ORNL/TM-2022/2748

Proposed Subcritical Assembly for Nuclear Criticality Safety Training at the Oak Ridge National Laboratory

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January 2023

OAK RIDGE
National Laboratory

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Fusion and Fission Energy and Science Division
and
DOE/NNSA Nuclear Criticality Safety Program

PROPOSED SUBCRITICAL ASSEMBLY FOR NUCLEAR CRITICALITY SAFETY TRAINING AT THE OAK RIDGE NATIONAL LABORATORY

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ACRONYMS AND ABBREVIATIONS

AGN-201M	Aerojet-General Nucleonics 201-M Research Reactor
BeRP	beryllium-reflected plutonium
CCR	coarse control rod
DAF	Device Assembly Facility
DOE	US Department of Energy
FCR	fine control rod
ICSBEP	International Criticality Safety Benchmark Experiments Project
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
NCERC	National Criticality Experiments Research Center
NCS	nuclear criticality safety
NCSP	Nuclear Criticality Safety Program
NDA	non-destructive assay
NNSA	National Nuclear Security Administration
NNSS	Nevada National Security Site
ORNL	Oak Ridge National Laboratory
ORSA	Oak Ridge Subcritical Assembly
SNL	Sandia National Laboratories
SNM	special nuclear material
SPR/CX	Sandia Pulse Reactor/Critical Experiment
SR	safety rods
T&E	training and education
TACS	Training Assembly for Criticality Safety
Y-12	Y-12 National Security Complex

ABSTRACT

The design of a new subcritical assembly at Oak Ridge National Laboratory (ORNL) has been finalized. This design takes the feasibility study of the subcritical assembly performed in August 2020 [1] to an implementable design. This subcritical assembly will support the Nuclear Criticality Safety Program (NCSP) training and education program. The addition of this subcritical assembly into the NCSP training and education will enhance the program by providing backup capacity for training if nuclear facility operations are disrupted at Sandia National Laboratories or the National Criticality Experiments Research Center; providing a new location that is more accessible to students in the Eastern portion of the United States; providing flexibility to support students from a diverse background (e.g., university students, foreign nationals). The proposed subcritical assembly uses legacy AGN-201M research reactor fuel plates that are available at the Y-12 National Security Complex. The final design of this subcritical assembly contains approximately 617 grams of ^{235}U as UO_2 powder distributed homogeneously in polyethylene. The fuel plates will have a graphite neutron reflector to obtain a core multiplication, *M*, from 10 to 20, corresponding to a k_{eff} of 0.90 to 0.95, respectively. The subcritical assembly will be able to support at least four experiments for the training courses: (1) the addition of fissile material to the core (mass), (2) a core separation experiment (interaction), (3) the addition of moderators to the core (moderation), and (4) the addition of neutron absorbers to the core (poison/absorption). The subcritical assembly will be designed to be inherently safe—subcritical under all normal and abnormal conditions—and will provide the capability to conduct hands-on training to support NCSP and general nuclear criticality safety staff training and qualification goals.

1. INTRODUCTION

Nuclear criticality safety (NCS) is the field involved with protecting personnel who are processing, handling, storing, and transporting fissionable material. Fissionable material has the potential to become unsafe in certain circumstances and configurations, producing an uncontrolled neutron chain reaction that can result in a potentially dangerous burst of radiation to nearby personnel. Operational staff that work in environments that involve fissile material must take NCS training, including instruction in hands-on operations with fissionable materials, to ensure that all workers are aware of the risks involved with these types of operations. Training assemblies are used in these efforts to provide adequate, safe training that meets regulatory and consensus standard requirements. There are two types of these training assemblies: critical and subcritical assemblies. Critical assemblies involve hands-on operations that can be used until safety limits are reached. At this stage, remote operations are implemented until a critical configuration is achieved. The critical point, also known as *delayed critical*, is the point at which neutron production has been balanced with neutron leakage, neutron absorption (parasitic capture and fission production), and neutron scattering (reflection). Delayed critical is the sensitive window during which a critical assembly is dependent on both delayed and prompt neutrons instead of prompt neutrons alone. The radiation or power level can be low (zero) or raised to a higher level by increasing the neutron population. Prompt critical burset assemblies have a configuration with sufficient reactivity to achieve a prompt critical burst that resembles a criticality accident in a process facility. Subcritical assemblies are strictly designed to be safe under all normal and credible abnormal conditions [2] for approach-to-critical experiments until the allowed neutron multiplication is achieved. These assemblies are discussed further in Section 1.1. These assemblies are opportune for demonstrating the principles of NCS in a safe training environment.

1.1 CRITICAL AND SUBCRITICAL ASSEMBLIES IN THE UNITED STATES

In the United States, there are currently two nuclear facilities at which critical assemblies are operated to support NCS hands-on training. These facilities are operated by the US Department of Energy (DOE) National Nuclear Security Administration (NNSA). NCS training is conducted by the DOE/NNSA Nuclear Criticality Safety Program (NCSP) training and education (T&E) programs.

1.1.1 Sandia Pulse Reactor/Critical Experiment Critical Facility

The Sandia Pulse Reactor/Critical Experiment (SPR/CX) critical facility at Sandia National Laboratories (SNL) performs critical measurements for training and the generation of high-quality benchmark critical experiments for the International Criticality Safety Benchmark Experiments Project (ICSBEP) Handbook. This facility utilizes low-enriched light-water reactor fuel pins loaded into a grid plate and filled with water to perform approach-to-critical and delayed critical measurements (Figure 1). Typically, four hands-on experiments are conducted for NCS training courses to train students on the principles of reactor physics and NCS: (1) the approach-to-critical experiment on fuel loading (examining the effect of adding fissile mass), (2) the approach-to-critical experiment on moderator level (examining the effect of adding moderator), (3)) the approach-to-critical experiment of removing interior fuel rods from the fuel array (examining the effect of increasing reactivity by removing fissile mass and adding moderation), and (4) the approach-to-critical experiment on the spacing of two fuel arrays (examining the effect of increasing neutron interaction between fissile masses) [3]. Hands-on training at SNL can be attended by students with and without security clearances, including foreign nationals.

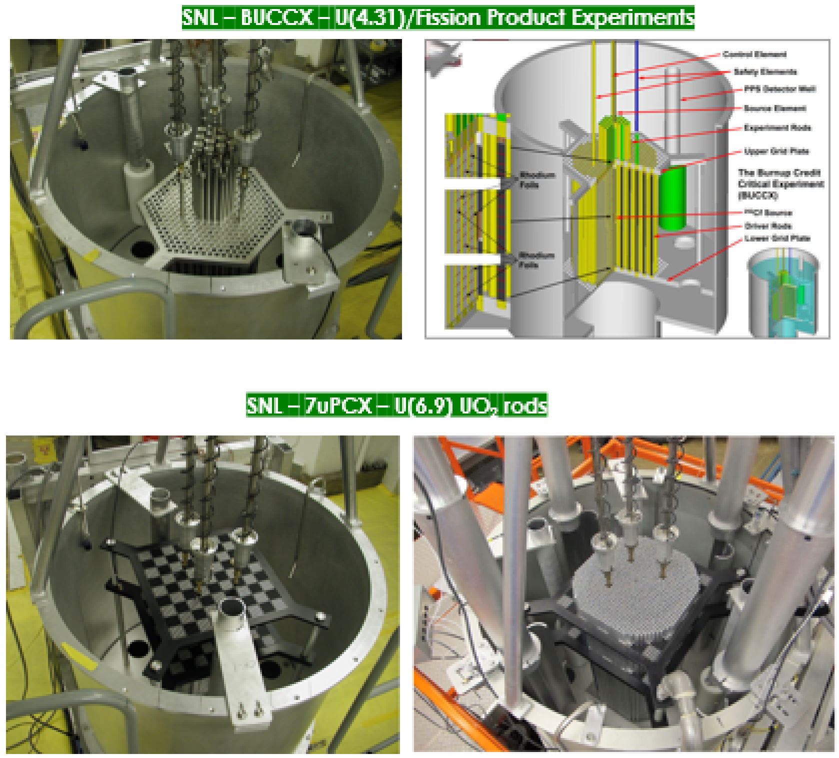


Figure 1. SNL SPR/CX Critical Assembly [4].

1.1.2 Nevada National Security Site Device Assembly Facility

The other nuclear facility that conducts subcritical and critical experiments is located at Nevada National Security Site (NNSS) in the Device Assembly Facility (DAF). The facility used in the DAF for hands-on training is the National Criticality Experiments Research Center (NCERC), which contains a special nuclear material (SNM) vault, a high bay for subcritical and other experiments, and four critical assemblies (Figure 2): the Godiva IV fast-burst assembly for prompt supercritical experiments, Flattop for critical and delayed critical experiments, Planet for approach-to-critical experiments, and the Comet vertical split-table assemblies. All assemblies except Comet are used for NCS training. Additionally, a subcritical demonstration is performed at NCERC involving the beryllium-reflected plutonium (BeRP) ball (4.5 kg α-phase Pu) and Np sphere (6 kg ^{237}Np). A large variety of experiments can be conducted at NCERC, which is currently operated by Los Alamos National Laboratory (LANL) for the NCSP. Lawrence Livermore National Laboratory (LLNL) currently operates a subcritical training assembly known as the *Training Assembly for Criticality Safety* (TACS) to support NCSP training.

Figure 2. Critical and Subcritical Assemblies at NNSS DAF [4].

1.1.3 NCSP Nuclear Criticality Safety T&E Program

The NCSP training program began with hands-on operations at LANL until 2004, when TA-18 (Pajarito Site) was closed, and the critical assemblies, fuel, and other operations were relocated to DAF. During this time, LLNL performed the hands-on training for the NCSP using the TACS's subcritical assembly. In 2011, hands-on training operations were restarted at DAF in NCERC for the NCSP. TACS operations continued at LLNL after operations at DAF/NCERC restarted [5].

The NCSP T&E program consists of two training courses: (1) a two-Week Hands-On Training for NCS Engineers Course and (2) a one-Week Managers Training Course. The two-week course includes one week of lecture at the Nevada Field Office or the National Atomic Testing Museum and one week of hands-on training at SNL or NCERC. Students with DOE "Q" clearances can attend the NCERC hands-on training, and students with DOE "L" or "Q" clearances or those who are uncleared or foreign nationals can attend the SNL hands-on training.

Approximately 60–70 students attend the NCSP training courses each year, and about 500 NCS students have attended the training since 2011. Additional courses can be added as needed to accommodate the training needs for the NCS community. For example, a special hands-on course was held for the Y-12

National Security Complex to accommodate an influx of new hires going through the Y-12 training and qualification process.

1.1.4 Backup Capability to Conduct Hands-On Training and Experiments

NCSP currently funds the SNL and NCERC facilities to perform NCS hands-on training and critical experiments for students from domestic and international NCS communities. Operations in these nuclear facilities can be paused or delayed due to the operational complexities. For example, safety basis issues, criticality safety infractions, fires, or electrical issues could impact the NCS training courses and normal nuclear facility operations.

NCERC and SNL have historically provided backup capabilities for each other. However, using NCERC as a backup for SNL presents an issue because many students are either uncleared or possess a DOE “L” clearance, and cannot access the DAF to attend the training. For these students, the NCSP management team must reschedule the course, which results in student backlog. This challenges the NCSP T&E vision to remain adaptable and responsive [6].

Since 2011, multiple events at NCERC and SNL have impacted or have had the potential to impact NCSP T&E courses. Because the NCSP NCS training program is important for NCS engineering training and qualification programs in the United States [5], issues at NCERC, DAF, and SNL nuclear facilities can significantly delay student qualification progress.

The purpose of this work is to support the NCSP T&E vision and provide a backup venue for the United States as an alternative training location in the event of DAF/Sandia nuclear facility issues, as well as to provide additional NCS training bandwidth. ORNL is an ideal location because it is (1) easily accessible to a more diverse set of students, (2) geographically ideal for potential students for whom the East Coast is more convenient, and (3) not as suspect to the typical complications that arise in nuclear facilities due to security or safety basis issues.

2. OAK RIDGE SUBCRITICAL ASSEMBLY BACKGROUND

2.1 SUBCRITICAL MULTIPLICATION

2.1.1 Background

The life of a neutron in a fissile system is quite chaotic. As a neutron scatters, it eventually either leaks out of a system or is absorbed within a system. For systems with fissile material, the absorbed neutron can result in a fission populating the system with additional neutrons. Criticality is typically defined by the neutron multiplication produced by a fissile system, commonly referred to as the *effective multiplication factor*, k_{eff} (pronounced "k-effective"). k_{eff} mathematically is the ratio of the neutrons in the current generation to the number of neutrons in a previous generation as defined in Eq. (1).

$$k_{eff} = \frac{Number\ of\ neutrons\ in\ the\ current\ generation}{Number\ of\ neutrons\ in\ the\ previous\ generation} \tag{1}$$

When a system is subcritical, the k_{eff} of that system is less than one. This means that for each future generation, a fraction of the current population will be produced through fission reactions with the fissile material. If a pulse of neutrons were produced as the first generation, the second generation would have a fraction (equal to the subcritical eigenvalue) of that population produced, continuing until the neutron population dies out. The multiplication of the original source population produced over all subsequent generationsis defined in Eq. (2).

$$M \times S_0 = S_0 + k_{eff} \times S_0 + {k_{eff}}^2 \times S_0 + \ldots = \frac{S_0}{(1 - k_{eff})} \tag{2}$$

$$M = \frac{1}{(1 - k_{eff})} \tag{3}$$

If a constant source such as ^{252}Cf is applied to a subcritical system, the neutron flux would reach a steady state that is also defined by Eq. (2) with the multiplication of the source defined by Eq. (3). At precise critical (i.e., $k_{eff} = 1$), each neutron presented in the system may start a sustained chain reaction. If a neutron source continues to present neutrons to the critical system, the neutron multiplication would continue to grow without bounds. Thus, measuring the reciprocal of the multiplication, *M*, system approaching critical would result in zero when the system is critical.

2.1.2 Reciprocal Multiplication Method or Inverse Method

The most common procedure for critical experiments is to measure the inverse multiplication (1/M). A neutron source serves as the reference of the neutron population for comparison of the multiplication produced by the subcritical system. The experiment considers a systematic change to a single parameter (e.g., mass, reflection, spacing/interaction) of interest in the experiment. Plotting the reciprocal neutron counting rate or its ratio to a reference initial counting rate, the critical estimate is "guessed" by extrapolating to zero.

An example of the reciprocal method is demonstrated in Figure 3 from a training class performed at the SPR/CX facility. At this point, the students have already performed an experiment determining how many rods in a flooded assembly are required to go critical. Now, the assembly already contains enough fuel such that it is critical when flooded, and the students are determining the height of water required for the reactor to go critical. The reference count rate is the initial count rate at a specific height. As the water height is increased, the inverse of the count rate decreases until the critical height is reached.

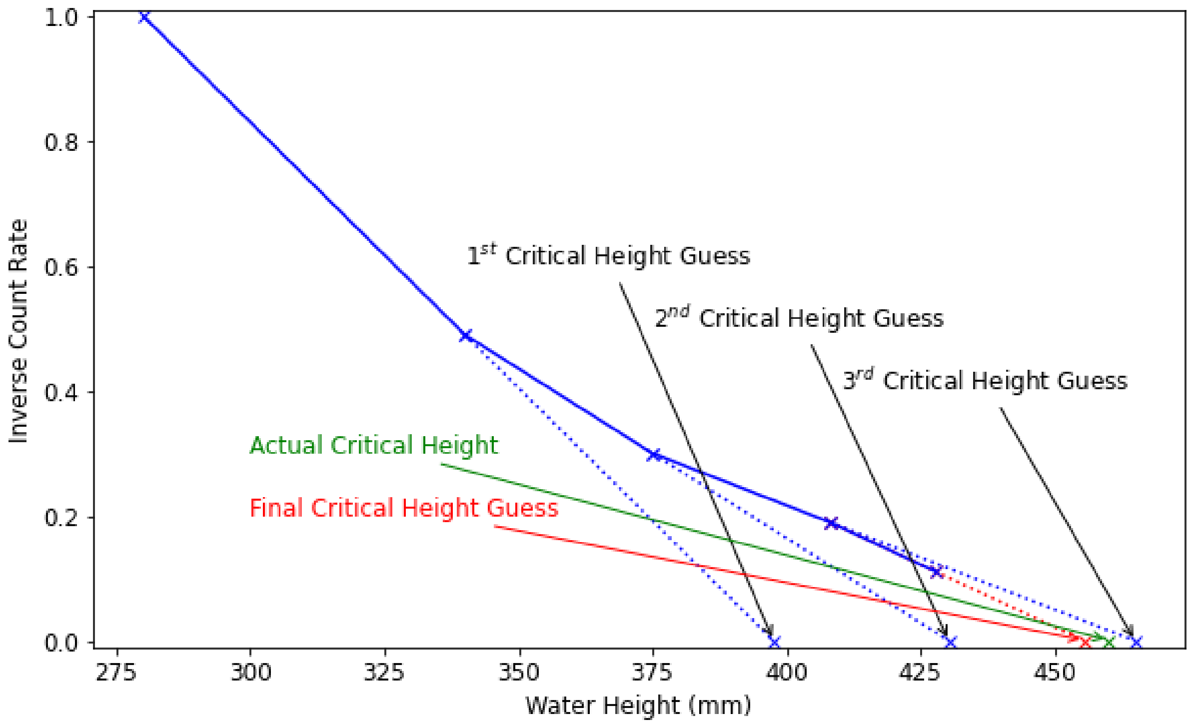


Figure 3. 1/M measurements performed during Hands-On Training at SNL with SPR/CX Critical Facility.

