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IER 203 CED-2 Report: LLNL Final Design for BERP Ball With a Composite Reflector of Thin Polyethylene Backed by Nickel

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July 18, 2016

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

LLNL Final Design for BERP Ball With a Composite Reflector of Thin Polyethylene Backed by Nickel

IER-203 CED-2 Report

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Auspices
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0.0 Executive Summary

This report documents the results of final design (CED-2) for IER 203, BERP Ball Composite Reflection, and focuses on critical configurations with a 4.5 kg α-phase plutonium sphere reflected by a combination of thin high density polyethylene (HDPE) backed by a thick nickel reflector. The Lawrence Livermore National Laboratory's (LLNL's) Nuclear Criticality Safety Division, in support of fissile material operations, calculated surprisingly reactive configurations when a fissile core was surrounded by a thin, moderating reflector backed by a thick metal reflector. These composite reflector configurations were much more reactive than either of the single reflector materials separately. The calculated findings have resulted in a stricter-than-anticipated criticality control set, impacting programmatic work. IER 203 was requested in response to these seemingly anomalous calculations to see if the composite reflection effect could be shown experimentally.

A total of four critical configurations were designed as part of CED-2. The universal critical assembly machine Comet, at the National Criticality Experiments Research Center (NCERC) will be used for the IER 203 experiments. These configurations use close-fitting polyethylene reflector shells with thicknesses of 1, 1.25, 1.5, and 1.75 cm backed by cylindrical nickel reflectors with an overall radius of 25.4 cm. The optimal polyethylene thickness for this configuration was found to be 1.5 cm.

The assessment of experimental uncertainties gave very good results, with the total predicted uncertainty for the experiments as 0.00226 Δk_{eff}. The largest contributor to uncertainty is the uncertainty in the polyethylene and nickel reflector mass and dimensions. As the reflectors have yet to be fabricated, these perturbations were educated guesses and thus can be lessened through procurement specifications and piece-by-piece measurements. A concerted effort can also be made to lessen and quantify any gaps between plates in the assembly, which also have a relatively large effect on k_{eff}.

Fabrication costs are estimated to be $98,500, largely due to the cost of the large nickel reflectors. Since the fissile material is existing, the parts to be fabricated are polyethylene reflectors, nickel reflectors, and the aluminum upper platen for use with the Planet critical assembly machine. Composition and impurity analysis of the manufactured parts is estimated at $5,000. Additionally, inspection, dimensional analysis, and contour measurements for a representative subset of all experimental parts (fissile and non-fissile) is estimated to be $5,000.

Based on the amount of time it will take to prepare experimental paperwork and make procurements, the IER 203 experiments could reasonably begin in early FY2017, with publication in Q3/Q4 2017.

1.0 Introduction

The Lawrence Livermore National Laboratory's (LLNL's) Nuclear Criticality Safety Division, in support of fissile material operations, calculated surprisingly reactive configurations when a fissile core was surrounded by a thin, moderating reflector backed by a thick metal reflector. These composite reflector configurations were much more reactive than either of the single reflector materials separately. The calculated findings have resulted in a stricter-than-anticipated criticality control set, impacting programmatic work. In FY2014, the U.S. Department of Energy (DOE) Nuclear Criticality Safety Program (NCSP) approved and funded the final design for Integral Experiment Request (IER) 203, Composite Reflection Experiments, to focus on design of critical experiments to experimentally investigate this computational result. This report fulfills the requirements of Critical Experiment Design (CED)-2 and focuses on the Beryllium Reflected Plutonium (BERP) ball as a fissile material core reflected by polyethylene and nickel.

2.0 Summary of CED-1

Critical Experiment Preliminary Design (CED-1) for IER 203 was completed in FY2014[1]. The Monte Carlo code MCNP5 was used to investigate the feasibility of creating critical configurations using the BERP ball with a combination of common reflector materials. Composite reflectors investigated were polyethylene and twelve different candidate metals: nickel (Ni), iron (Fe), chromium (Cr), titanium (Ti), manganese (Mn), Zirconium (Zr), Tungsten (W), aluminum (Al), lead (Pb), cobalt (Co), copper (Cu), and depleted uranium (U). These specific metals were chosen because they are commonly used as structural materials in nuclear applications. For example, many of these metals are components of stainless steel alloys.

In the MCNP models, a layer of polyethylene (PE) of variable thickness was located around the BERP ball and backed by the metal reflector, which was fixed at 30 cm (infinite) thickness. Figure 2.1 shows a 2D representation of the 3D MCNP geometry used for the calculations. The purple region is the spherical BERP ball, surrounded by the variable thickness reflector of high density polyethylene (shown in light blue). The gray area is the 30 cm fixed-thickness metallic reflector.

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[1] Percher, C. and S. Kim. *IER-203 CED-1 Report: LLNL Preliminary Design for BERP Ball with Composite Polyethylene and Nickel Reflection.* Lawrence Livermore National Laboratory. April 2, 2014.

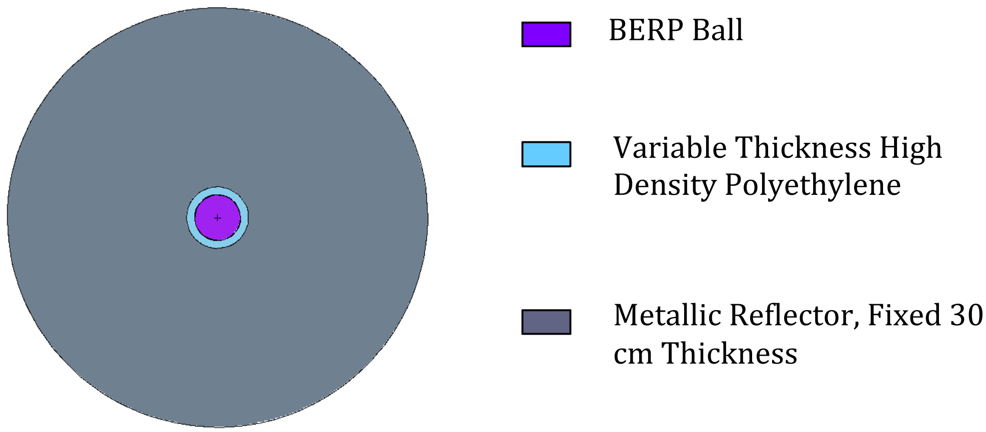

Figure 2.1: MCNP5 Geometry for BERP Ball Surrounded by Various Composite Reflectors.

Figure 2.2 displays the results from the MCNP5 calculations for composite reflectors with varying polyethylene thickness backed with 30 cm of various metals. Not all metals displayed the composite effect, namely tungsten and cobalt. The highest reactivity for tungsten (black line, shaded circles) and cobalt (purple line, shaded circles) was calculated when there was no polyethylene reflector at all. Depleted uranium and polyethylene composite reflectors (red line, shaded circles) displayed interesting behavior as k_{eff} initially decreases with the addition of polyethylene and then displays a composite reflection increase, taking the configuration just above critical around 2 cm of PE thickness. The initial decrease is likely due to the reduced density of the reflector as DU is replaced with PE and increased absorption as neutron energy is reduced through moderation. All other metals displayed some degree of the composite reflection effect, with reactivity increasing with increasing polyethylene reflector thickness and then leveling off and approaching a keff of 0.9434(2), the reactivity of the BERP ball reflected by infinite PE alone.

