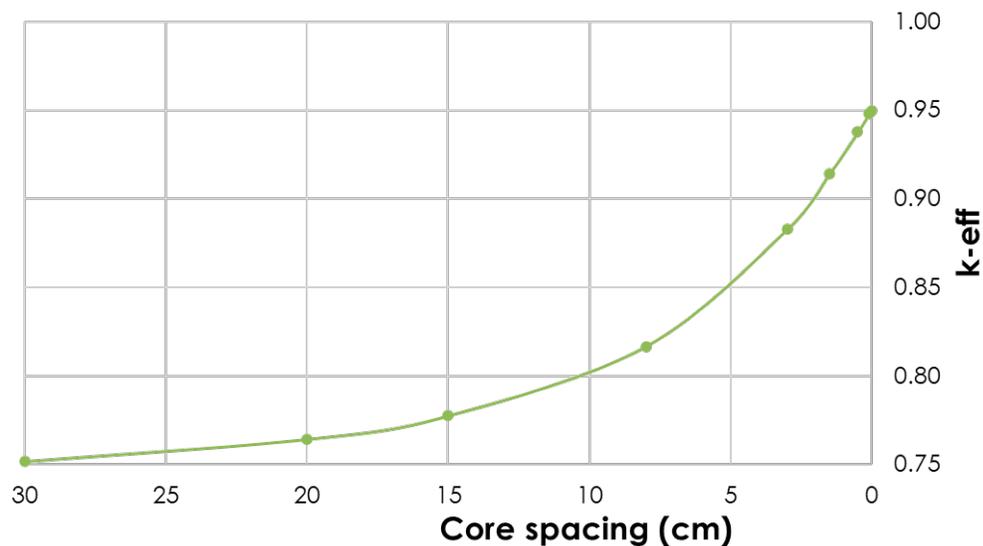
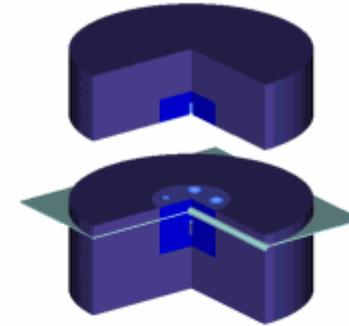
- Interaction
 - Fully-Reflected Assembly
 - Separation starts at 30-cm



Hands-On Experiments

Experiment 2: Interaction

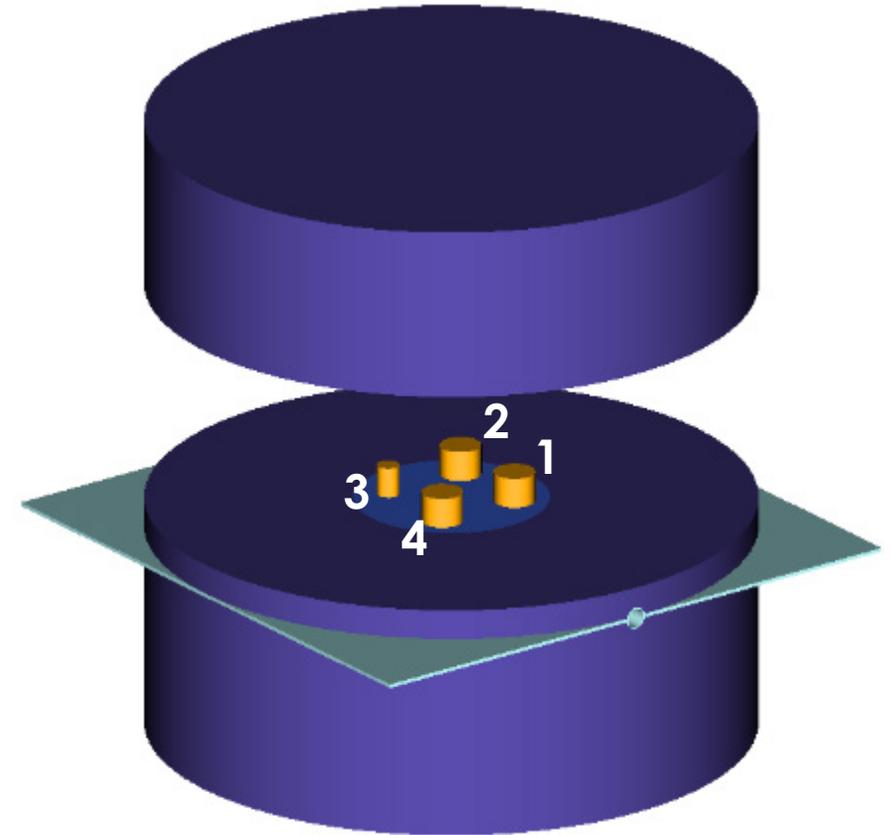
- Interaction
 - Fully-Reflected Assembly
 - Separation starts at 30-cm