Specifically for the Oak Ridge Subcritical Assembly (ORSA), the approach-to-critical will be designed to not exceed a neutron multiplication of 20 (i.e., $k_{eff} = 0.95$); however, neutron multiplication can be increased as long as the effective multiplication factor does not exceed the upper subcritical limit. This is consistent with the ANSI/ANS-1 standard for manual operations [2]. This standard is not required for subcritical assemblies, but it provides applicable guidance for similar experiments.

The following rules may be considered in the ORSA operating procedures once operations are approved:

- Everyone is responsible for safety.
- Generate the 1/M critical approach curve as a “measure” of the critical point with the assembly.
- Ensure that the core multiplication is below 0.95 for the duration of the hands-on training activity.
- Adhere to the “safe first and second loading rule,” which requires that the first (no fissile loading) and second reactivity additions are always safe when personnel are present. Therefore, the first measurement corresponds to a known subcritical configuration that sets the core multiplication of 1.0, which corresponds to no fissile loading. The second measurement corresponds to the first fissile loading, and the third corresponds to the second fissile loading. These two measurement points make a line for the 1/M plot to estimate the critical point.
- Follow the *halfway rule* so that no single step addition of fissile mass, reflection, etc., goes more than halfway to the estimated critical value.

- Follow the *three-quarter* rule to ensure that no hand assembly step will be performed if the resulting active mass is greater than three-quarters of the estimated critical mass.

These rules provide learning points for discussion throughout the hands-on training and ensure that operations are safe. In addition to implementation of these procedures, ORSA will be designed such that a neutron multiplication greater than 20 (k_{eff} = 0.95) during normal or credible abnormal conditions is not achieved.

2.2 AGN-201M REACTOR

The final design of ORSA will use fuel from the retired Aerojet-General Nucleonics 201-M Reactor (AGN-201M) available at the Y-12 National Security Complex (Y-12). The reactor design is intended to be as "safe and foolproof as possible" with an effectively infinite operating lifetime [7]. The inherently safe and secure design as well as the availability of the fuel for this reactor are an ideal choice for ORSA.

2.2.1 AGN-201M Reactor Background

The AGN-201M is a low-power thermal reactor designed in the 1950s for educational, medical, and industrial applications [7]. The reactor is capable of operating at 100 milliwatts to a maximum of 5 Watts. A schematic of the AGN-201M reactor can be seen in Figure 4.

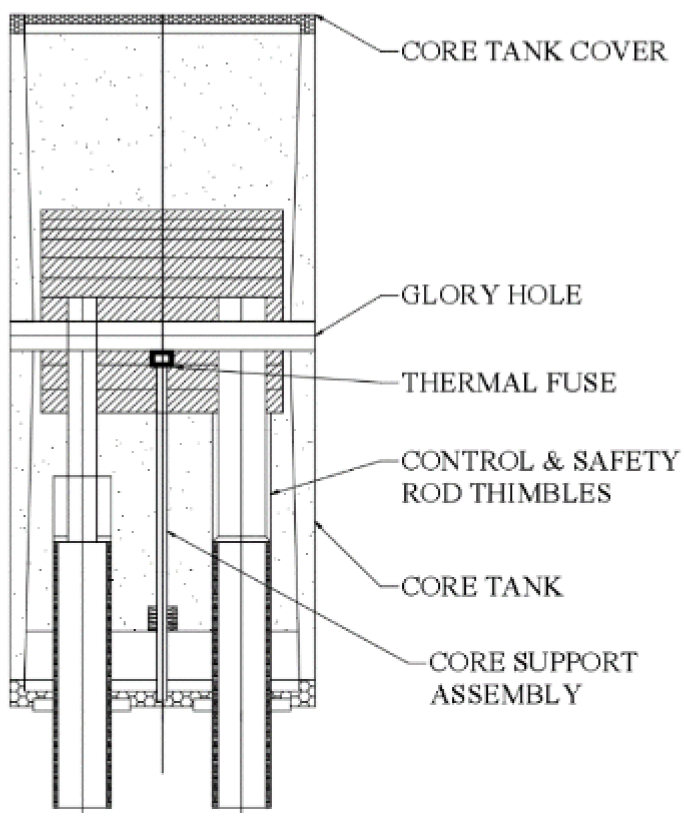
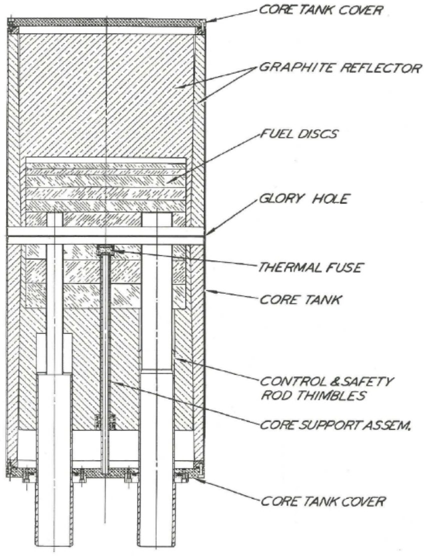


Figure 4. Schematic of AGN-201 Reactor [7].

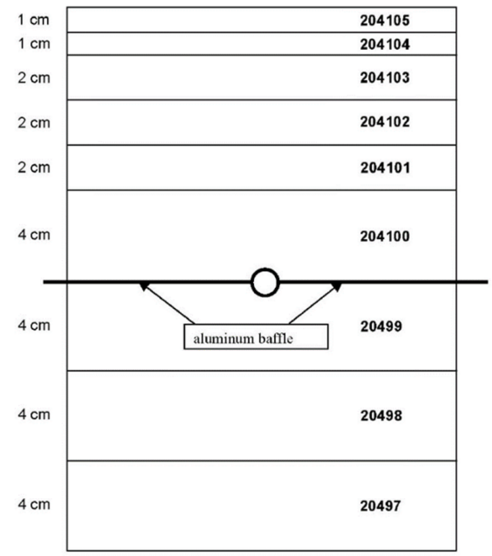
The reactor uses uranium oxide at 19.5 wt % enriched ^{235}U embedded in polyethylene disks as the fuel with a 20 cm thick graphite reflector. The total fuel mass is around 3,330 g of uranium and 10,900 g of polyethylene. The reactor is capable of going critical with only 665 g ^{235}U, where the majority of the neutron flux is thermal energy spectrum. The reactor is controlled using two safety rods (SR1 and SR2), one coarse control rod (CCR) and one fine control rod (FCR). Typically, a control rod is made of a neutron poison to suppress the neutron flux in a reactor. These control rods are made of the same fuel to increase reactivity and are held in place in the reactor from below. A thermal fuse is designed to trigger an ejection of the control rods out of the core during transient conditions, causing them to drop and sufficiently shut down the reactor. The reactor is surrounded by a lead gamma shield and a thick water jacket to shield against fast neutrons. As a research reactor, the AGN-201M contains four ports that penetrate the shielding up to the core. Additionally, the reactor has a glory hole (as seen in Figure 4) penetrating through the core itself. Originally, there were 15 reactors operating globally. The majority have been decommissioned, with five reactors still in operation today [8]. Y-12 National Security Complex has records of fuel plates from four decommissioned reactors [9].

2.2.2 AGN-201M Fuel

The AGN-201M fuel consists of uranium dioxide power matrixed within polyethylene disks. Uranium is enriched at nearly 20 wt % ^{235}U, and the disks are 25.6 cm in diameter with varying thicknesses. The disk thickness can either be 1 cm, 2 cm, or 4 cm. The 1 cm and 2 cm disks are solid pieces. The 4 cm disks have different cutouts depending on the intended stacking configuration for the AGN-201M reactor. The stacking configuration of fuel plates in an AGN-201M reactor can be seen in Figure 5. All 4 cm disks have four cutouts used for control rod inserts, which can also be seen in Figure 5. Four cm disks may have a center cutout, intended as an insert for the thermal fuse and core support assembly. Other 4 cm disks may have a bevel along the face of the disk for the intended glory hole of the AGN-201M reactor. A 4 cm disk with the bevel cutout can be seen in Figure 5.

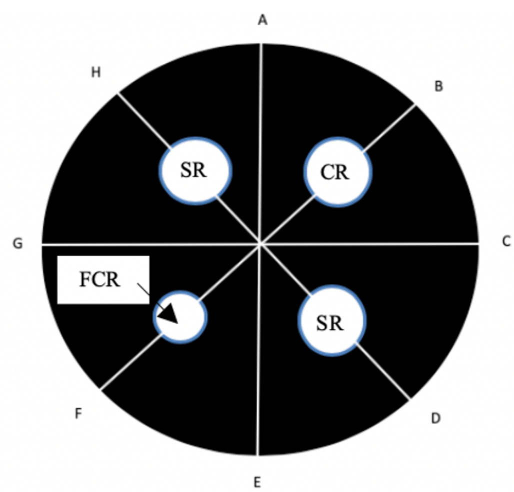


AGN-201M Reactor Core Assembly



Disk stacking configuration for AGN-201M Reactor

4 in. disk with glory hole bevel cutout



SR – Safety Rod Insert CR – Coarse Rod Insert FCR – Fine Control Rod Insert

Figure 5. AGN-201M Reactor Core Assembly and fuel disk [1].

3. OAK RIDGE SUBCRITICAL ASSEMBLY (ORSA) FINAL DESIGN ANALYSIS

This section provides additional analysis of the subcritical assembly for final design considerations. In [1], parametric studies of ORSA were performed to demonstrate proof of concept. Consideration was given to the reflector around the stacked fuel, materials that can be placed in the control rod inserts, and demonstration of hands-on training activities. This section expands on the parametric studies performed for final design considerations. These studies evaluate variations of ORSA to consider for final design while ensuring that the assembly can achieve a neutron multiplication no greater than 20 (i.e., $k_{eff} = 0.95$).

3.1 ORSA COMPONENTS

3.1.1 AGN-201M Fuel Plates

Components of several retired AGN-201M reactors were sent to Y-12 National Security Complex. During the feasibility study [1], Y-12 reviewed records and provided a list of fuel plates currently in storage. This list can be seen in Table 1 and includes information about the site of origin, fissile material part description, net mass of the fissile part, net uranium mass in the part, enrichment of U-235 in the part, total U-235 mass in the part, fissile material chemical form, and the actual U-235 mass in the part based on part characterization. With the availability of four full AGN-201M cores, there is flexibility in the design of the fuel plates.

There is the potential for students to receive some contamination with direct handling of the fuel plates. To mitigate any contamination, several options for encasing the fuel plates are considered. Communication with the University of New Mexico (UNM) lab director supervisor indicated coating the fuel with acrylic spray material has demonstrated minimum direct contamination [9]. The spray material is a commercially available product that is typically used for spraying items such as outdoor furniture. The coating used is clear, and periodic swabs of the fuel plates are taken to ensure coating is maintained. Communication with ORNL laboratory staff indicates a similar practice on metal sources. Several coatings are applied to the source. The first coating is a white color. Any additional coatings are of another color. This way, degradation of the coating can be identified quickly and repaired before the fuel plate is exposed. This method has been approved by on-site radiation protection. One other option that was considered was canning the fuel plates in aluminum. This presented several challenges in the assembly design and hands-on course. Therefore, this option is no longer considered.

Table 1. AGN-201M research reactor fuel and components available at Y-12 National Security Complex

Original Site	Material Description	Net Mass (g)	Net U mass (g)	Enrichment (wt% ^{235}U)	^{235}U mass (g)	Chemical form/code	Actual part ^{235}U mass (g)
Catholic University of America	1 cm thick fuel plate (204104 or 204105)	142.00	142.00	19.85	28.00	UO2/21	30
	4 cm thick fuel plate (20497 or 20498)	499.00	499.00	19.85	99.00	UO2/21	99
	4 cm thick fuel plate (20497 or 20498)	494.00	494.00	19.85	98.00	UO2/21	98
	2 cm thick fuel plate (204102 or 204103)	287.00	287.00	19.85	56.00	UO2/21	58
	1 cm thick fuel plate (204104 or 204105)	142.00	142.00	19.85	28.00	UO2/21	30
	4 cm thick fuel plate (20499 or 204100)	475.00	475.00	19.85	94.00	UO2/21	94

	4 cm thick fuel plate (20499 or 204100)	464.00	464.00	19.85	92.00	UO2/21	94
	2 cm thick fuel plate (204102 or 24103)	287.00	287.00	19.85	57.00	UO2/21	58
	2 cm thick fuel plate (204102 or 24103)	286.00	286.00	19.85	56.00	UO2/21	58
Idaho State University	AGN core (1/3)	4,876.00	1,105.00	19.57	221.00	UO2/21	666.91
	AGN core (2/3)	4,763.00	1,086.00	19.57	217.00	UO2/21	
	AGN core (3/3)	4,876.00	1,105.00	19.57	221.00	UO2/21	
Georgia Tech	AGN core (1/2)	7,108.00	1,631.00	19.99	327.00	UO2/41	666.91
	AGN core (2/2)	7,400.00	1,700.00	19.99	339.00	UO2/41	
Memphis State University	AGN core (1/5)	3,408.00	789.00	19.84	157.00	UO2/41	666.91
	AGN core (2/5)	3,282.00	760.00	19.84	151.00	UO2/41	
	AGN core (3/5)	3,403.00	788.00	19.84	156.00	UO2/41	
	AGN core (4/5)	3,325.00	770.00	19.84	153.00	UO2/41	
	AGN core (5/5)	1,024.00	237.00	19.84	47.00	UO2/41	
University of Oklahoma	Materials are likely a combination of AGN-201M and AGN-211 core material. AGN-211P critical mass is 780 g ^{235}U and AGN-201M critical mass is 665 g ^{235}U	1,248.00	1,248.00	19.84	248.00	UO2/41	1,441.91
		1,120.00	1,120.00	19.84	222.00	UO2/41	
		1,375.00	1,375.00	19.84	273.00	UO2/41	
		1,454.00	1,454.00	19.84	288.00	UO2/41	
		1,491.00	1,491.00	19.84	296.00	UO2/41	
		1,331.00	1,331.00	19.84	264.00	UO2/41	
Naval Postgraduate School	Extra plate to support research above nominal power	907.00	150.00	19.79	30.00	02	—

3.1.2 Neutron Source

To determine the change in neutron multiplication, a reference neutron source is needed. The neutron source considered is an encapsulated ^{252}Cf source with a source strength of 10 MBq or 0.27 mCi. The neutron energy spectrum can be seen in Figure 6 for different decay periods of the source. Decayed sources may be used to support the experiments. The neutron source provide a reference leakage spectrum from which neutron multiplication is determined as neutrons increase in the fissile material from the fission process.