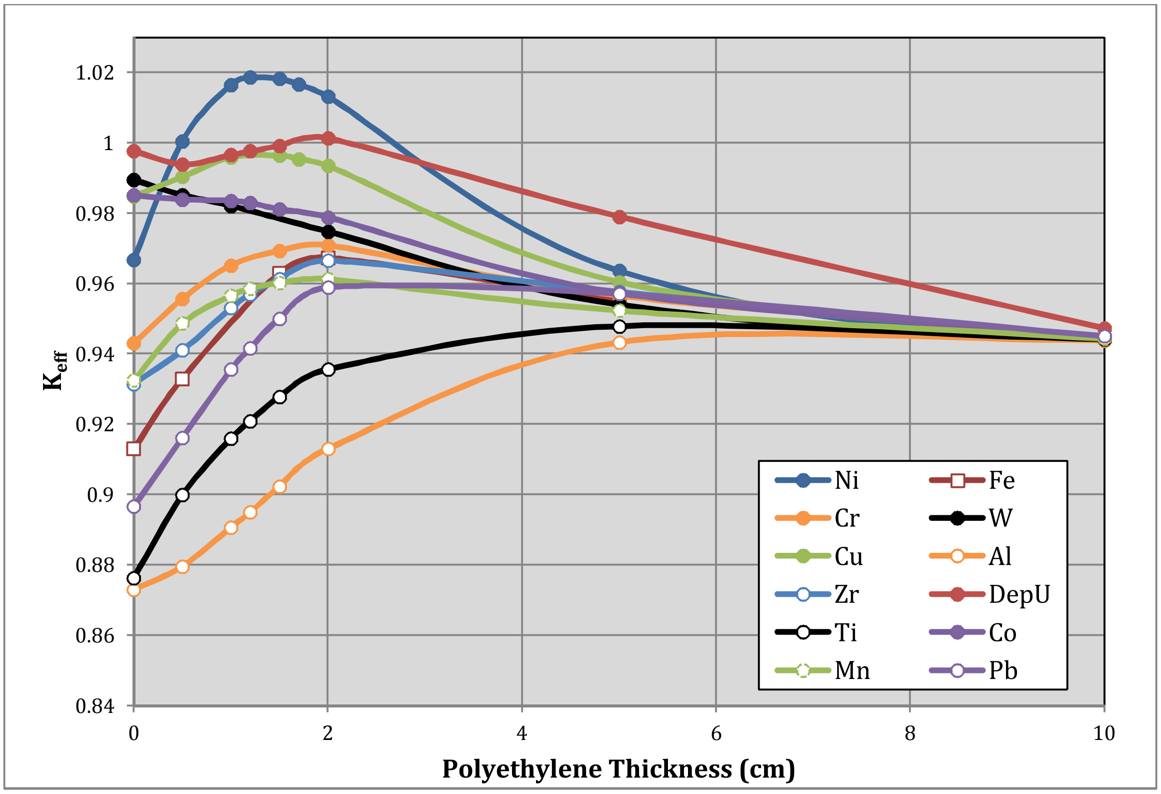

Figure 4.2: K_{eff} of the BERP Ball as a Function of Varying Thicknesses of Polyethylene Reflection Backed by 30 cm Thick Metallic Reflectors

From the configurations studied, the combination of nickel and PE was shown to have the largest effect on BERP ball reactivity, peaking at a k_{eff} of 1.0186(2) at 1.2 cm of PE. This corresponds to an increase in k_{eff} of approximately 3.5% from the purely nickel reflected case and an increase of 9.3% over the purely polyethylene reflected case. The only other reflector combination shown to produce a critical configuration was depleted uranium and polyethylene. However, at a peak keff of 1.0013(2), this configuration is likely marginal for a critical experiment when experimental realities (such as reflector gaps) are considered. The other combinations of reflector materials failed to produce a critical configuration with the BERP ball, but could be candidates for critical reflectors for other fissile cores.

Additional calculations from the CED-1 report looked at reducing the nickel reflector from 30 cm. With a spherical nickel thickness of 20 cm, the excess reactivity of the system, as calculated by MCNP5, was 0.0128. An investigation of International Criticality Safety Benchmark Evaluation Project [2] fast critical benchmarks with polyethylene and nickel reflection showed a small positive bias to the MCNP5 calculations. Even when taking this bias into account (0.005 combined Δk), the level of

[2] NEA/NSC/DOC(95)03. *International Handbook of Evaluated Criticality Safety Benchmark Experiments.* September 2013 Edition. Nuclear Energy Agency. Organisation for Economic Cooperation and Development.

excess reactivity calculated for 1.2 cm of PE and 20 cm of nickel surrounding the BERP ball provided confidence that a critical assembly can be achieved.

3.0 Experiment Description

3.1 Assembly Machine

Due to the weight of the nickel parts, the universal critical assembly machine Comet, at the National Critical Experiments Research Center (NCERC), will be used for the IER 203 experiments. Comet is a vertical lift machine that is used to separate a critical assembly into halves. The upper half of the assembly is supported on a stationary platen and the bottom half is supported by a movable platform. The bottom platform is raised to achieve or approach criticality and is raised until it contacts the top portion of the assembly. Figure 3.1 shows a picture of the Comet machine with a previously conducted experiment. The figure was taken from the ICSBEP Handbook, evaluation HEU-COMP-INTER-003[3].

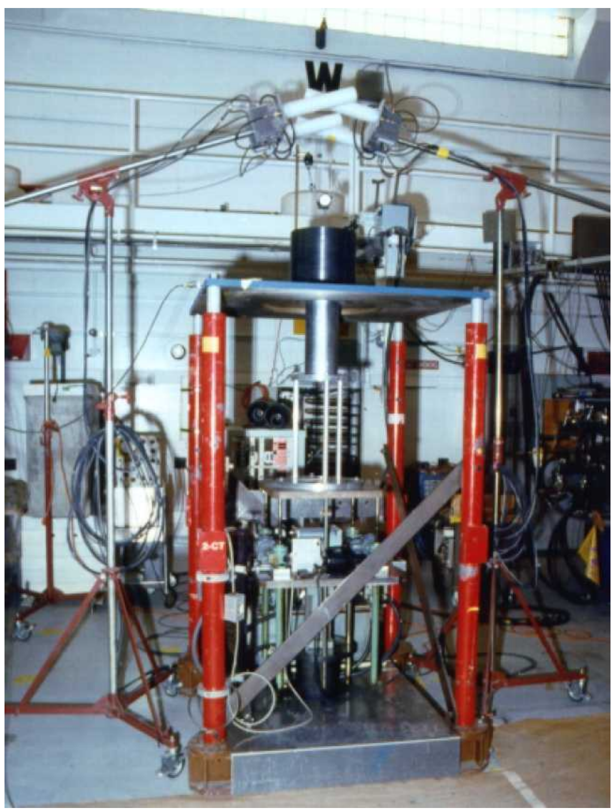

Figure 3.1: Planet Machine in Loaded with a Highly Enriched Uranium-Hydride Experiment (HEU-COMP-INTER-003)

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3 Brewer, R. and R. LaBauve. HEU-COMP-INTER-003, *Reflected Uranium-Hydride Cylindrical Assemblies.* International Handbook of Evaluated Criticality Safety Benchmark Experiments. NEA/NSC/DOC(95)03/I. September 2015 Edition.