Hands-On Experiments

Experiment 3: Moderators

Material	Source Multiplication (M)				
	No Rods	Rod 1	Rods 1-2	Rods 1-3	Rods 1-4
HDPE	20.1	21.0	22.3	23.7	25.5
H ₂ O (20°C)	-	21.4	23.2	23.7	27.2
H ₂ O (70°C)	-	21.9	24.4	26.0	29.7
D ₂ O (20°C)	-	23.5	29.7	31.8	43.6
Be	-	24.4	32.6	35.9	55.2

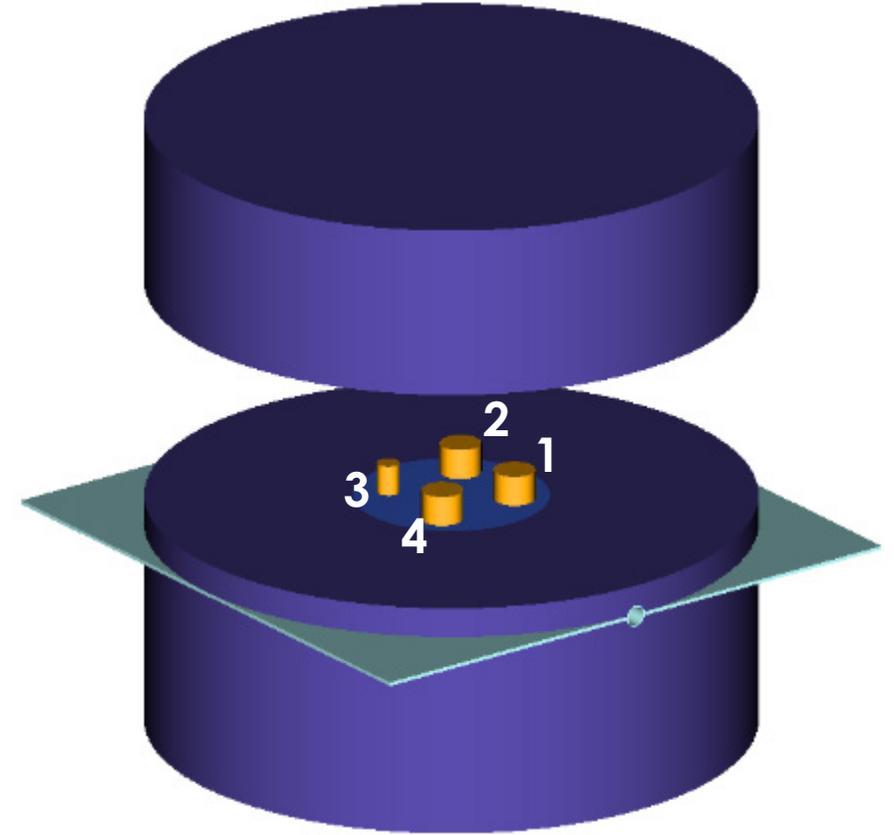


Please note that this is a conceptual exercise to identify possible student hands-on experiments

Hands-On Experiments

Experiment 4: Absorbers

	Source Multiplication (M)				
Material	No Rods	Rod 1	Rods 1-2	Rods 1-3	Rods 1-4
Al	20.1	19.7	19.4	19.2	19
Borated HDPE	-	11.7	8.2	6.7	5.1
SS304	-	15.4	12.4	11	9.2
Sulfur	-	18.4	17.1	16.5	15.5
B ₄ C	-	3.2	2.9	2.7	2.4