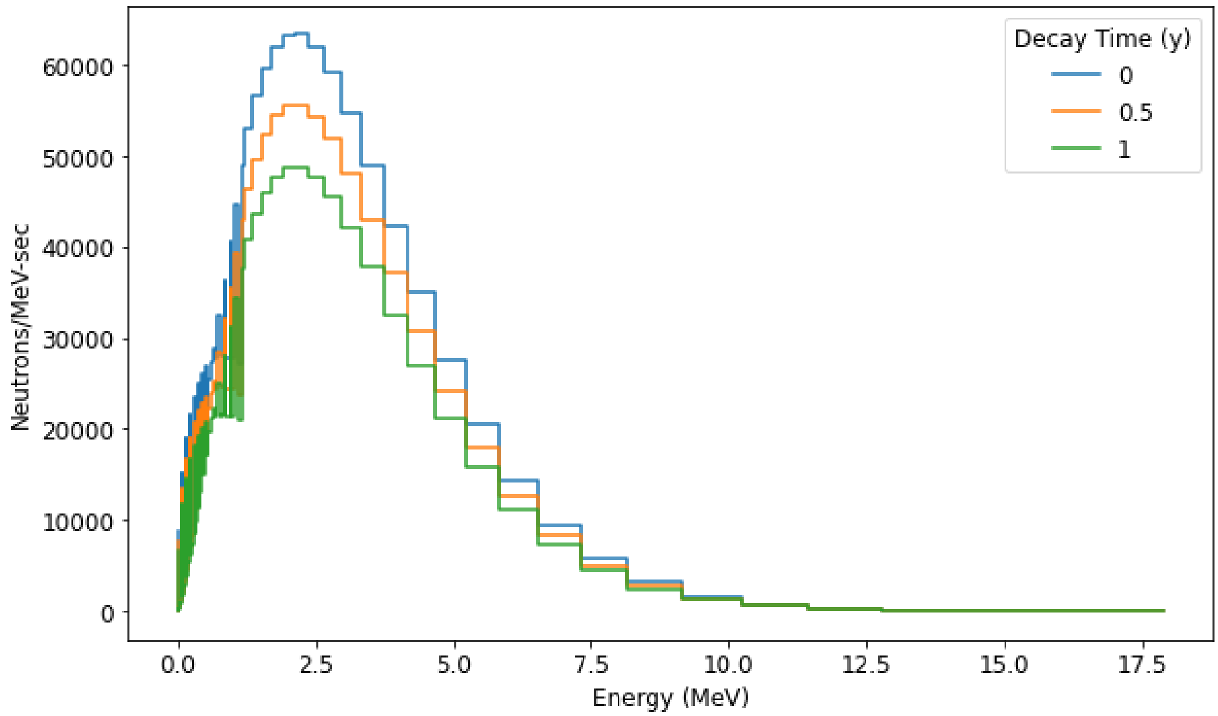
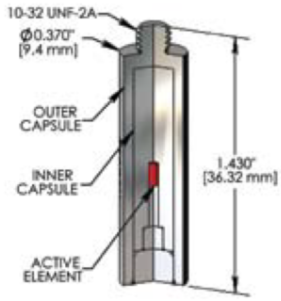


Figure 6. Neutron energy spectrum for a 0.27 mCi ^{252}Cf source.

The ^{252}Cf source and encapsulation are based on the sealed source that can be procured from Eckert & Ziegler Isotope Products [11]. The source is double-encapsulated in a stainless-steel container as seen in Figure 7.

3014 capsule

Double-encapsulated stainless steel point source. ISO rating: C66535



Nominal Activity		Part Numbers	Regulatory
mCi	MBq	3014	SS&DR / SFC
0.0001	0.0037	CF230140100N	Yes / No
0.005	0.185	CF230140005U	Yes / No
0.01	0.37	CF230140010U	Yes / No
0.5	18.5	CF230140500U	Yes / No
1	37	CF230140001M	Yes / No
			Availability: 4 weeks

Intermediate activities are available upon request.

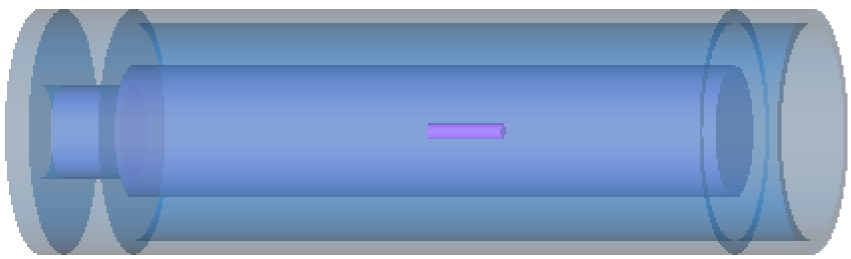
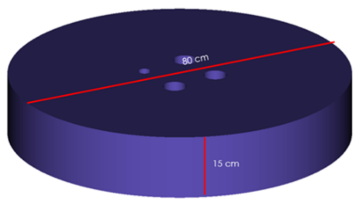
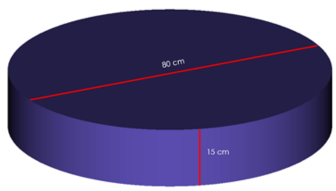
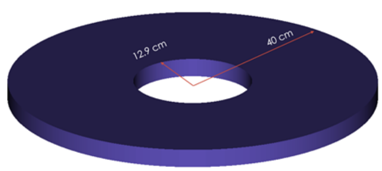


Figure 7. ^{252}Cf source description from product catalog [11] and SCALE model of the source and encapsulation.

3.1.3 Graphite Reflector

Graphite will be used as a neutron reflector for ORSA with a density of at least 1.75 g/cm^3. Table 2 provides a description for each reflector piece. Every graphite component will be of a cylindrical shape with an outer radius of 40 cm. Annular disks that overlay a fuel disk will have an inner radius of 12.9 cm. The top and bottom reflectors are solid graphite disks with a thickness of 15 cm. One solid reflector will have cutouts that match the control rod inserts for the 4 cm fuel disks. Graphite plugs will be used to fill the cavity. This will provide access to the fuel assembly core for material and detector placement while the assembly is fully reflected. The top and bottom reflectors cannot be handled directly due to the weight. A few options are being considered for the hands-on activity, such as having these pieces fixed to the assembly so that no handling is needed. Ergonomic considerations are in place for the 4 cm annular disks as well. If necessary, the 4 cm annular disks can be replaced with two 2 cm disks. ORNL's capabilities to print reflector parts were limited to parts much smaller than the reflector, so a quote was requested from an outside vendor. The vendor typically makes graphite parts intended to be used as molds for high temperature activities.

Table 2. Description of Graphite Reflector Components.

Piece	Description	Minimum Needed for ORSA	Weight per piece (kg)
	Solid disk with control rod cutouts	1	131
	Solid disk	1	132
	4-cm thick annular disk	4	31.5
	2-cm thick annular disk	2	15.8
	1-cm thick annular disk	4	7.9
Total Weight for ORSA (kg)			**452.2**

3.1.4 Neutron Detection

The neutron detector modeled for ORSA activities is a ^{3}He gas proportional counter. Neutrons interact with the detector from the ^{3}He(n,p) reaction. The number of neutrons detected is proportional to the number of neutrons produced by ORSA. As the multiplication factor of the system increases, the count rate of the system also increases. With the low mass of UO_2 powder and the powder matrixed within polyethylene, neutron leakage from ORSA will essentially be in the thermal spectrum. Neutron detectors will not need additional thermalizing cases (e.g., poly-wrapped) to detect leaked neutrons. The modeled ^{3}He detector is based on the manufactured detector from LND, Inc. [12]. This detector operates at a gas pressure of 7,600 torr at 21°C. The small volume of the chosen detector for the modeling studies is advantageous for two reasons: it limits the neutron absorption by detection, interfering as little as possible with the assembly, and it also allows for insertion in the fuel plates' control rods holes.

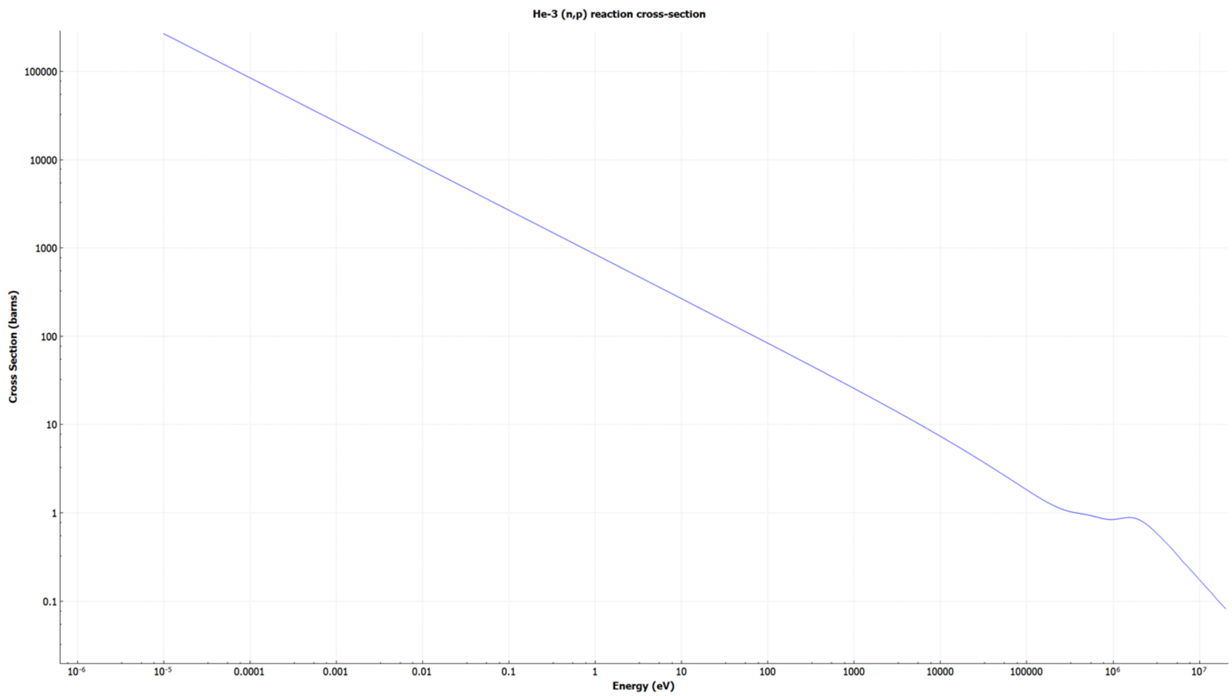


Figure 8. Cross section of the ^{3}He (n,p) reaction.

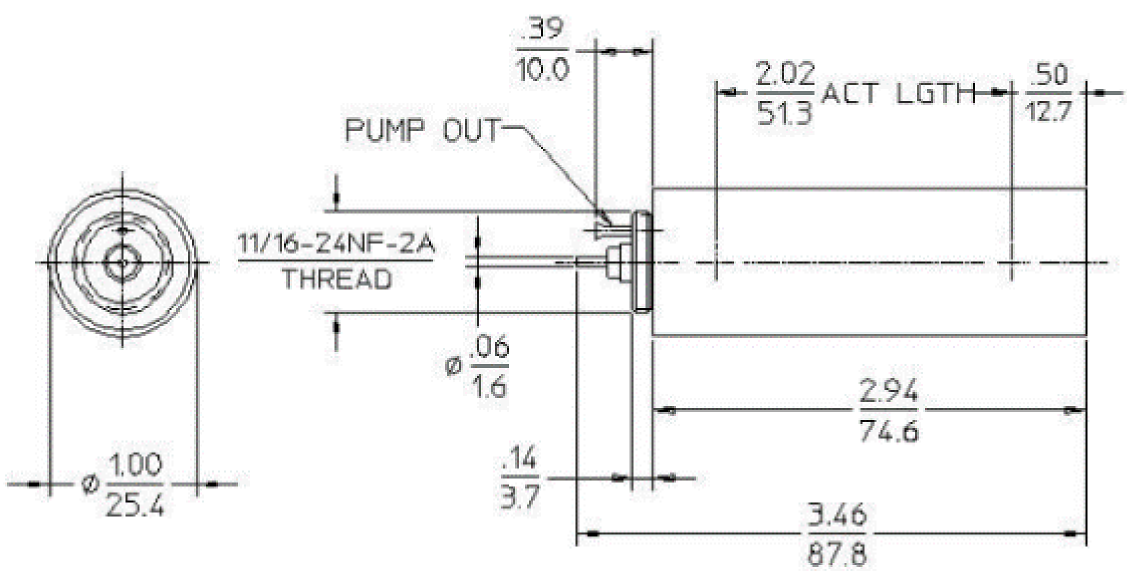


Figure 9. Schematic of manufacturer ^{3}He detector.

3.1.5 ORSA Assembly System

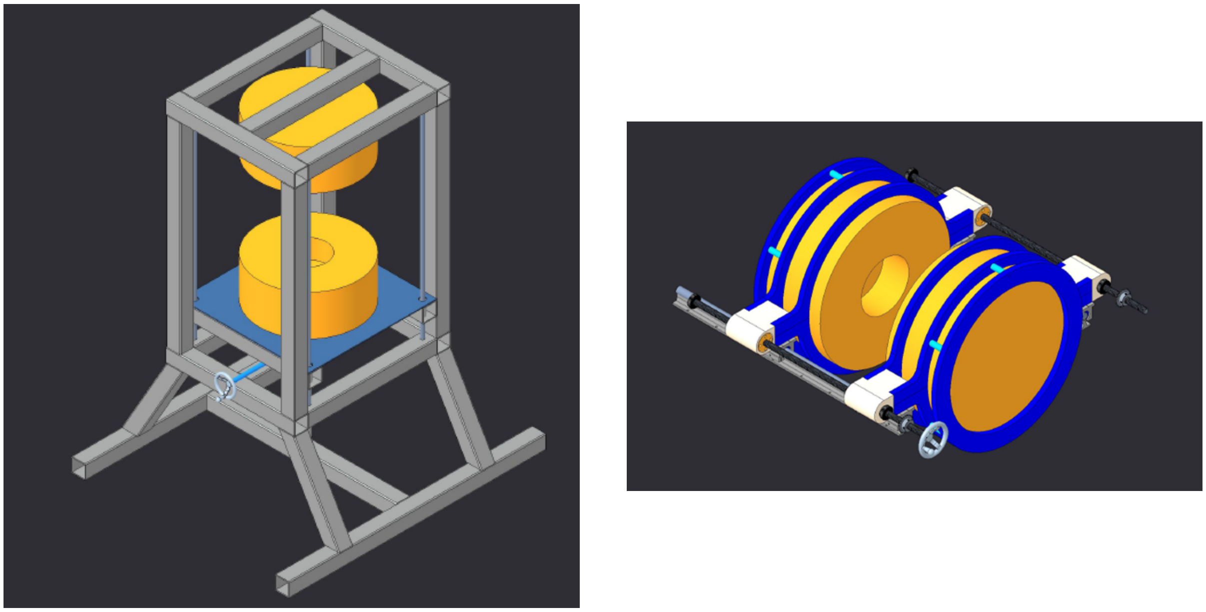


Figure 10. Preliminary mechanical designs of the ORSA assembly—vertical lift (left) and horizontal split (right).

The assembly system has two preliminary designs for consideration: a vertical lift or horizontal assembly. These preliminary designs can be seen in Figure 10. The assembly is a support structure that allows manipulation of one portion of the assembly. Both systems use gear and threading contact to move a portion of the assembly. The manipulation can be done by a hand-crank or with a power drill. The adjustments evaluated were about five threads per inch and 0.04 in. per turn, which is more than enough fidelity to perform the hands-on split experiment (see Section 3.4.4.2).

Originally, the concept was a vertical lift. The design is a standalone structure and experiments would be simple to perform. The support structure is currently 7.5 ft tall and has a 5 ft × 6 ft base. The upper portion of the assembly is attached to the support. Another membrane is needed to keep the fuel within the upper reflector. The bottom portion can be manipulated to move towards the top.

The horizontal support has a base of 4 ft × 5 ft and could be set on a table. In this design, grooves within the reflector allow attachment of the reflector to the brackets (blue components in Figure 10). Another design consideration is to make the brackets of the reflector part of the graphite. The design options are manipulation of one portion while the other portion is fixed, or both portions manipulated toward or away from each other simultaneously. Additional components in consideration are to stabilize the fuel and reflectors when placed within the reflector.

Both structures can support the graphite reflector mass, but the horizontal support has a significant reduction in industrial hazard risks when compared to the vertical support structure. There are also additional design challenges for both concepts to consider such as detector placement, access to the control rod inserts, and keeping the plates and reflectors fixed.