The IER 203 experimental setup consists of the BERP (BEryllium Reflected Plutonium) Ball, an α-phase plutonium sphere, reflected by a combination of thin high density polyethylene (HDPE) shells backed by a thick nickel reflector comprised of a stack of plates. The upper platen, with outer dimensions of 45 in by 45 in, will be rigidly attached to the Planet or Comet supports. A drawing of the platen design, which will need to be fabricated before use, is shown in Appendix B. The outer edge of the platen is 1" thick Aluminum 6061 and it has an 18" circular hole in the middle of the plate. The plate will support the upper half of the nickel reflectors. A picture of the platen is shown in Figure 3.2, which shows all the holes for mounting experimental fixturing. The lower half of the assembly will be resting on an existing aluminum plate that is 1.5 in thick and 31 in by 31 in square. The lower assembly is comprised of the nickel reflector plates, the polyethylene shells, and the BERP ball, which will be raised to mate with the upper nickel reflectors on the stationary platen.

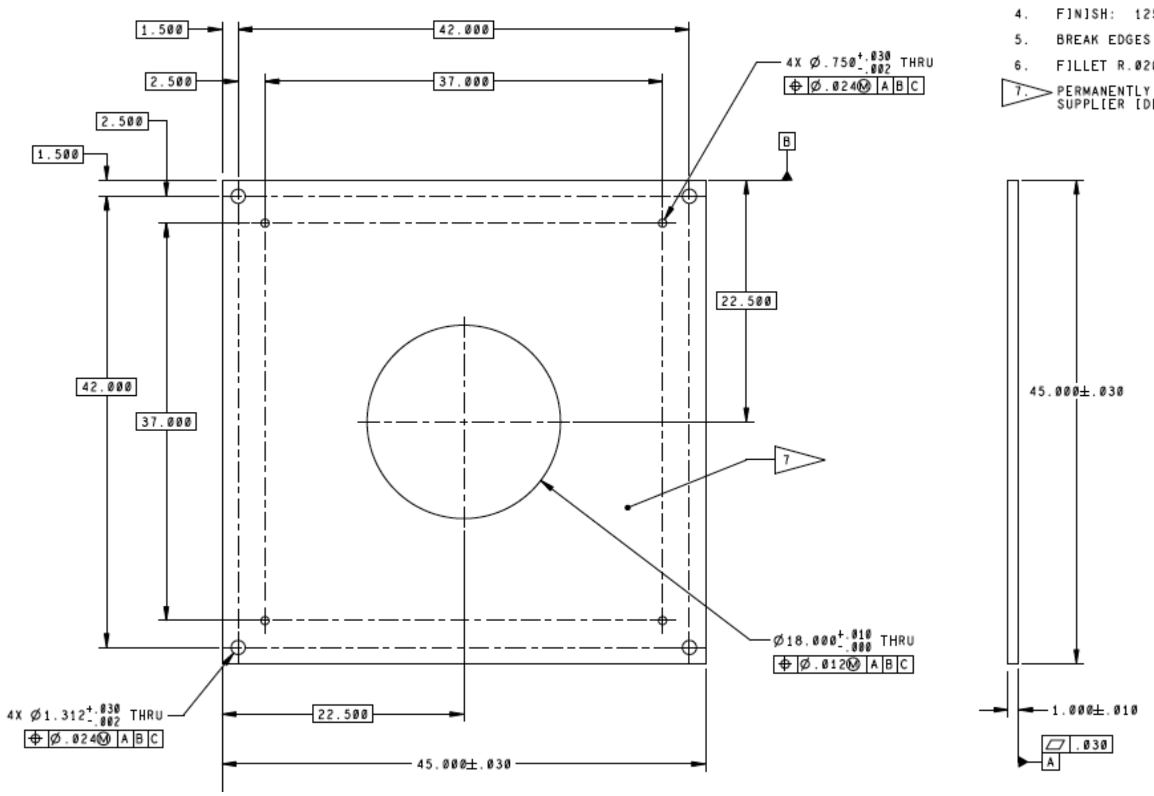

Figure 3.2: Drawing of the Upper Aluminum Platen for Composite Reflection Experiment.

3.2 BERP Ball

The BERP Ball has been used extensively by Los Alamos National Laboratory for critical and subcritical experiments. The following description of the BERP ball was largely taken from ISCBEP evaluation PU-MET-FAST-038, *Plutonium Sphere Reflected* *by Beryllium*[4], with additional details provided by FUND-NCERC-PU-HE3-MULT-001, *Nickel-Reflected Plutonium-Metal-Sphere Subcritical Measurements*.

3.2.1 BERP Ball Fabrication and Dimensional Information

The α-phase plutonium sphere was made in October 1980 by Los Alamos National Laboratory (LANL). After casting, the plutonium sphere was turned to a mean diameter of 7.5876 cm. The density of the plutonium sphere was calculated as 19.6039 g/cm^3 based on a weight of 4483.884 grams and a volume of 228.72 cm^3. After machining, the sphere was wiped with cheesecloth to remove loose contamination. The plutonium sphere was partially immersed in Freon to contract it and then placed into two stainless steel hemishells for a tight-fitting cladding. The 304 SS cladding consists of two identical hemispheres with IDs and ODs of 3.014 and 3.038 inches. The cladding also has a flange with an OD of 3.446 inches and a thickness of 0.036 inches. The stainless steel hemishells were electron-beam welded together. The total mass of the plutonium sphere including the cladding is 4537.173 g. The BERP ball and cladding is shown in Figures 3.3-3.5. All figures of the BERP ball are taken from PU-MET-FAST-038.

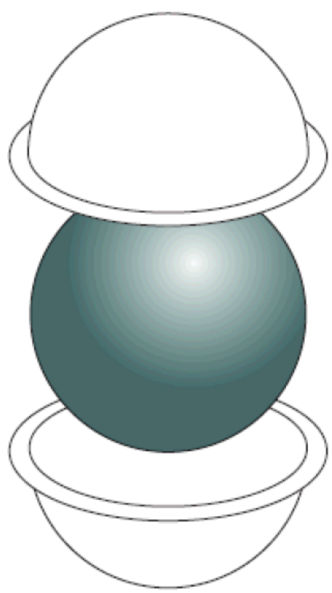

Figure 3.3: BERP Ball and Stainless Steel Cladding Hemishells (Exploded View).

[4] Hutchinson, J. and D. Loaiza. PU-MET-FAST-038, *Plutonium Sphere Reflected by Beryllium.* International Handbook of Evaluated Criticality Safety Benchmark Experiments. NEA/NSC/DOC(95)03/I. September 2013 Edition.

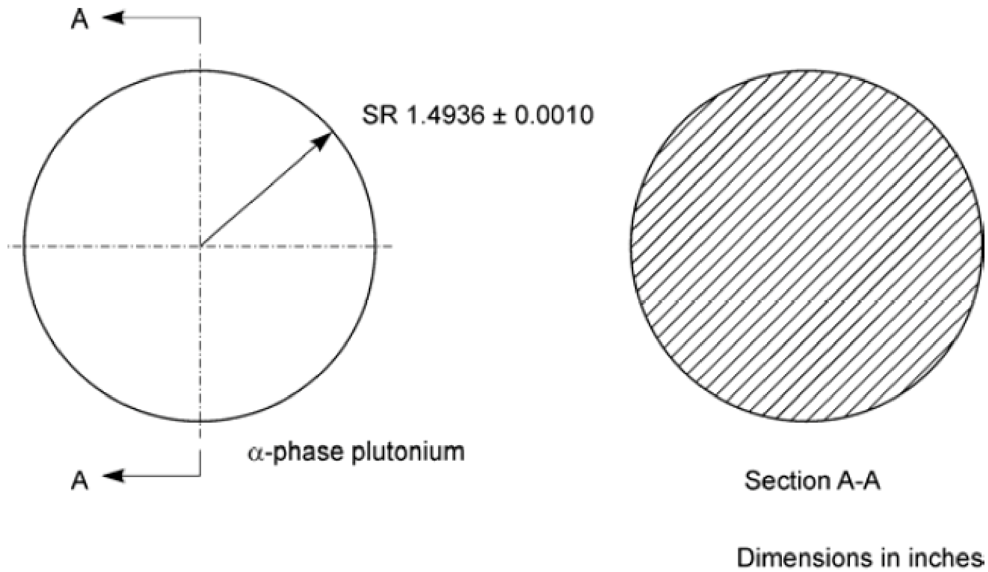

Figure 3.4: BERP Ball Plutonium Sphere Drawing (in inches).