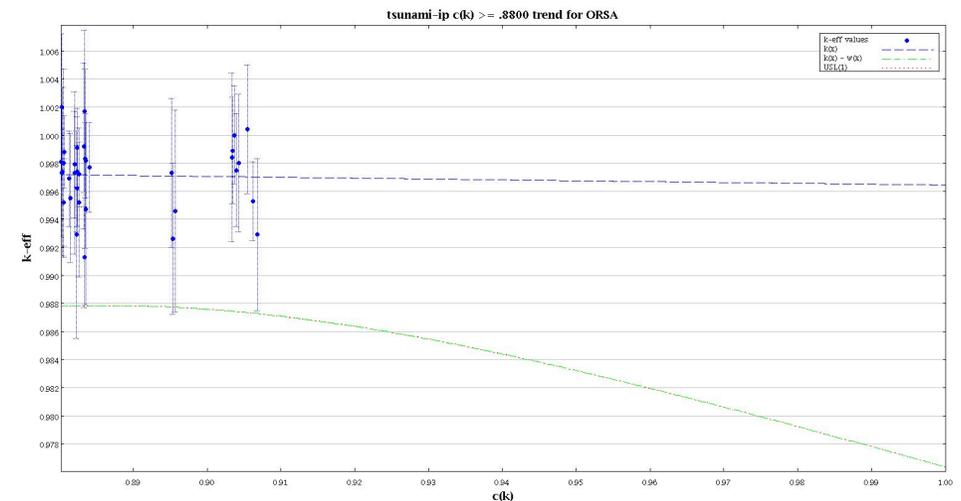
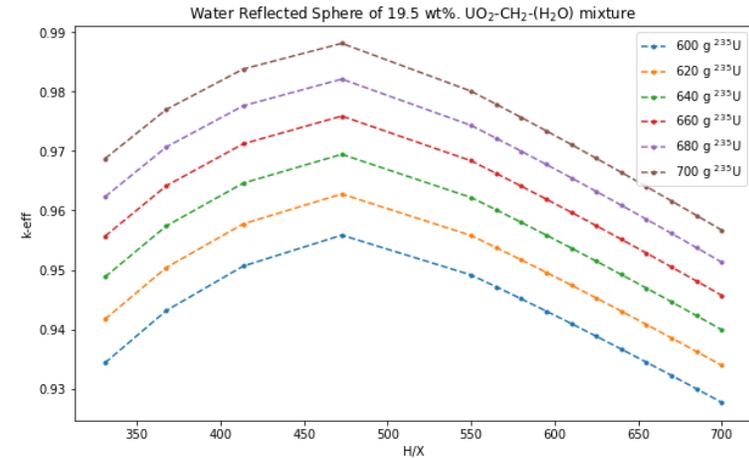


Regulatory Considerations

- Nuclear Criticality Safety
 - ANSI/ANS-8.1
 - System is below the single-parameter subcritical limit for U-235. A criticality is not credible
 - ANSI/ANS-1
 - Manual operations shall not exceed a multiplication factor higher than 20 ($k_{\text{eff}} \sim 0.95$)
 - Not required for a subcritical assembly, but following guidance
 - If the moderator experiment exceeds 20 multiplication, activity will remain below USL
- Facility Safety
 - DOE-STD-1027
 - Since criticality is not credible, operations can be held in a \leq Cat. 3 Facility
 - Segregation controls may be necessary to ensure facility inventory meets this Standard

Regulatory Considerations -Criticality Safety Scoping Studies

- Water-reflected spheres
 - Spheres with UO_2 at 19.5 wt% enriched
 - 30 cm thick H_2O reflection
 - Add CH_2 until ORSA mixture ratio is reached ($\text{H}/\text{X} \sim 550$)
 - Additional moderator added is H_2O
- Validation
 - Validation based on complete assembly of ORSA with full graphite reflection
 - Similarity assessment (c_k) used to determine applicable benchmarks
 - 35 cases from VALID with $c_k \geq 0.88$
 - USL – 0.9763