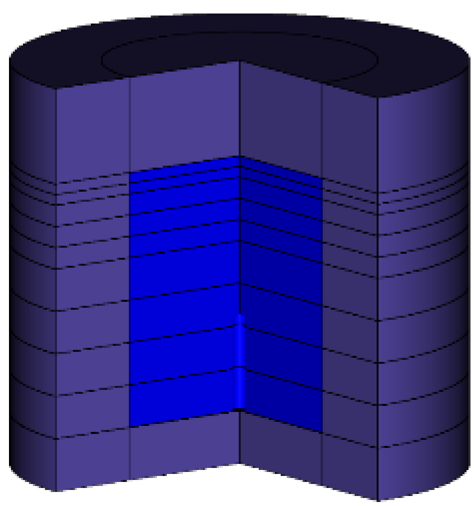
3.2 FINAL DESIGN CONSIDERATIONS

Although the parametric study performed in the conceptual design study [1] is sufficient to demonstrate feasibility of the ORSA activities, additional considerations are given in this section for final design and implementation. For example, adding coating to the fuel disks will help protect the disk as well as prevent contamination during hands-on activities. The exact fuel composition is unknown until the fuel plates are obtained and in-house characterization is performed, so the material definition was changed to reflect a most probable average composition. A few other elements were also removed or added from the preliminary study model. These changes impacted the reactivity of the system, changing the amount of reflector needed to reach the required subcritical level for the ORSA activities. The final design modeling study starts with the fully stacked and fully reflected configuration determined in [1] and shown in Figure 11. The disk configuration was as follows, from bottom to top:

- Two 4 cm disks with the support assembly cutout in the center
- One 4 cm disk with a partial support assembly cutout in the center
- One 4 cm disk with no additional cutouts other than the control rod inserts
- Three 2 cm disks
- Two 1 cm disks

The graphite reflector was 8.5 cm thick radially and on the top. The bottom reflector was 5 cm thick. In [1], an aluminum rod was placed where the thermal fuse and core support would be located.

The final design modeling of ORSA is performed using SCALE 6.3 KENO-VI [13] with the ENDF/B-VII.1 continuous-energy cross section library. All KENO-VI results are given with a 30 pcm absolute uncertainty.



$k_{eff} = 0.94723$

Figure 11. Nominal configuration from the conceptual study performed in 2020 [1].

3.2.1 Addition of the source

To perform subcritical experiments with ORSA, a neutron source is needed. A ^{252}Cf source within a source holder was modeled, as described in section 3.1.2. The aluminum rod located in the thermal fuse and core support from the original AGN core were replaced by the encapsulated source located in the central hole of the 4 cm thick fuel plates, as shown in Figure 12. Replacing the aluminum rod with the source and source holder had an insignificant impact on the assembly k_{eff} (<50 pcm).

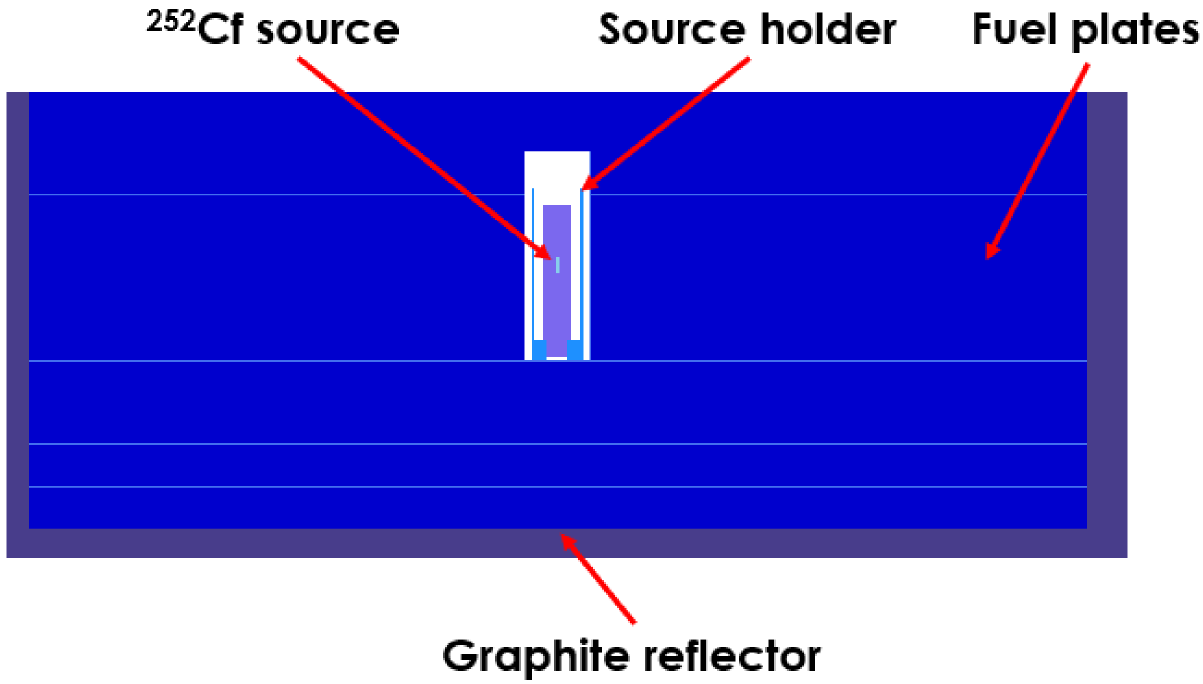


Figure 12. ^{252}Cf source and source holder in the ORSA SCALE model.

3.2.2 Coating of the fuel disk

To prevent accidental damage of fuel and to mitigate radiological contamination, coating of the fuel disk is being considered for the final design of ORSA. Different materials and types were considered. A first idea was to use tight-fitting aluminum shell encompassing the fuel disk, also including the cutouts of the 4 cm disk. A more realistic aluminum cladding was also considered, including air gaps between the fuel plates and the aluminum. With the thickness of aluminum and of the air gaps, the impact of the cladding on the assembly k_{eff} was extremely high (>10,000 pcm), due to the apparition of voids between the fuel plates and the cladding. Thus, a different type of cladding was chosen for the final design, which uses a synthetic rubber or acrylic spray, as described in Section 3.1.1. This coating presents several advantages compared to aluminum. The recommended thickness is between 1 and 20 mils (0.00254 and 0.0508 cm), no gaps between the fuel plates and the coating are needed, and it has a low density of about 0.81 g/cm^3. These factors are all theoretically less impactful for the assembly criticality. An overview of the assembly with the coating modeled is shown in Figure 13. For modeling purposes, the material composition found in the material safety data sheet of a commercially available spray was used [14]. An uncertainty resides in the exact material composition of the rubber, as, for example, in the concentration and composition of resin and naphtha hydrocarbon. The impact of the fuel plates' rubber coating on the assembly k_{eff} is shown in Table 3, for different composition and thickness possibilities and a given subcritical configuration of ORSA. A coating of pure aluminum of equivalent thickness is also shown for information. The study shows that k_{eff} decreases by about 700 pcm when using the rubber coating, and that the thickness and rubber dip material uncertainties have a low or insignificant impact on k_{eff}. The decrease in k_{eff} brought about by using this type of fuel coating is acceptable, especially compared with using pure aluminum coating, but more reflector is required to compensate for the 700 pcm loss. For the rest of the study, all the fuel disks are coated with the rubber coating composition #2 (naphtha is modeled as C_8H_{14}) with a thickness of 0.0125 cm. This composition was chosen because it is the most impactful on k_{eff}. The material composition of the rubber coating used in the ORSA final design SCALE model is shown in Table 4.

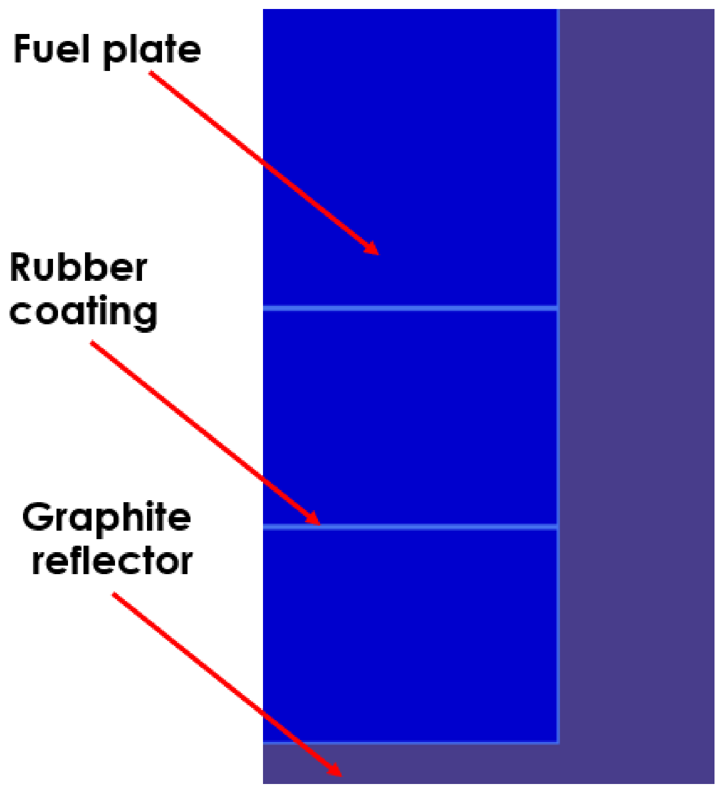


Figure 13. Overview of the assembly with rubber coating.

Table 3. Impact of different cladding possibilities.

Cladding thickness (cm)	k_{eff}			
	Pure Aluminum	**#1 Rubber coating (without Naphtha and resins)**	**#2 Rubber coating (Naphtha is C_8H_{14})**	**#3 Rubber coating (Naphtha is $C_{14}H_{30}$)**
0	0.95026	0.95026	0.95026	0.95026
0.00254	0.94169	0.94270	0.94176	0.94228
0.01270	0.93966	0.94274	0.94213	0.94251
0.02540	0.93633	0.94277	0.94331	0.94256
0.05080	0.93161	0.94331	0.94107	0.94182

Table 4. Rubber coating material composition.

Density	0.81 g/cm^3
Element	**Weight percent**
Hydrogen	10.28
Carbon	79.44
Nitrogen	1.97
Oxygen	7.12
Sulfur	1.19

3.2.3 Addition of the Baffle Plate

Compared to the conceptual design, a baffle plate was added, located around the axial midpoint of the assembly. The addition of the baffle plate allows the use of the AGN-201M glory hole where materials and components can be placed in the center of ORSA. This could be used for detector placement, subcritical measurements using the “Source Jerk Method” [15], or for material analysis with a thermal neutron spectrum. The baffle plate is a 0.5 cm thick aluminum plate with the same planar dimensions as the diameter of ORSA with reflector. The glory hole of the baffle plate is centered along the plane of the plate with a 2.54 diameter and a 0.2 cm thick aluminum shell. The addition of the baffle plate to the nominal configuration drops the k_{eff} from 0.94723 to 0.92210, necessitating another adjustment of the reflector thickness.

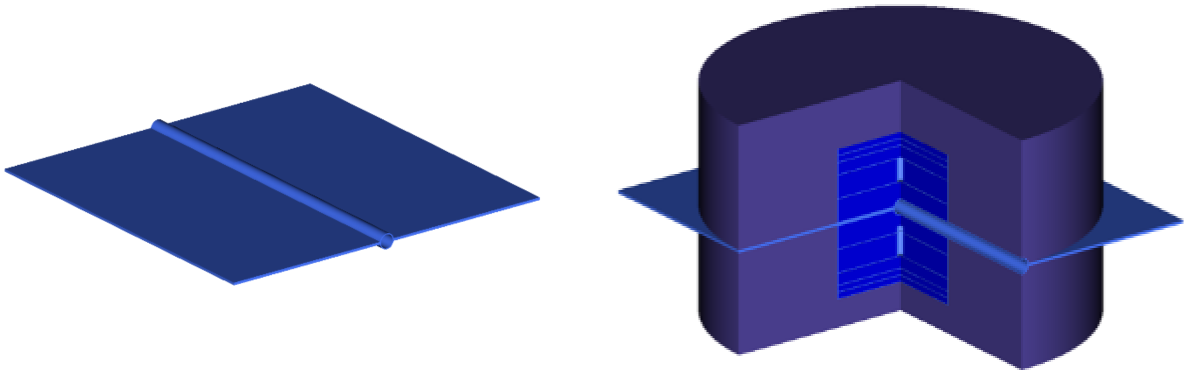


Figure 14. Left: Overview of the baffle plate. Right: Baffle plate within ORSA.

3.2.4 Reconfiguration of Fuel Plates

Several options were explored for reconfiguring the fuel disks for a more symmetrical configuration. The new final design arrangement chosen is shown in Figure 15, including the baffle plate.

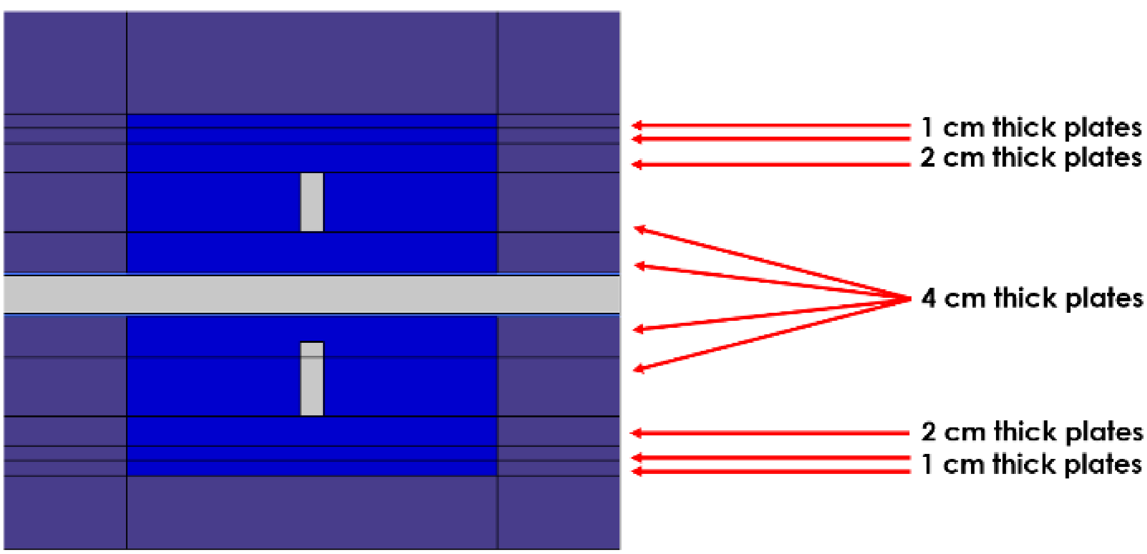


Figure 15. ORSA final design fuel plates arrangement.

3.2.5 Fuel Plate Material Composition

Most of the AGN-201M reactors existing in USA were built in the 1950s, practically by hand, so all reactors and all fuel plates from the various facilities are unique. Until characterization is performed on the plates selected to fabricate the ORSA, it is impossible to know the exact material composition of the fuel plates. The AGN-201M fuel plates have been modeled in the past, and several material compositions of the fuel plates were reported, using varying methods and assumptions [16,17,18]. A few of those configurations are shown in Table 5. Please note that in ORNL/TM-2019/1410 [16] Table 8-1, the hydrogen and carbon compositions are reversed, and the report will be corrected in the near future. Also of note, the fuel definition from the 2020 ORSA conceptual design [1] seems to have high atomic densities of uranium isotopes compared to the other sources. The different fuel plates' material compositions were tested on a single ORSA model, and the influence on k_{eff} is significant, as shown in Table 6. The k_{eff} difference between the fuel compositions is between 244 and 1,573 pcm. For the ORSA final design calculations, the material composition #2 was chosen for two reasons. This material composition originates from mass spectroscopy measurements of the Idaho State University AGN-201M fuel plates and described in ORNL/TN/2019/1410 [16], so they are highly trusted. Moreover, using an average composition for all the plates seems more realistic than using the different specific plates material compositions because it is uncertain which AGN-201M reactor fuel plates from Y-12 will be used to contruct the ORSA. Using this fuel material definition is modifying the subcritical properties of ORSA compared to the conceptual design study.

Table 5. Review of different AGN-201M fuel material composition definitions in atom densities unit.