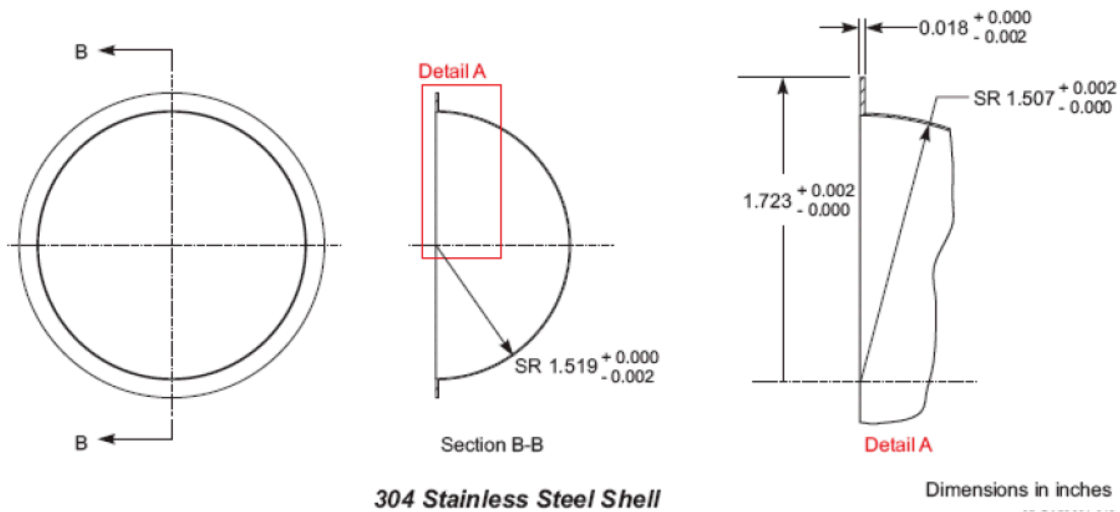

Figure 3.5: BERP Ball Stainless Steel Hemishell Drawing Showing Flange (in inches).

As described in FUND-NCERC-PU-HE3-MULT-001, two radiographs have been taken of the BERP ball, one in 1980 and the second in 2014. Based on the radiographs, it was determined that the Pu sphere has no voids and that it rests on the bottom of the stainless steel cladding, as expected.

3.2.2 BERP Ball Mass and Isotopic Information

Composition data presented here was taken from ICSBEP evaluation PU-MET-FAST-

038. The masses and densities of the plutonium sphere and 304 SS cladding are shown in Table 3-1. The densities were calculated by dividing the measured masses by the calculated volumes based on measurements and drawings. All mass measurements were taken prior to the encapsulation of the plutonium sphere in 1980. The accuracy of the balance was not recorded in the original reports, and thus was not reported in the benchmark evaluation.

Table 3-1: Mass and Density of BERP Ball Components

Part	Mass (g)	Calculated Density (g/cm^3)
alpha Pu sphere	4483.884	19.6039
304 SS cladding	53.289	7.74262

Isotopic composition of the BERP Ball plutonium was performed by CMB-11, a chemical group at LANL in 1980. Two separate isotopic analyses were performed. As reported in PU-MET-FAST-038, the report generated by the analysis showed that 99.52 wt% of the sphere was plutonium. The Pu/Am isotopic composition is detailed in Table 3-2.

Table 3-2: Pu/Am Composition of the BERP Ball in 1980

Isotope	Weight Percent Analysis 1	Weight Percent Analysis 2
^{238}Pu	0.20	0.020
^{239}Pu	93.73	93.74
^{240}Pu	5.96	5.94
^{241}Pu	0.268	0.269
^{242}Pu	0.028	0.028
^{241}Am	557 ppm	

Emission spectroscopy with arc source was used to determine the impurities in the plutonium. The known impurity weight percents are shown in Table 3-3. A total of 0.35% of the plutonium is unaccounted for.

Table 3-3: Impurities in the BERP Ball Plutonium

Element	ppm (wt.%)	Assay Report Date
Fe	10	9/24/1980
Ga	335	9/24/1980
Be	<1	10/3/1980
Al	<5	10/3/1980
Ni	<5	10/3/1980
Mo	9	10/3/1980
Pb	<5	10/3/1980
B	<1	10/3/1980
Si	<5	10/3/1980
Cu	<1	10/3/1980
Ag	<1	10/3/1980

Bi	<1	10/3/1980
Na	<50	10/3/1980
Ca	3	10/3/1980
Zn	<5	10/3/1980
Cd	<10	10/3/1980
Mg	<1	10/3/1980
Cr	<5	10/3/1980
Zr	<100	10/3/1980
Sn	<5	10/3/1980
C	230	10/9/1980
Unknown	3500*	n/a

* Value derived by adding all known constituents (plutonium, americium, and impurities) and subtracting from 100 wt.%.

3.3 Polyethylene Reflectors

Hemishells of polyethylene have been designed to provide thin, close-fitting reflection to the BERP Ball for this experiment. Four sets of two hemishells will be machined out of High Density Polyethylene (HDPE) blocks. The polyethylene hemishells will be fabricated to provide 1 cm, 1.25 cm, 1.5 cm, and 1.75 cm (nominal) of radial reflector on the outside of the BERP ball, as shown in Figure 3.6.

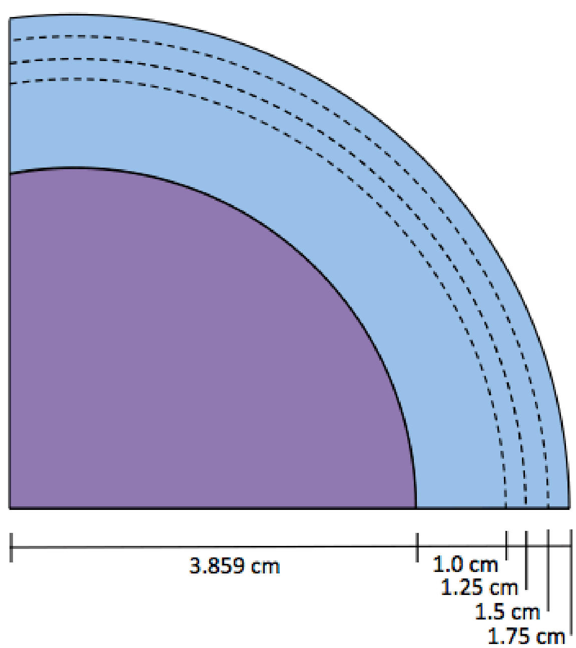

Figure 3.6: Nominal Thicknesses of Polyethylene Reflectors around the BERP Ball for the Composite Reflection Experiments. The polyethylene reflectors are shown in light blue, while the BERP ball is shown in purple.