Regulatory Considerations

- Nuclear Material Control & Accountability
 - Fuel disks considered Cat. IV Attractiveness Level 3
 - Will require an MBA custodian and a secure place for storage when not in use
- Radiological Safety
 - Radiological Dose
 - Uranium is primarily an alpha emitter. Neutron source will be the primary contributor to dose
 - Radiological Contamination
 - Polyethylene plates could be considered potential contamination from handling
 - Rubber coating has been demonstrated at ORNL and a similar practice works for the AGN-201M reactor at UNM

Regulatory Considerations - Dose Estimations

- Dose calculated using MAVRIC

Source Description	Total dose rate at 1 meter ($\mu\text{Gy/h}$)	Total dose rate at 2 meter ($\mu\text{Gy/h}$)	Total dose rate at 3 meter ($\mu\text{Gy/h}$)
^{252}Cf Source (0.27 mCi)	6.13×10^{-1}	1.54×10^{-1}	6.77×10^{-2}
4 plates – no reflector	3.32×10^{-1}	8.26×10^{-2}	3.65×10^{-2}
4 plates with reflector	5.76×10^{-1}	1.43×10^{-1}	6.31×10^{-2}
Full Assembly with reflector	8.64×10^{-1}	2.02×10^{-1}	8.72×10^{-2}

Location Comparison Criteria

Criterion	Description	Criterion Importance
1	Minimal Impact to Safety Analysis	+4
2	Minimal Impact to Industrial/Radiological Safety	+3
3	Minimal Impact to ORNL's Current Missions	+3
4	Minimal modifications needed for building	+2
5	Human Comforts	+1

Qualitative Overview Results

Building	Criteria					Total
	1	2	3	4	5	
7709	✓	✗	✓	✗	✗	7
7735	✓	✗	✗	✓	✓	7
7710	✓	✓	✗	✗	✗	7
1521	✗	✓	✗	✓	✓	6
1509	✗	✓	✗	✓	✓	6
5500 X-Ray Vault	✗	✓	✗	✓	✓	6
5800	✗	✗	✓	✓	✓	6
7603	✗(✓)	✓	✓	✓	✓	9 (13)
7603-Vault	✓	✓	✓	✓	✓	13

- 7603 area shows the most promising.
- The two primary challenges with all other areas
 - Laboratories could not meet criterion 1 because ORSA caps the administrative facility inventories and requires “source shuffling” for the ORNL complex
 - Laboratories could not meet criterion 2 due to high-priority missions that could interfere with training at a moment’s notice

7603 Area

- 7603 has lab spaces owned by Fusion and Fission Energy Science Division (FFESD) and Nuclear Nonproliferation Division (NND)
- ORNL is currently modernizing lab space throughout the complex
 - In recent discussions, FFESD has offered a dedicated lab space in 7603 to perform the training
 - Dedicated lab space has the potential to meet security and segregation requirements
 - However, this space availability is dependent on the modernization schedule
- Discussions with NND provide options that are available for the implementation of ORSA

7603 Area – Vault Option

- NND also owns 7603 labs and vault areas near 7603
 - Meetings resulted in positive collaboration
 - ORSA beneficial for both parties
 - New uranium source for the group
 - Flexibility to perform classes
- Building labs would require “source shuffling”
 - NND proposed procuring a vault as a dedicated space meeting segregation and security requirements
- Vault would allow ORSA a fixed area for experimentation
 - Vault is relatively inexpensive
 - Hands-On experiments can be performed comfortably within the vault
 - Would not be impacted by other missions
 - Easy location and close to 7603 facility
 - Can easily handle a diverse student base with minimal hassle



Conclusions

- ORSA design has moved from conceptual to implementable
- ORSA hands-on experiments will remain subcritical under normal and credible abnormal conditions
 - Fully-assembled $k_{\text{eff}} = 0.95024 \pm 0.0003$
 - USL = 0.9763
- Locations will have minimal security and safety basis impact
 - Available options can meet security criteria for ORSA material
 - Options will have less mass than the ANS-8.1 single parameter limit for ^{235}U either by segregation or functioning as its own facility
- Locations are feasible for a diversity of students
- The implementation of ORSA will improve upon NCSP T&E's vision to remain adaptable and responsive