	Atom densities				
ZAID	**#1 ORNL/TM-2019/1410 Table 8-1 plate 20497 with corrected H and C (2019)**	**#2 ORNL TM Table 8-1 average of all plates with corrected H and C (2022)**	**#3 Idaho State University M.S. Thesis (2012)**	**#4 BWXT report (2007)**	**#5 ORSA Conceptual Design (2020)**
1001	7.64E-02	**7.71E-02**	7.94E-02	7.59E-02	7.65E-02
1002	8.79E-06	**8.87E-06**	9.13E-06	8.73E-06	—
6012	3.78E-02	**3.81E-02**	3.97E-02	3.76E-02	3.78E-02
6013	4.09E-04	**4.12E-04**	—	4.06E-04	4.09E-04
8016	1.42E-03	**1.43E-03**	1.44E-03	1.44E-03	1.55E-03
8017	5.40E-07	**5.43E-07**	5.48E-07	5.49E-07	5.89E-07
8018	2.92E-06	**2.93E-06**	—	2.96E-06	3.18E-06
92234	8.39E-07	**8.46E-07**	8.64E-07	—	—
92235	1.42E-04	**1.43E-04**	1.44E-04	1.42E-04	1.53E-04
92236	1.48E-06	**1.49E-06**	1.51E-06	—	—
92238	5.67E-04	**5.70E-04**	5.76E-04	5.80E-04	6.22E-04

Table 6. Impact of using different AGN-201M fuel plates material composition on the ORSA k_{eff}.

Configuration description	**#1 ORNL TM Table 8-1 plate 20497 with H and C switched (2019)**	**#2 ORNL TM Table 8-1 average of all plates with H and C switched (2022)**	**#3 Idaho State University M.S. Thesis (2012)**	**#4 BWXT report (2007)**	**#5 ORSA Conceptual Design (2020)**
k_{eff}	0.93214	0.93639	0.94463	0.93134	0.94707
k_{eff} difference compared to conceptual design definition (2020) (pcm)	−1493	−1068	−244	−1573	(ref)

3.2.6 Graphite Material Composition

The graphite density used in the conceptual design study [1] was 2.3 g/cm^3. After furtherresearch and discussion with graphite manufacturers, the commonly fabricated nuclear-grade graphite has a density of around 1.75 g/cm^3, as previously described in Section 3.1.3 and Table 2 with the quoted price for ORSA graphite. The final design ORSA SCALE model uses 1.75 g/cm^3 for the graphite reflector density, modifying the subcritical properties of ORSA.

3.3 FINAL DESIGN OF ORSA

An overview of the ORSA final design is shown in Figure 16 for 3D views and in Figure 17 for a side view. As a result of the assembly modifications described in Section 3.2, the final design of ORSA dramatically changed from the conceptual design created in 2020 [1]. The most significant change is the need to substantially increase the graphite reflector thickness such that a k_{eff} of 0.95 can be reached, which is equivalent to a subcritical multiplication factor of 20. The reflector dimensions are 40 cm radius, 27.1875 cm thickness of graphite around the coated fuel plates, with two solid blocks of 15 cm thick and 40 cm radius on the top and bottom of the fuel plates, as described in Section 3.1.3. ORSA will use a total of 10 fuel plates from legacy AGN-201M reactors, with four 4 cm plates, two 2 cm plates, and four 1 cm plates, all with a 12.8 cm radius. Considering the 0.0125 cm thickness of coating around each plate and the newly added 0.5 cm thick baffle plate, the height of the 10 plates stacked is of 24.75 cm. The total modeled ^{235}U mass is of approximately 617.2 g, recalling an uncertainty of a few tenths of grams exists, depending on which fuel plates will be actually used in the ORSA fabrication. The detailed materials specifications for the three main materials of the model, the fuel plates, the graphite, and the fuel coating, are found in Table 7. Note that the "h-poly" SCALE cross-section is used for the hydrogen in polyethylene, corresponding to the "9001001" ZAID. With these characteristics, the assembly k_{eff} is 0.95024 ± 30 pcm, conforming with the goal of sub-critical multiplication of 20.

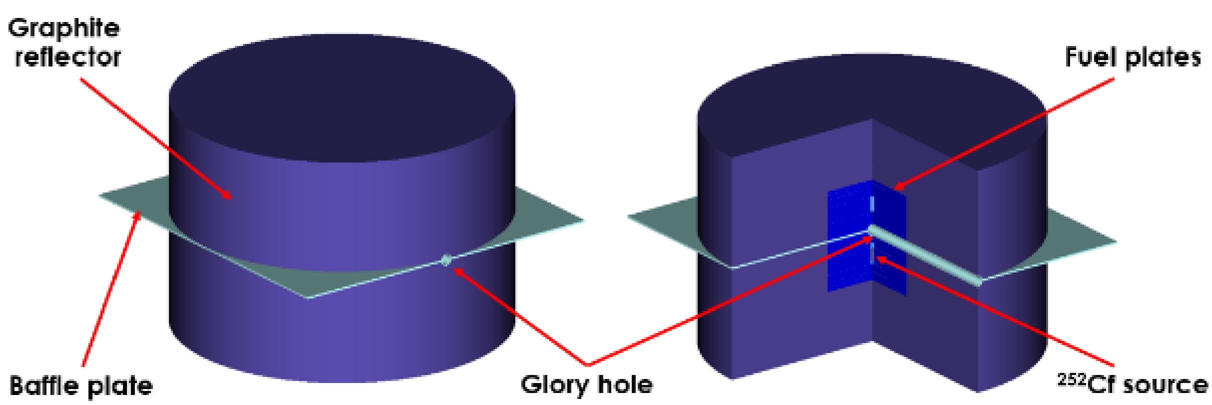


Figure 16. Overview of the final design of the ORSA SCALE model, standard 3D view (left), front-right quarter 3D view (right).

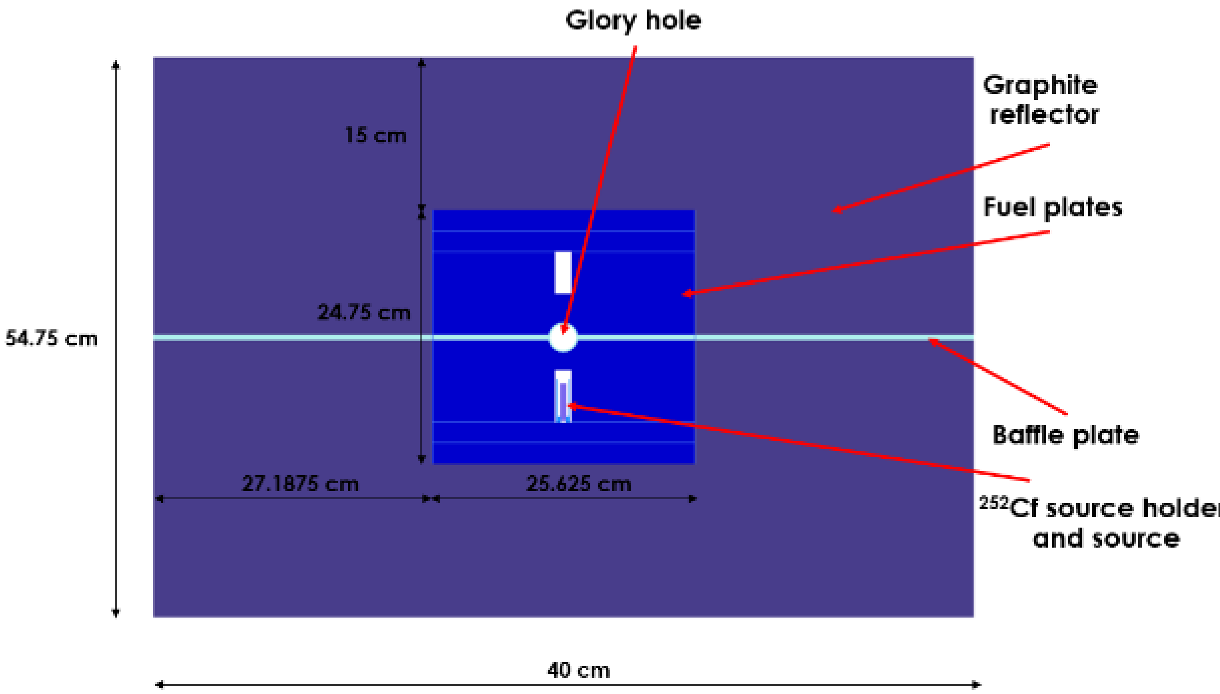


Figure 17. Overview of the final design of the ORSA SCALE model, side view.

Table 7. Material compositions of the three main materials of the ORSA final design SCALE model.

Fuel Plate Density 1.2178 g/cm^3		Rubber coating Density 0.81 g/cm^3		Graphite Density 1.75 g/cm^3	
ZAID	**Atom density**	**ZAID**	**Atom density**	**ZAID**	**Atom density**
9001001	7.71E-02	1001	4.97E-02	3006000	8.78E-02
1002	8.87E-06	1002	5.72E-06		
6012	3.81E-02	6012	3.19E-02		
6013	4.12E-04	6013	3.45E-04		
8016	1.43E-03	7014	6.84E-04		
8017	5.43E-07	7015	2.50E-06		
8018	2.93E-06	8016	2.17E-03		
92234	8.46E-07	8017	8.25E-07		
92235	1.43E-04	8018	4.45E-06		
92236	1.49E-06	16032	1.72E-04		
92238	5.70E-04	16033	1.36E-06		
		16034	7.69E-06		
		16036	1.81E-08		

3.4 SUBCRITICAL EXPERIMENTS

3.4.1 Overview of experiments planned

Four different experiments are considered for the hands-on training. The first experiment shows the influence of fissile mass and reflection on criticality by stacking fuel plates with and without the graphite reflector. The second experiment considers separating the assembly into two halves vertically or horizontally and observing the influence of reducing the core spacing on criticality. In Experiments 3 and 4, solid rods of different materials are inserted into the 4 cm thick fuel plates control rods inserts to show the influence of adding moderator materials (Experiment 3) and neutron absorber materials (Experiment 4) on reactivity. The experiments are illustrated in more detail in the next sections. Moreover, their feasibility is demonstrated with both criticality calculations by determining k_{eff} and the neutron multiplication, *M*, for each step of each experiment. More experiments can be designed from combinations of the experiments described in this report—such as, for example, an approach to critical combining stacking plates and performing a separation of two halves of the assembly (Experiment 1 and Experiment 2) or performing the separation experiment with moderation rods in the control rods inserts (Experiment 2 and Experiment 3).

3.4.2 Demonstration of k_{eff} feasibility with SCALE/KENO calculation

SCALE/KENO-VI and the final design of the ORSA SCALE model are used to determine k_{eff} and the equivalent multiplication factor M for each step of each experiment. These calculations are a test of feasibility; additional steps can be taken if the halfway step in approaching criticality is judged too high to be safely done during the training. All KENO-VI calculations results are given for a 30 pcm absolute uncertainty.

3.4.3 Demonstration of shielding feasibility with SCALE/MAVRIC calculation

In the real-life subcritical hands-on training, k_{eff} is not a measurable quantity. Instead, neutron detectors are used to determine a ratio of counted neutrons and equivalent multiplication factors M and 1/M plots by using the reciprocal multiplication method or inverse method as described in Section 2.1.2. SCALE/MAVRIC and the final design of the ORSA SCALE model are used to model the hands-on training as closely as possible, determining a neutron count rate from ^{3}He detectors placed at different locations in the assembly, from startup ^{252}Cf source neutrons and the multiplication provided by the assembly. Thus, a ratio of neutron count rates between each step and an equivalent multiplication factor can be obtained. For Experiments 1 and 2, three detector locations are modeled: detector 1 is placed outside the assembly, detector 2 is placed in the graphite reflector, and detector 3 is placed inside one of the control rods insert of the 4 cm fuel plates, as shown in Figure 18. By using different detector locations around the assembly, different 1/M plots should be obtained, similarly to the NCSP hands-on training at SNL's SPR/CX critical facility [3]. The ^{3}He detector modeled is described in Section 3.1.4. The small active volume of the detector is efficient enough to detect the neutron multiplication provided by the assembly in the calculations, but a future study will be pursued to determine the best neutron detector arrangement in the ORSA hands-on training. Note that an approximation is used, as every neutron interacting with the ^{3}He by the (n,p) reaction is considered counted, ignoring the next processing steps involving electronics of the detector, but the ratio of counts between each step should be very similar in a real-life situation. For each MAVRIC calculation with each ^{3}He detector modeled, a corresponding KENO-VI calculation is also performed to determine the influence of the neutron detector neutron absorption on the assembly. In the case of detector 1, no influence is found on k_{eff}. This is explained by the fact that the detector is completely outside the assembly. In the case of detector 2, k_{eff} decreases by less than 100 pcm. This is explained by replacing graphite reflector material with the neutron detector, an absorbing material, but in a location relatively far from the center of the assembly. In the case of detector

3, k_{eff} decreases by about 1300 pcm. This is explained by replacing void with the neutron detector, a neutron absorbing material, directly in the center of the assembly. As a result of placing detector 3 in the assembly, the maximum multiplication factor decreases from 20 to about 15.8. In the next calculations, the graphite thickness is not adjusted to compensate for the detector 3 loss of multiplication, but this is information to remember in the future when the neutron detection apparatus is chosen for ORSA. All MAVRIC calculations results have a relative uncertainty below 5%.

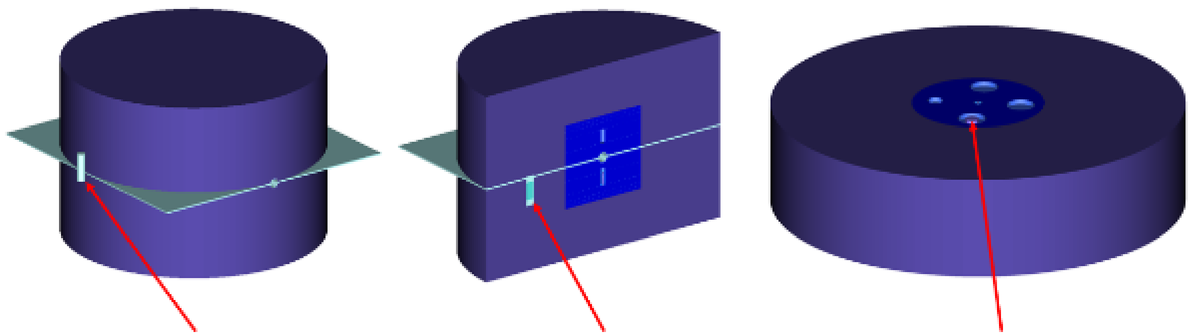


Figure 18. Different ^{3}He detectors locations modeled in SCALE around the assembly, outside the assembly (left), in the graphite reflector (middle), and in one of the fuel plates hole (right).

3.4.4 Subcritical experiments description

3.4.4.1 Experiment 1: Assembling fuel assembly (Mass and Reflection)

The first experiment considered for the hands-on training at ORSA is to show the influence of fissile mass and reflection on criticality. With the configuration modifications previously described, the method of stacking fuel plates also changed compared to the conceptual design study. Table 8 and

Table 9 provide information about the stacking steps and corresponding k_{eff} and neutron multiplication, *M*, results, without and with reflector, respectively. In steps 1 to 6, the fuel plates are stacked without graphite reflector, and in steps 7 to 12, the fuel plates are stacked with graphite reflector. The steps shown in Tables 8 and 9 illustrate the configuration, provide a description and show results for the ORSA experiments. This is subject to change in the actual ORSA hands-on training. The representation of the ORSA k_{eff} evolution with the increasing ^{235}U mass is shown in Figure 19 with and without reflector configurations. The representation of the ORSA k_{eff} evolution with the increasing step counts is shown in Figure 20. Those results demonstrate that ORSA is subcritical during all the stacking steps.

Table 8. Experiment 1: Stacking fuel disks without graphite reflector overview.