Drawings for the polyethylene reflectors, including manufacturing tolerance and gap allowances, are shown in Figures 3.7 through 3.10.

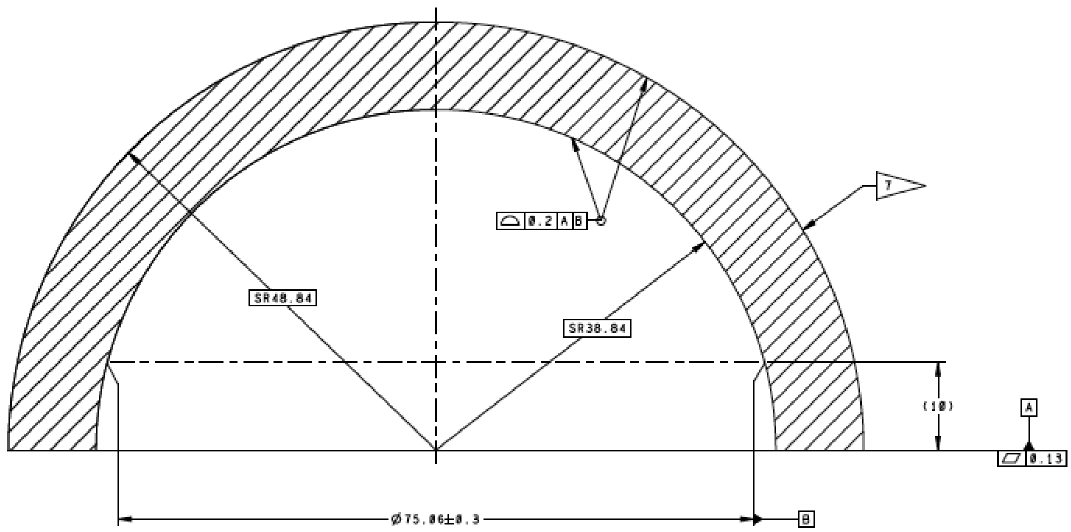

Figure 3.7: Polyethylene Reflector Shell P1A and P1B for the Composite Reflection Experiments. The inner diameter is meant to mate up with the outer diameter of the BERP Ball. This reflector provides 1 cm of HDPE reflection. All dimensions in mm.

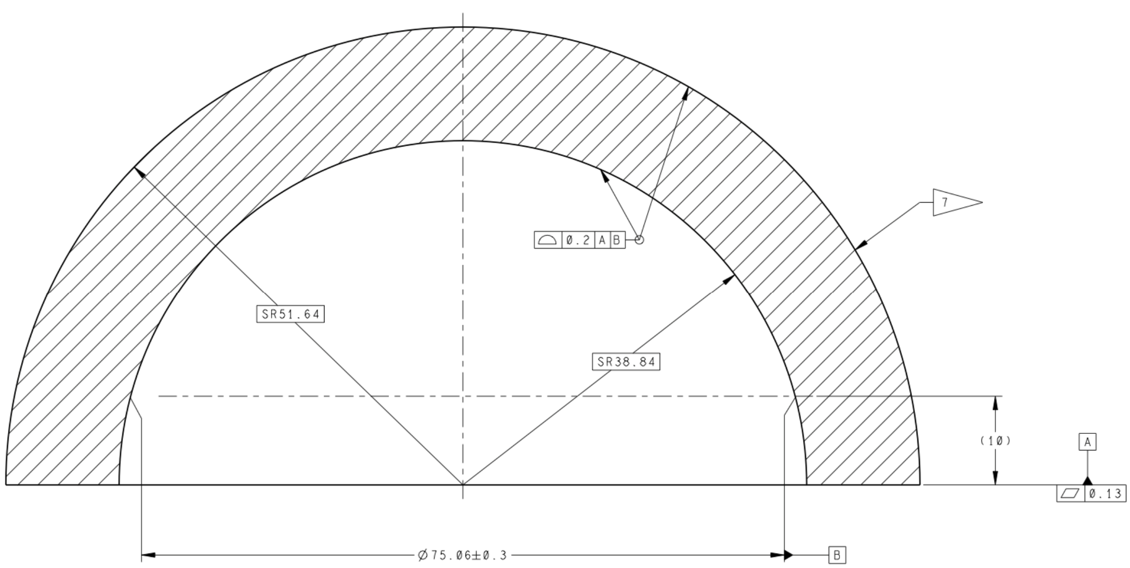

Figure 3.8: Polyethylene Reflector Shell P2A and P2B for the Composite Reflection Experiments. The inner diameter is meant to mate up with the outer diameter of the BERP Ball to provide 1.25 cm of HDPE reflection around the BERP Ball. All dimensions in mm.

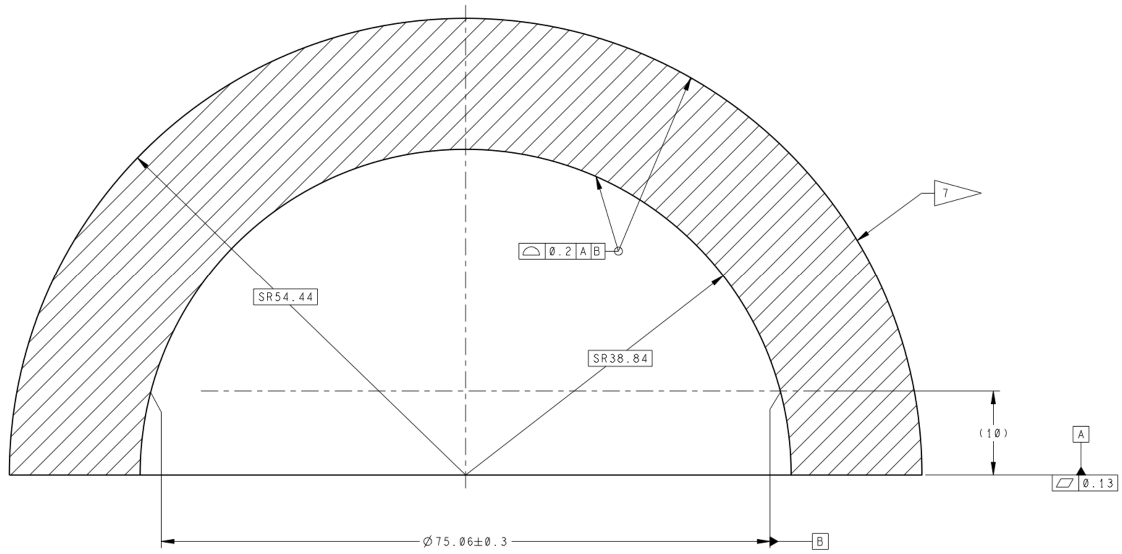

Figure 3.9: Polyethylene Reflector Shell P3A and P3B for the Composite Reflection Experiments. The inner diameter is meant to mate up with the outer diameter of the BERP Ball to provide 1.5 cm of HDPE reflection around the BERP Ball. All dimensions in mm.

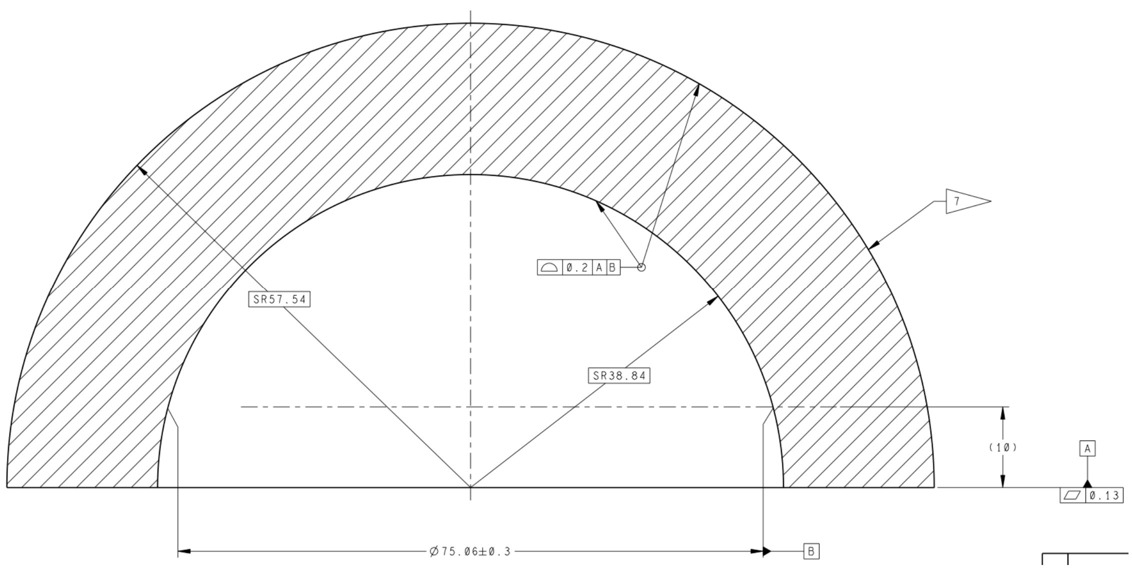

Figure 3.10: Polyethylene Reflector Shell P4A and P4B for the Composite Reflection Experiments. The inner diameter is meant to mate up with the outer diameter P3A and P3B to provide 1.75 cm of HDPE reflection around the BERP Ball. All dimensions in mm.

The polyethylene reflectors have yet to be fabricated. The nominal density of polyethylene assumed for final design is 0.967. The density and impurity content of the HDPE will be quantified during fabrication of the HDPE parts.

3.4 Nickel Reflector Parts

As shown by CED-1, thick nickel reflection (> 12 cm) is required to drive the BERP ball critical under composite reflection by HDPE and nickel. Nesting nickel hemishells were determined to be prohibitively costly (with the lowest estimates around $0.5 million). Therefore, LLNL has designed a combination of hemishells and plates of nickel that will provide reflection in concert with the HDPE reflectors detailed in Section 3.3. Four sets of two hemishells will be fabricated from nickel 200. In addition, two cylindrical nickel discs, 20” in diameter and 5” thick will be fabricated from nickel 200. When stacked together, these nickel discs will provide the main cylindrical reflection around the BERP ball. Additional 1” nickel plates will be fabricated that can augment the 5” discs on top and bottom of the stack, as shown in Figure 3.10. Figure 3.10 provides an overview of how the nickel reflectors will be stacked around the BERP ball and hemishell reflectors. Figures 3.11-3.17 show the nickel drawings for fabrication.

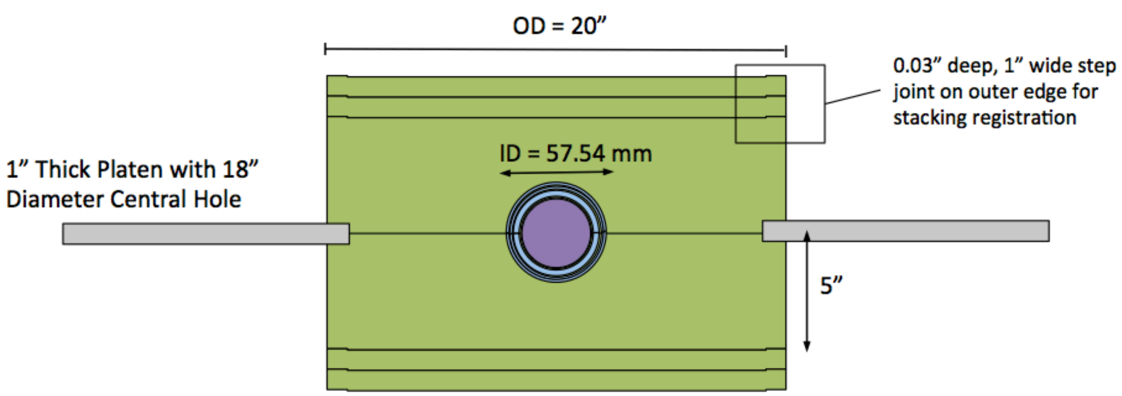

Figure 3.11: Overview of Experimental Configuration Showing BERP Ball and Reflectors. The BERP ball is shown in purple. The nesting hemishell reflectors, which can be either polyethylene or nickel 200 depending on the experiment, are shown in light blue. The nickel 200 plates are shown in green. The upper nickel plates rest on an aluminum diaphragm (shown in gray) with an 18” diameter hole in the center. The bottom plates rest on an existing 1.5” aluminum plate.

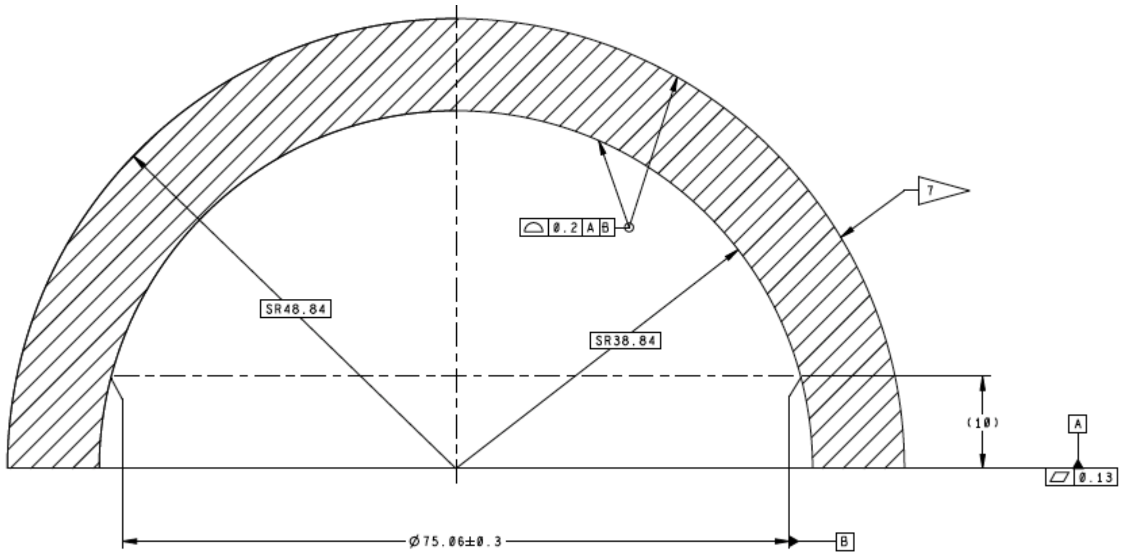

Figure 3.12: Nickel Reflector Shell N1A and N1B for the Composite Reflection Experiments. The inner diameter is meant to mate up with the outer diameter of the BERP Ball. All dimensions in mm.