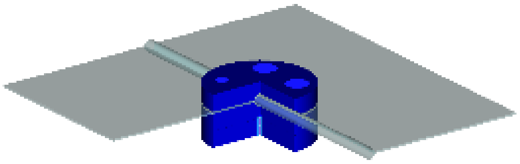
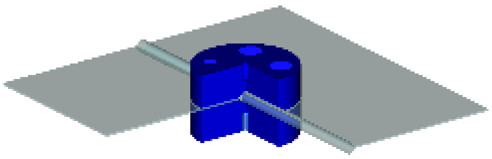
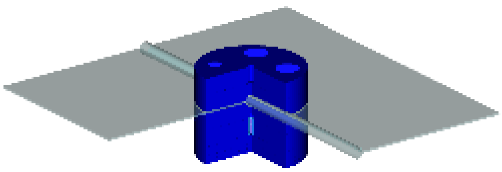
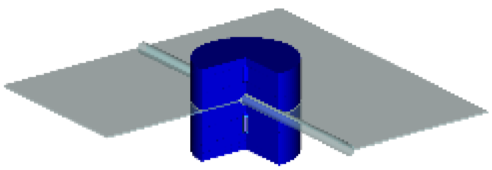
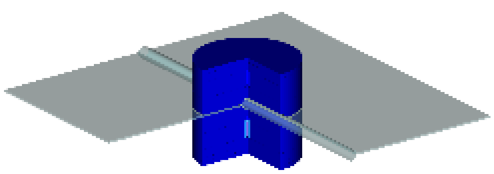
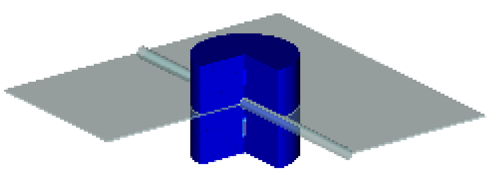
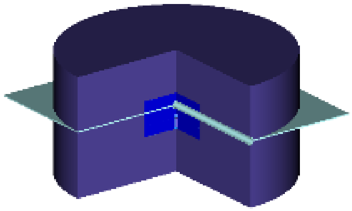
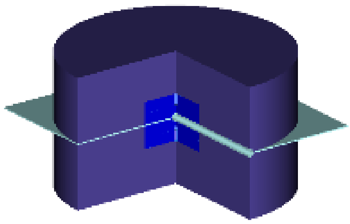
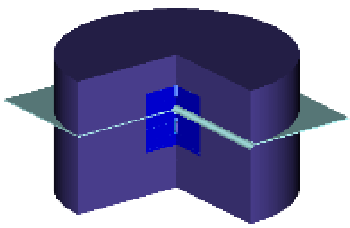
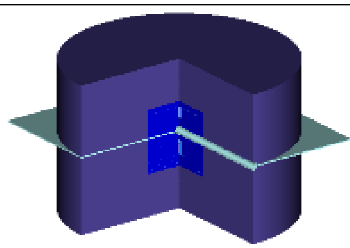
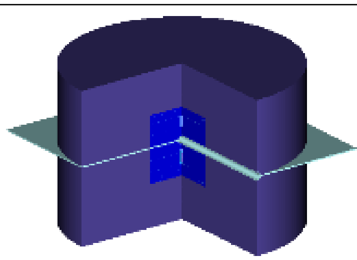
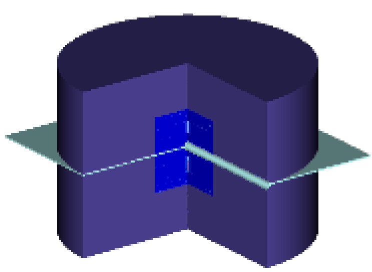
Step #	Assembly representation	Description	k_{eff}	M (=1/(1-keff))
1		• Three 4 cm thick fuel plates around the baffle plate • No reflector • ^{235}U mass: 287.8 g	0.40046	1.67
2		• Addition of one 4 cm thick fuel plate • No reflector • ^{235}U mass: 386.8 g	0.50162	2.01
3		• Addition of one 2 cm thick and two 1 cm thick fuel plates • No reflector • ^{235}U mass: 502 g	0.60527	2.53
4		• Addition of one 2 cm thick fuel plate • No reflector • ^{235}U mass: 559.9	0.63938	2.77
5		• Addition of one 1 cm thick fuel plate • No reflector • ^{235}U mass: 588.6	0.65427	2.89
6		• Addition of one 1 cm thick fuel plate • No reflector • ^{235}U mass: 617.2 g	0.66903	3.02

Table 9. Experiment 1: Stacking fuel disks with graphite reflector overview.

Step #	Assembly representation	Description	k_{eff}	M (=1/(1-keff))
7		• Three 4 cm thick fuel plates around the baffle plate • Graphite reflector around fuel plates and on top and bottom • ^{235}U mass: 287.8 g	0.72097	3.58
8		• Addition of one 4 cm thick fuel plate • Graphite reflector around fuel plates and on top and bottom • ^{235}U mass: 386.8 g	0.80963	5.25
9		• Addition of one 2 cm thick and two 1 cm thick fuel plates • Graphite reflector around fuel plates and on top and bottom • ^{235}U mass: 502 g	0.88362	8.59
10		• Addition of one 2 cm thick fuel plate • Graphite reflector around fuel plates and on top and bottom • ^{235}U mass: 559.9	0.92359	13.09
11		• Addition of one 1 cm thick fuel plate • Graphite reflector around fuel plates and on top and bottom • ^{235}U mass: 588.6	0.93740	15.97
12		• Addition of one 1 cm thick fuel plate • Graphite reflector around fuel plates and on top and bottom • ^{235}U mass: 617.2 g	0.95024	20.04

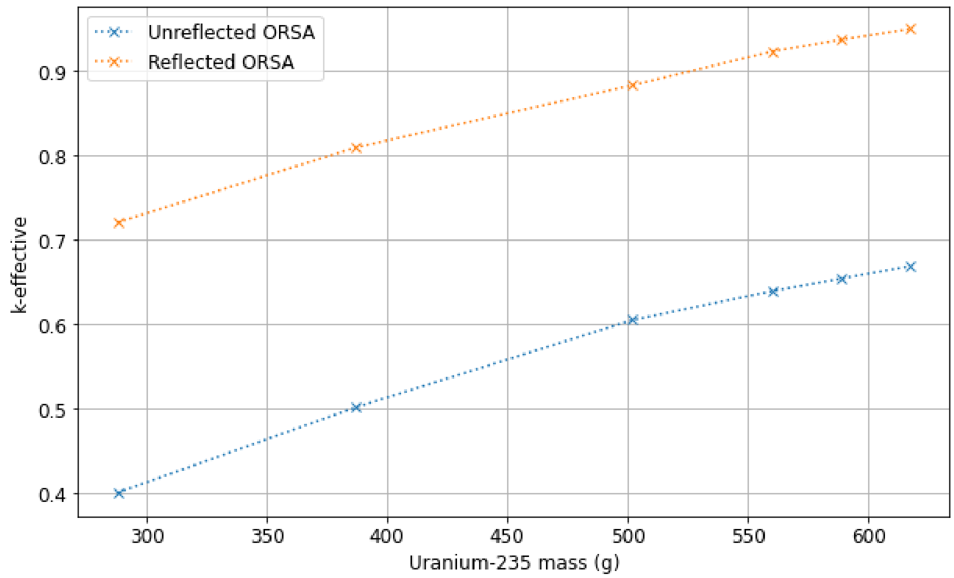


Figure 19. Experiment 1: Mass and reflection calculations overview, demonstrating increasing k_{eff} with increasing fissile mass and reflector, shown by increasing ^{235}U mass.

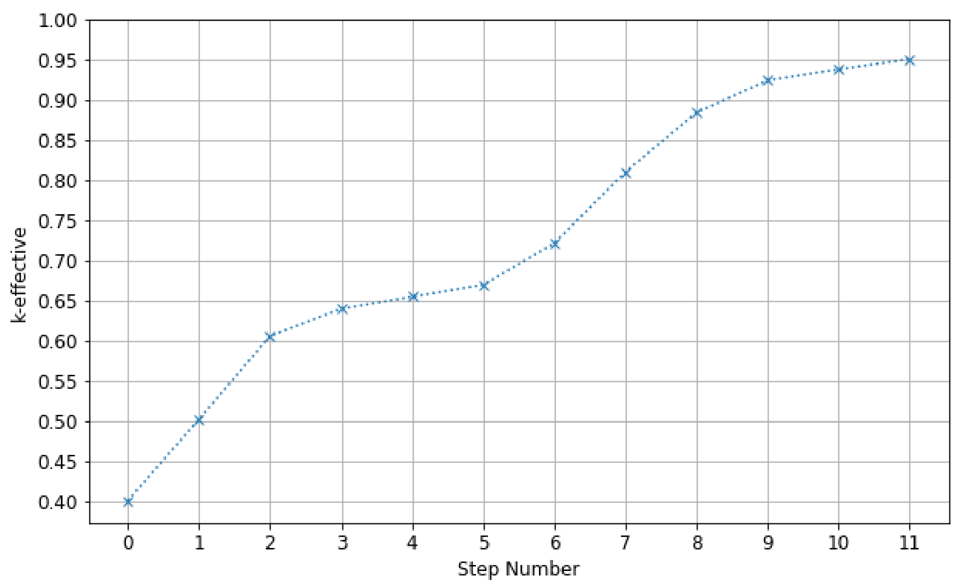


Figure 20. Experiment 1: Mass and reflection calculations overview, demonstrating increasing k_{eff} with increasing fissile mass and reflector, shown by step number.

Additionally, the inverse multiplication factor 1/M obtained from the neutron count rates in MAVRIC calculations are shown in Figure 21 and Figure 22 for the different detector locations and different stacking steps, for the bare and reflected ORSA, respectively. The 1/M results obtained from k_{eff} calculation with KENO-VI are also shown for ORSA modeled with detector 3. The behavior of the detector response is modeled using MAVRIC. The detector positioning provides three unique approaches to critical by inverse multiplication method. Detector 3 demonstrates a result that would indicate a non-conservative approach, over-predicting the critical mass. Detector 1 response demonstrates a result that would indicate a conservative approach, under-predicting the critical mass. Detector 2 response results indicate something in between Detector 1 and Detector 2 responses, close to a linear shape, giving an accurate prediction of the critical mass. These observations are as expected: detector 3 is close to the ^{252}Cf source, so the effects of the neutrons multiplication are partially masked. Detector 1 is outside the assembly, so practically all neutrons counted are thermalized. Detector 2 is in the graphite reflector, a middle ground between the other two configurations. A representation of the 1/M plot from the three detector configurations for each stacking step is shown in Figure 23. This figure corresponds to what the students would typically obtain from the hands-on training, as it considers the multiplication factor from the first step of the stacking. The results of the SCALE/KENO-VI and SCALE/MAVRIC calculations show that the Experiment 1 demonstration of mass and reflection effects on subcritical assembly is feasible and safe.

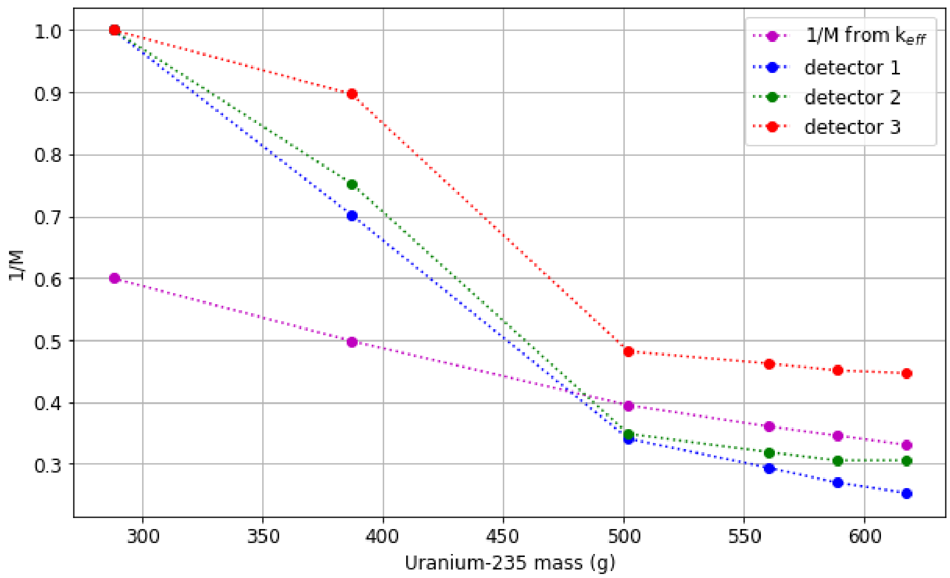


Figure 21. Evolution of the inverse multiplication of the bare ORSA with ^{235}U mass for three different detector locations, obtained with KENO-VI and MAVRIC calculations.

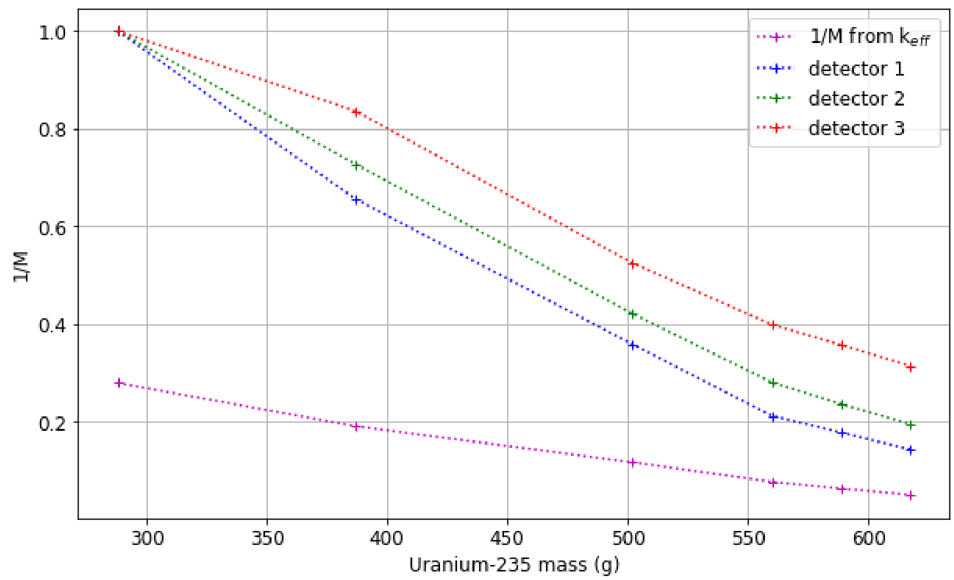


Figure 22. Evolution of the inverse multiplication of the reflected ORSA evolution with ^{235}U mass for three different detector locations, obtained with KENO-VI and MAVRIC calculations.

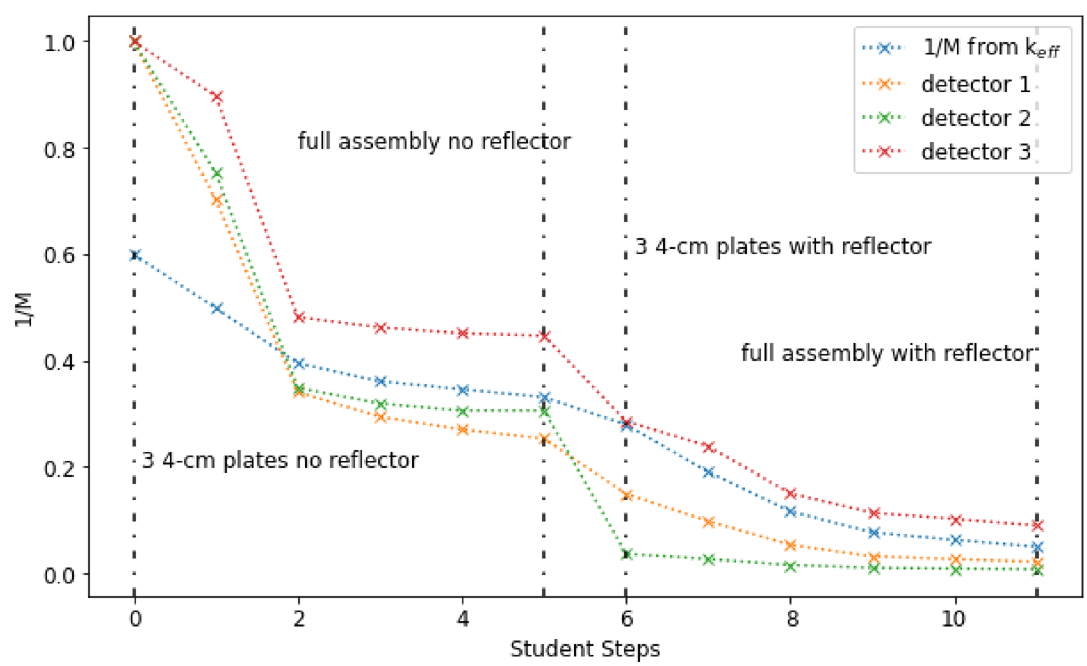


Figure 23. Evolution of the inverse multiplication of the ORSA with stacking steps for three different detector locations, obtained with KENO-VI and MAVRIC calculations.

3.4.4.2 Experiment 2: Separation of Fuel Assembly (Interaction)

The second experiment considered for the hands-on training with ORSA is to show the influence of interaction on criticality. In the first step of the experiment, the two halves of the assembly are separated by 30 cm axially. The two core halves include both fuel plates and graphite reflector. The distance between the two halves of the assembly is decreased during each step, for a final step where the halves are in contact, and the assembly reaches k_{eff} of 0.95 and a corresponding multiplication factor of 20. Table 10 provides information about the separation steps and corresponding k_{eff} results. The steps shown are feasibility demonstrations and are subject to change in the actual ORSA hands-on training. The representation of the ORSA k_{eff} evolution with the decreasing assembly separation is shown in Figure 24. Those results show that ORSA remains subcritical during all the separation steps.

Table 10. Experiment 2: Separation of Fuel Assembly steps overview.

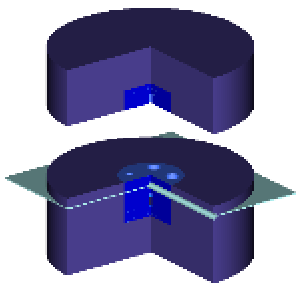
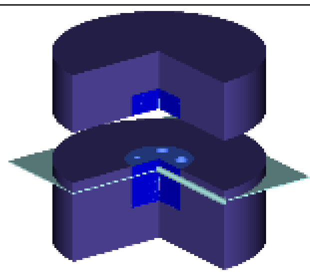
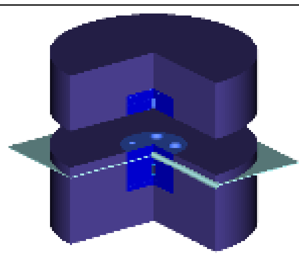
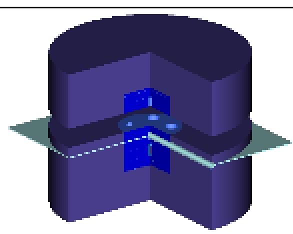
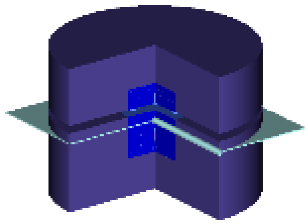
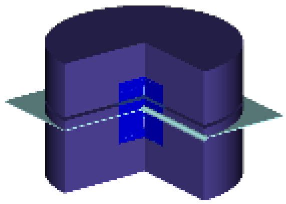
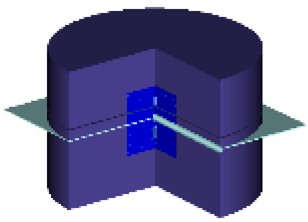
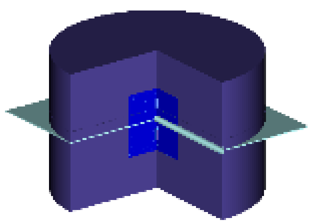
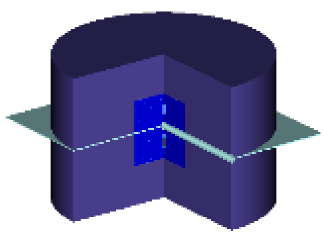
Step #	Assembly representation	Description	k_{eff}	M
1		Upper and lower halves separation distance: 30 cm	0.75183	4.03
2		Upper and lower halves separation distance: 20 cm	0.76439	4.24
3		Upper and lower halves separation distance: 15 cm	0.77765	4.50
4		Upper and lower halves separation distance: 8 cm	0.81682	5.46

Table 10. Experiment 2: Separation of Fuel Assembly steps overview (continued).

Step #	Assembly representation	Description	k_{eff}	M
5		Upper and lower halves separation distance: 3 cm	0.88286	8.54
6		Upper and lower halves separation distance: 1.5 cm	0.91413	11.65
7		Upper and lower halves separation distance: 0.5 cm	0.93767	16.04
8		Upper and lower halves separation distance: 0.1 cm	0.94798	19.22
9		Upper and lower halves separation distance: 0 cm	0.95024	20.10

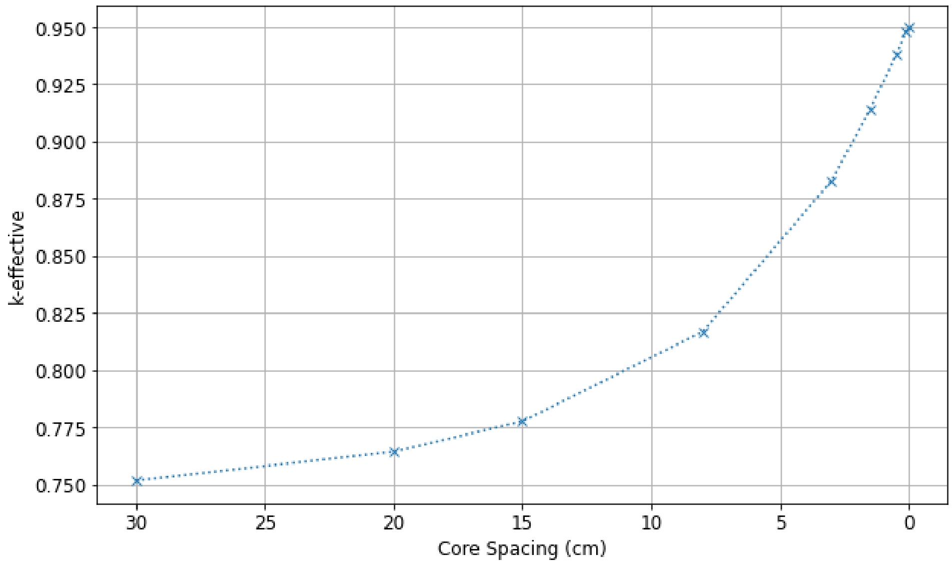


Figure 24. Experiment 2: Interaction calculations overview, demonstrating increasing k_{eff} with decreasing core spacing.

Additionally, the inverse multiplication factor 1/M obtained from the neutron count rates in MAVRIC calculations are shown in Figure 25 for the different detector locations and core spacing steps for the reflected ORSA. The 1/M results obtained from k_{eff} calculation with KENO-VI are also shown with the consideration of detector 3 in the model. The same expected tendency between the three detectors observed in the Experiment 1 is observed again, albeit more pronounced. Detector 3 results tend to be non-conservative, over-predicting the critical mass. Detector 1 results tend to be conservative, under-predicting the critical mass. Detector 2 results tend to be in between, closer to a non-conservative prediction of the critical mass. The results of the SCALE/KENO-VI and SCALE/MAVRIC calculations show that Experiment 2, demonstration of interaction effects on subcritical assembly, is feasible and safe.

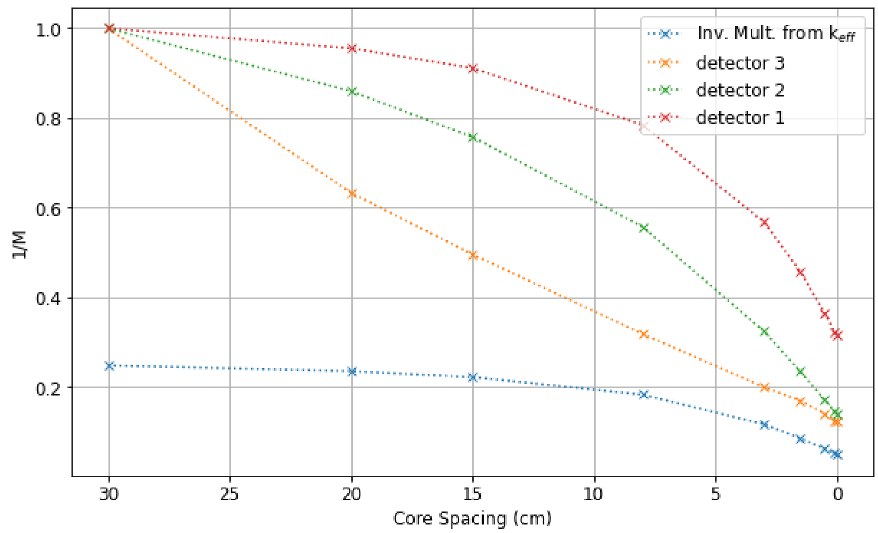


Figure 25. Evolution of the inverse multiplication factor of the ORSA with core spacing steps for three different detectors locations, obtained with KENO-VI and MAVRIC calculations.

3.4.4.3 Experiment 3: Addition of Moderating Materials into Control Rod Inserts (Moderation)

The third experiment involves adding rods of moderating materials into the void regions of the four 4 cm thick fuel plates. Three of those holes have a radius of 2.75 cm without considering the fuel coating and a 2.7375 cm radius considering the 0.0125 cm fuel coating. The fourth hole has a radius of 1.5 cm without considering the fuel coating and a 1.4875 cm radius considering the 0.0125 cm fuel coating. The four moderatingrods go through the four 4 cm fuel plates and the baffle plate for a total height of 16.6 cm. The four rods are added to the final design of the ORSA SCALE model one by one, following the numbering shown in Figure 26, similar to the conceptual design study [1], with the k_{eff} response calculated with KENO-VI. The calculated k_{eff} and derived multiplication factor M are shown in Table 11 for the different rod additions and five different moderator materials tested. As expected by the addition of moderator materials in the assembly, k_{eff} and M are always increased by inserting rods. The most plausible moderator material rod that will be used in the ORSA hands-on training is high-density polyethylene, which is relatively cheap and easy to manufacture. An increase of about 1,000 pcm in k_{eff} and an equivalent increase of 5.4 in M is obtained by using this material. The highest reactivities are obtained with beryllium rods, but beryllium poses significant health concerns, so it won't be used . It is interesting to note that the water at 70°C provides a higher increase in k_{eff} and M than the water at an ambient temperature of 20°C.

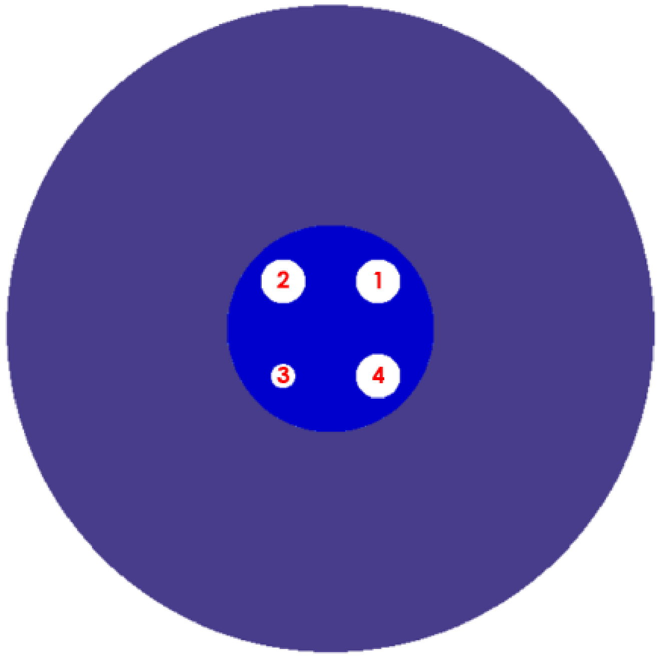


Figure 26. ORSA Experiment 3 and 4 rods addition map.

Table 11. Experiment 3: Moderation calculations overview for five different types of neutron moderator materials

Neutron moderating material	Rod arrangement	k_{eff}	M	Cumulative change in M
Base case, void	No rods	0.95024	20.1	—
High Density Polyethylene	Rod 1	0.95227	21.0	0.9
	Rods 1-2	0.95517	22.3	2.2
	Rods 1-2-3	0.95783	23.7	3.6
	Rods 1-2-3-4	0.96085	25.5	5.4
Water at 20 ºC	Rod 1	0.95331	21.4	1.3
	Rods 1-2	0.95684	23.2	3.1
	Rods 1-2-3	0.95783	23.7	3.6
	Rods 1-2-3-4	0.96330	27.2	7.1
Heavy water	Rod 1	0.95748	23.5	3.4
	Rods 1-2	0.96632	29.7	9.6
	Rods 1-2-3	0.96855	31.8	11.7
	Rods 1-2-3-4	0.97704	43.6	23.5

Table 11. Experiment 3: Moderation calculations overview for five different types of neutron moderator materials (continued)

Neutron moderating material	Rod arrangement	k_{eff}	M	Cumulative change in M
Water at 70 ºC	Rod 1	0.95425	21.9	1.8
	Rods 1-2	0.95901	24.4	4.3
	Rods 1-2-3	0.96161	26.0	6.0
	Rods 1-2-3-4	0.96637	29.7	9.6
Beryllium	Rod 1	0.95908	24.4	4.3
	Rods 1-2	0.96937	32.6	12.6
	Rods 1-2-3	0.97214	35.9	15.8
	Rods 1-2-3-4	0.98187	55.2	35.1

For the Experiment 3 demonstration, k_{eff} is higher than the imposed limit of 0.95 and an equivalent multiplication factor of 20, so the experiment cannot be performed as is. The assembly should be modified to be used with fewer plates, or the separation experiment described in Section 3.4.4.2 can be reproduced until a core spacing yielding an assembly k_{eff} of 0.95 is achieved. The latter technique was also studied with KENO-VI calculations: the assembly was separated into two halves as described in Experiment 2, and four rods of high-density polyethylene were added to the control rods inserts. The core spacing between the upper and lower part of the assembly is then decreased from 30 cm to 0 cm. A view of ORSA with four rods inserted in the control rods inserts and the two halves of the core separated by 30 cm is shown in Figure 27. The representation of the ORSA k_{eff} evolution with the decreasing assembly separation and four rods of high density polyethylene is shown in Figure 28. In that case, the multiplication factor limit of 20 is achieved with a core spacing of about 0.4 cm. Those results show that Experiment 3 can be performed.

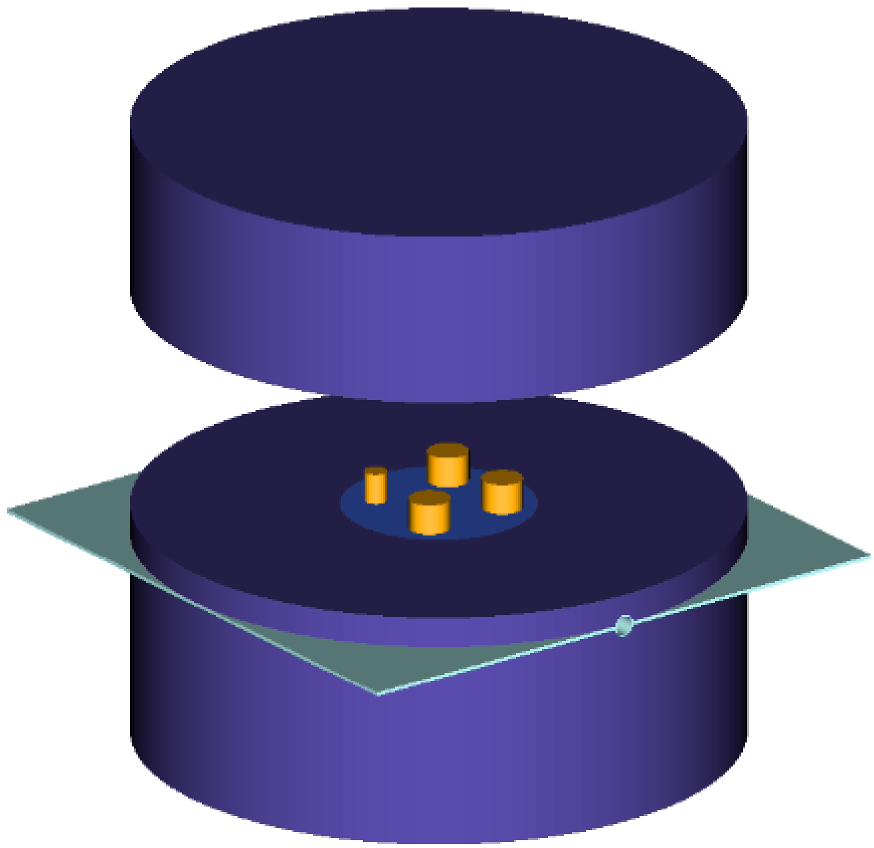


Figure 27. SCALE model 3D view of the combination of Experiment 2: separation and Experiment 3: moderation.