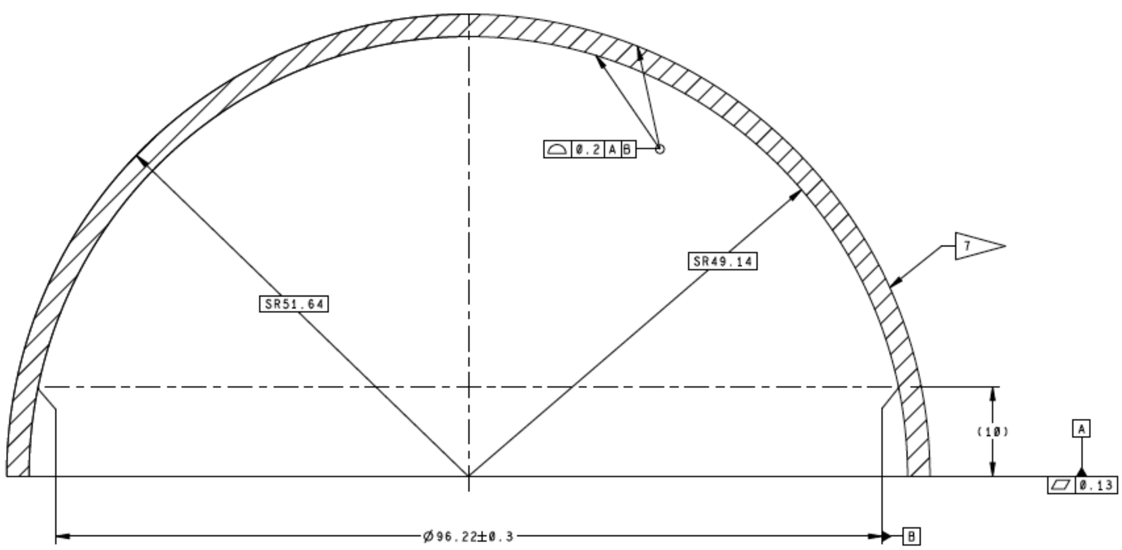

Figure 3.13: Nickel Reflector Shell N2A and N2B for the Composite Reflection Experiments. The inner diameter is meant to mate up with the outer diameter of the N1A/N1B or P1A/P1B. All dimensions in mm.

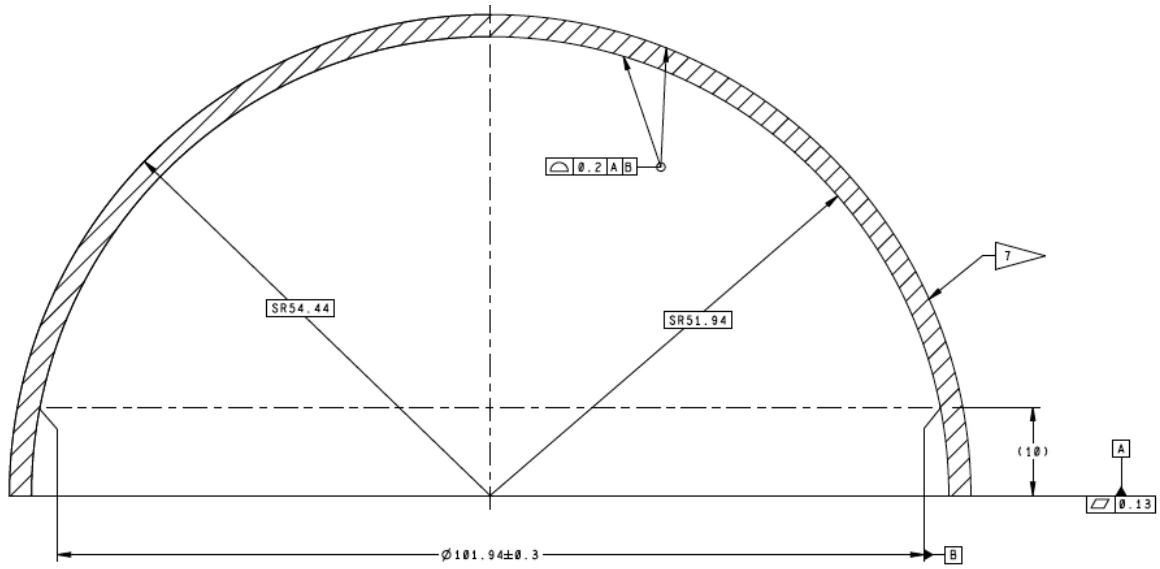

Figure 3.14: Nickel Reflector Shell N3A and N3B for the Composite Reflection Experiments. The inner diameter is meant to mate up with the outer diameter of P2A/P2B or N2A/N2B. All dimensions in mm.

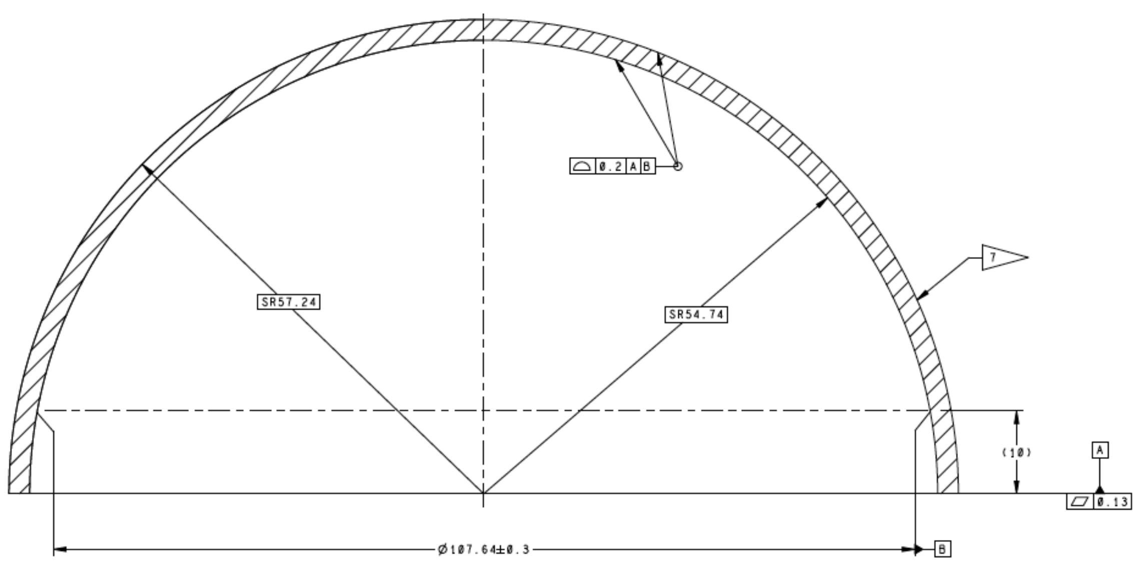

Figure 3.15: Nickel Reflector Shell N4A and N4B for the Composite Reflection Experiments. The inner diameter is meant to mate up with the outer diameter of P3A/P3B or N3A/N3B. All dimensions in mm.