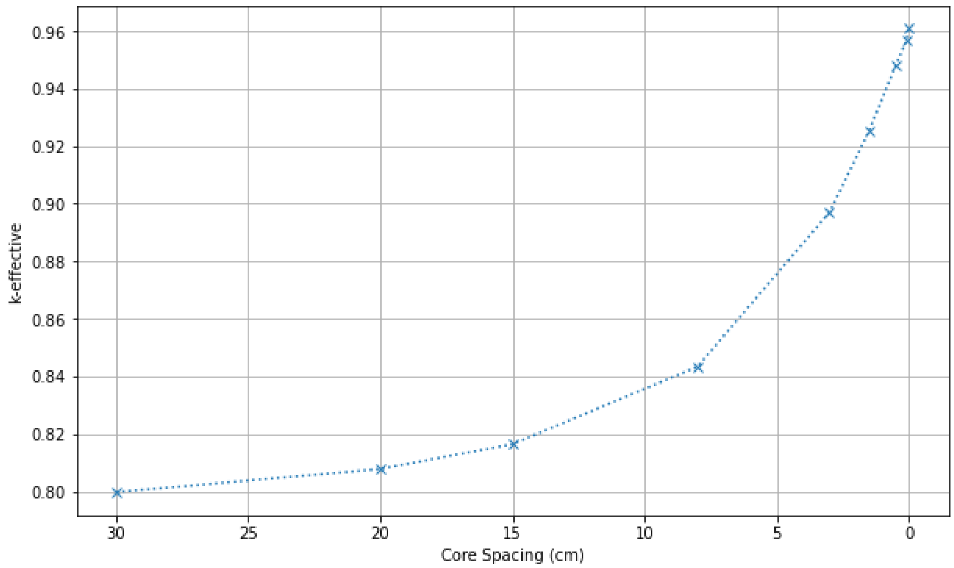


Figure 28. Experiment 3 and 2: Interaction calculations with four neutron moderator high-density polyethylene rods in the assembly, demonstrating increasing k_{eff} with decreasing core spacing.

3.4.4.4 Experiment 4: Addition of Absorbing Materials into Control Rod Inserts (Absorption)

The fourth experiment consists of adding rods of neutron-absorbing materials into the control rod inserts of the four 4 cm thick fuel plates, following the same process as previously described for Experiment 3. The calculated k_{eff} and derived multiplication factor M are shown in Table 12 for the different rod additions and five different neutron-absorbing materials tested. As expected by the addition of absorbing materials in the assembly, k_{eff} and M are always decreasing by inserting rods. The most plausible absorber material rod that will be used in the ORSA hands-on training is stainless steel 304, which is relatively cheap and easy to manufacture. A decrease of about 5900 pcm in k_{eff} and an equivalent decrease of 11 in M is obtained by using four rods of this material. The most significant changes are obtained by using B_4C rods. Those rods would be more complex to design, manufacture, and characterize; their cost would be higher than other materials, but their use can be considered in the future.

Table 12. Experiment 4: Absorption calculations overview for five different types of neutron-absorbing materials.

Neutron moderating material	Rod arrangement	k_{eff}	M	Cumulative change in M
Base case, void	No rods	0.95024	20.1	—
Aluminum	Rod 1	0.94921	19.7	−0.4
	Rods 1-2	0.94850	19.4	−0.7
	Rods 1-2-3	0.94795	19.2	−0.9
	Rods 1-2-3-4	0.94735	19.0	−1.1
Borated high density polyethylene	Rod 1	0.91485	11.7	−8.4
	Rods 1-2	0.87866	8.2	−11.9
	Rods 1-2-3	0.85026	6.7	−13.4
	Rods 1-2-3-4	0.80441	5.1	−15.0
Stainless steel 304	Rod 1	0.93516	15.4	−4.7
	Rods 1-2	0.91959	12.4	−7.7
	Rods 1-2-3	0.90877	11.0	−9.1
	Rods 1-2-3-4	0.89107	9.2	−10.9
Sulfur	Rod 1	0.94557	18.4	−1.7
	Rods 1-2	0.94154	17.1	−3.0
	Rods 1-2-3	0.93950	16.5	−3.6
	Rods 1-2-3-4	0.93558	15.5	−4.6
B_4C	Rod 1	0.69095	3.2	−16.9
	Rods 1-2	0.65973	2.9	−17.2
	Rods 1-2-3	0.62948	2.7	−17.4
	Rods 1-2-3-4	0.59051	2.4	−17.7

Similar to Experiment 3, the assembly was separated into two halves as described in Experiment 2, and four rods of neutron-absorbing stainless steel 304 were added to the control rod inserts. The same setup process is followed, and the core spacing between the upper and lower part of the assembly is decreased from 30 cm to 0 cm. The representation of the ORSA k_{eff} evolution with the decreasing assembly separation and four SS304 rods is shown in Figure 29. In this case, the multiplication factor limit of 20 is never achieved, as the neutrons produced by the assembly are heavily absorbed. Those results show that Experiment 4 can be performed.

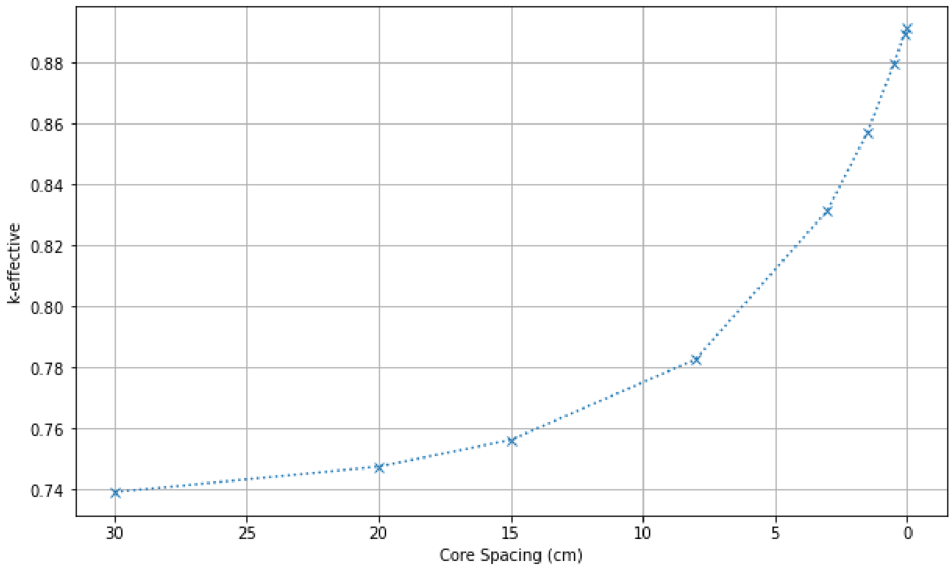


Figure 29. Experiment 4 and 2: Interaction calculations with four neutron-absorbing stainless steel 304 rods in the assembly, demonstrating increasing k_{eff} with decreasing core spacing.

4. ORNL SITE DETERMINATION

Determining the best location to perform the hands-on experiment involves many factors, including safety basis requirements, security requirements, building conditions, and mission impact. In addition, the receipt of fuel must be considered, but with a permanent location in mind. The intention is to select a location that will have minimal security and safety basis requirements so as to allow reduced strain and cost as well as a diversity of students.

Since the ORSA is inherently a subcritical system and unable to achieve a critical state on its own, a criticality event could be precluded by nature of process per the criteria of DOE-STD-1027-2018 [19]. The subcritical assembly would have minimal safety basis impact as long it is segregated to other fissile material operations. Operating the subcritical assembly in a "Below Hazard Category 3 Facility" per DOE-STD-1027-2018 is not only possible, but it would also mitigate interference of subcritical assembly training from other facility activities.

The subcritical assembly is a Cat. IV Attractiveness 3 security level material, which has minimal security requirements compared to facilities with HEU or Pu. Selection of a facility with less restrictive security requirements allows more flexibility for allowed students, which is beneficial for the NNSA DOE NCSP.

4.1 RECEIPT OF FUEL

Currently, there are approximately four cores of AGN-201M fuel in storage at Y-12 National Security Complex. The fuel plates are stored in containers that would no longer meet shipping requirements if opened. The fuel can either be transferred to new containers or received at risk in the current containers without any inspection. The containers can be sent with other ORNL shipments over the road. There are internal routes (i.e., non-public roads) between Oak Ridge National Lab and Y-12 National Security Complex. The AGN-201M fuel can be placed in containers that do not meet transportation requirements and shipped internally. This will require planning between security and operations.

4.2 LOCATION OF SUBCRITICAL ASSEMBLY

Several facilities are considered for the hands-on training with the ORSA. Discussions with ORNL operations narrowed down the selection to the facilities identified in Figure 30. Rankings are based on several criteria. Each criterion is given a qualitative importance value, which is assigned to the facility if it meets that criterion.

Impact to Safety Basis Analysis – Because the intent is to place ORSA in a facility that is a below Hazard Category 3 Facility, the minimal impact should not challenge a facility's requirement to meet DOE-STD-1027. ORSA design is below the single parameter subcritical ^{235}U mass limit of 720 grams [2]; thus it cannot achieve a credible critical configuration. However, the entire inventory of a facility is considered when meeting DOE-STD-1027. For a facility to accept ORSA and still meet the requirements, it must (1) easily credit segregation, (2) have the ability to perform a "source shuffle," or (3) have essentially no fissile material. These three criteria were discussed with safety basis personnel to determine whether it is an impact to a considered location.

Impact to Radiological/Industrial Safety – Because of potential contamination, coating the fuel is being reviewed and is now assumed in the ORSA design. The impact is based on the areas that perform radiological work having available space. If the provided location does not have a radiological area, this was determined to be an impact.

Impact to ORNL current missions – ORSA activities were assumed to be as frequent as the current training activities by NCSP. If there would be conflicts preventing training or preventing mission accomplishment in the potential location, this is considered an impact. For example, some locations considered would have “emergent task” that would require the laboratory space. These task could prevent hands-on training even if training were planned with plenty of notice.

Minimal modifications needed for building – Some potential locations needed to be modified to allow people for prolonged activities. If modifications were needed, this is considered impactful.

Human Comforts – Hands-on training is a time-consuming activity. Availability of drinking water, restrooms, and conditioned air were some factors that determined this impact.

The overall facility ranking is the summation of the criteria met with a higher ranking being more beneficial for the subcritical assembly. The weighted value of each criterion can be seen in

Table 13, and the final facility rankings are summarized in Table 14.

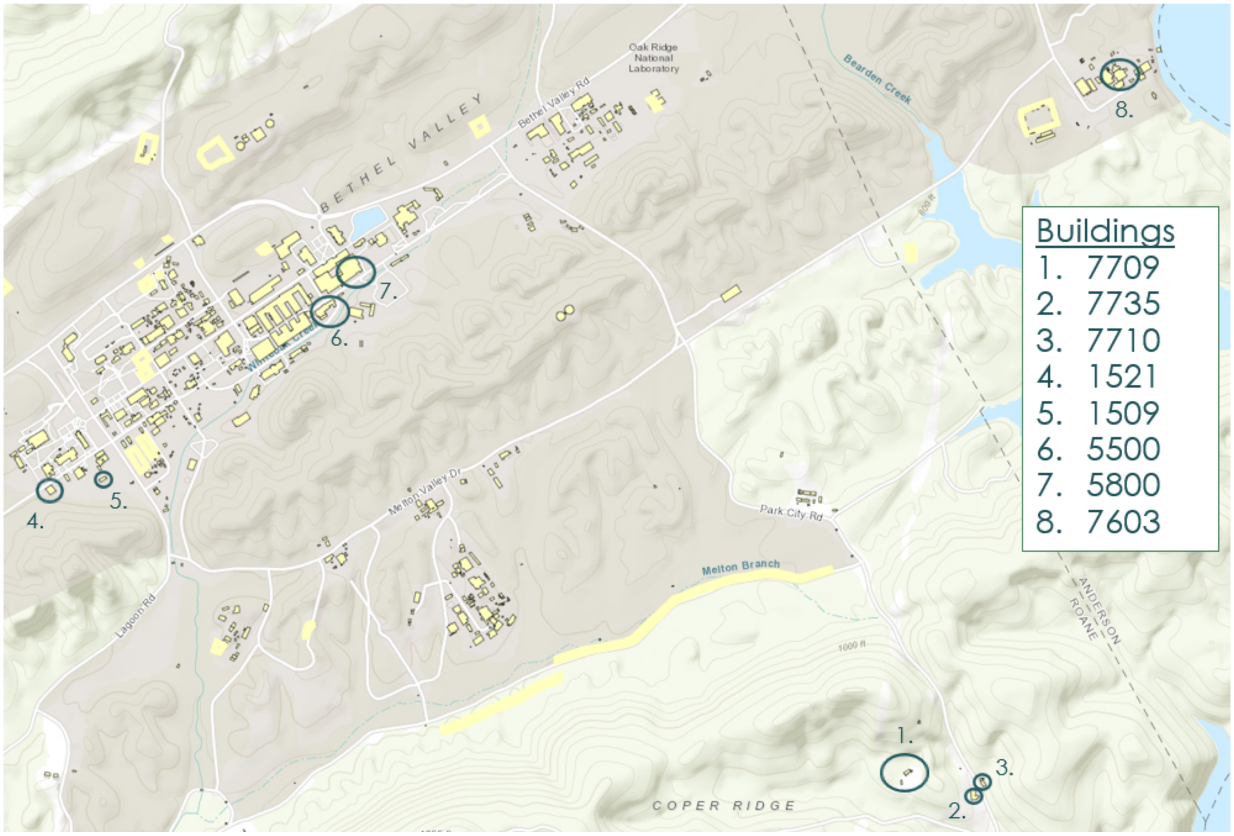


Figure 30. Facility Locations considered for the Subcritical Assembly.

Table 13. Facility selection criteria

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

[a] Encapsulation of the fuel may be required to meet radiological contamination requirements.
[b] Example of creature comforts includes access to potable water and conditioned air availability.

Table 14. Facility ranking

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
7603-Vault	✓	✓	✓	✓	✓	13

As seen in Table 14, 7603-vault option is the best candidate. This area as well as the laboratories in building 7603 support non-destructive assay (NDA) research and activities. Because several missions for the NDA organization support NCSP and the applications of ORSA for the NDA organization, a cohesive relationship between the two organizations makes this a feasible option. However, the primary challenge for using Building 7603 is to meet the segregation criteria per DOE-STD-1027-2018. Conservative administrative limits set by ORNL would require a "shuffling" of sources to allow ORSA fuel into the facility. Errors in source shuffling could lead to safety basis impacts; therefore, it is evaluated as greater than minimal impact to the safety analysis. The NDA group has space for vaults near the building. These vaults are powered, secure buildings that provide source segregation, security, power, and HVAC. Procurement of a new vault would allow a dedicated area for ORSA to perform hands-on activities and essentially no impact to the other programs. Building 7603 is within walking distance of access to laboratory tools as well as additional creature comforts (e.g., restroom, water) during the hands-on training.

Figure 31. Current vaults located near Building 7603.

5. CONCLUSION

Since the feasibility study performed in 2020, work has be done to develop the final design of ORSA and evaluate performing the hands-on training at ORNL. This evaluation took into consideration the reality of performing the hands-on experiments, which led to modifications from the feasibility study design. This primarily resulted in a significant increase in the amount of reflector needed, but designs of the assembly consider this significant amount. The fissile mass is still maintained below 720 g ^{235}U, allowing hands-on activities to be performed in a facility with minimal safety and security requirements. This allows a diversity of students and minimizes events that could strop training, thus increasing NCSP's training program to remain adaptable and responsive [6]. Four experiments from the feasibility report were reviewed again with the modified design and more focus on the student's interface. These experiments are not only feasible, but the 1/M curve has also been demonstrated with various detector placements. The assembly design of ORSA has been conceptualized and can manage the weight of the completed assembly with minimization of industrial hazards. Reflector designs are determined to be feasible. Finally, a site review was performed to determine the location of hands-on training. Discussions with Y-12 have determined multiple options for receiving fuel. Several locations were reviewed, and feasibility of the locations were qualitatively determined. All considerations for ORSA are now completed and ready for implementation.

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