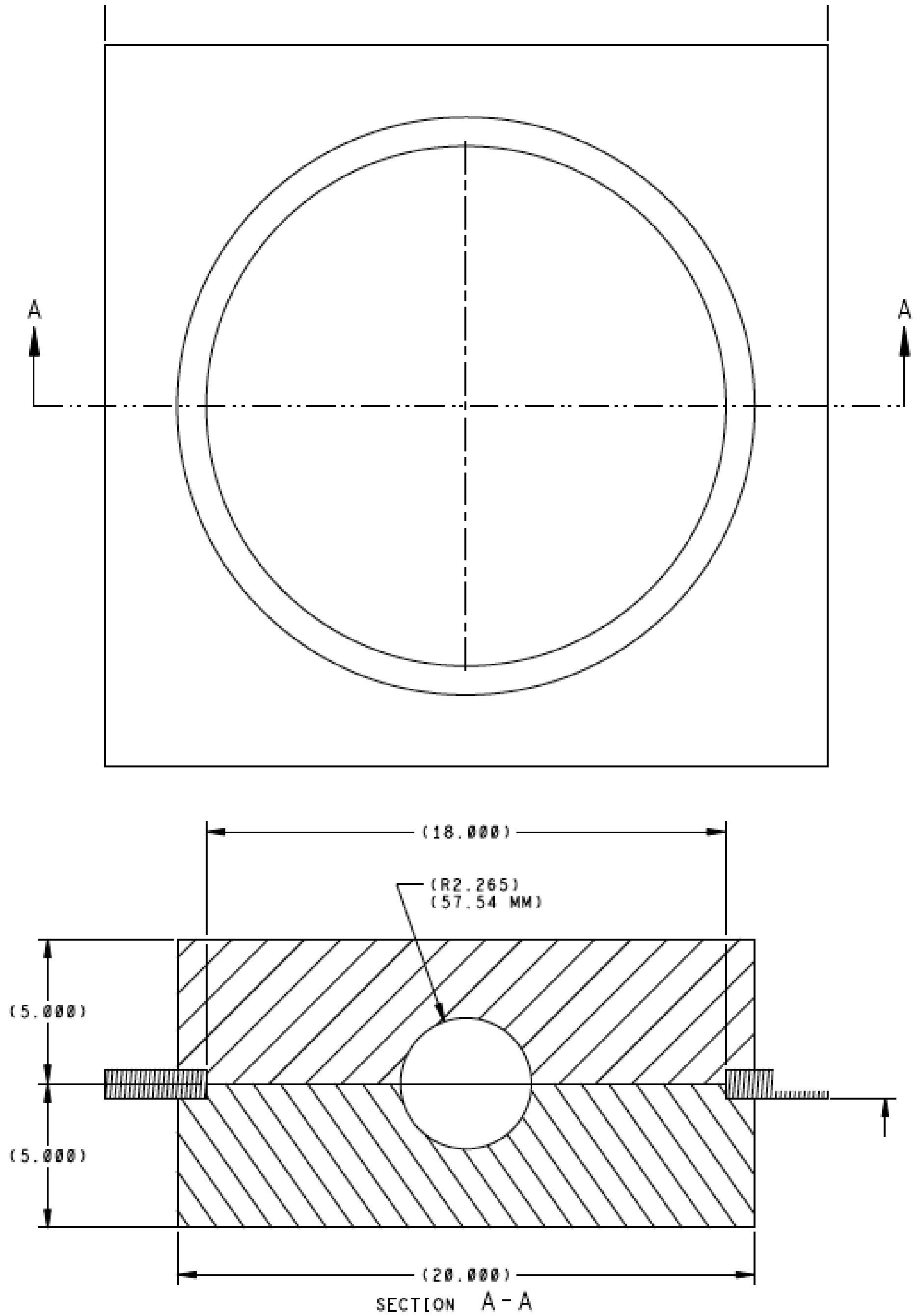

Figure 3.16: Nickel Reflectors Designed To Accommodate the BERP Ball and HDPE Reflector Hemishells. The inner diameter is meant to mate up with the outer diameter of P4A/N4A and P4B/N4B. All dimensions in mm. The reflectors show a 0.030" step joint that will be machined around the outside of the plates to facilitate stacking with other nickel plates.

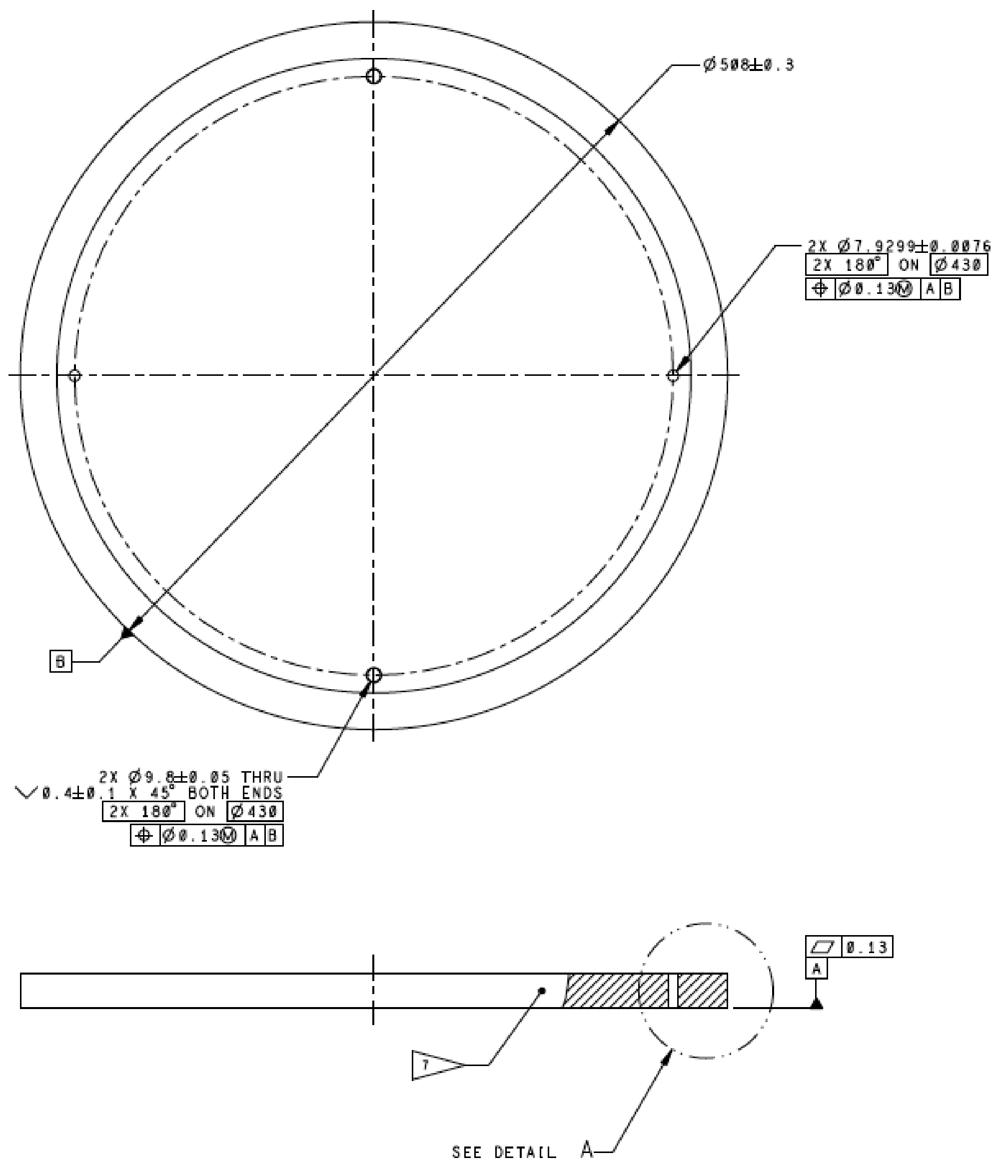

Figure 3.17: Additional Nickel Reflector Plates for Composite Reflector Experiments. These plates are designed to stack with the plates shown in Figure 3.16 to provide additional reflection to the BERP ball. The plates not show a 0.030" step joint that will be machined around the outside of the plates to facilitate stacking.

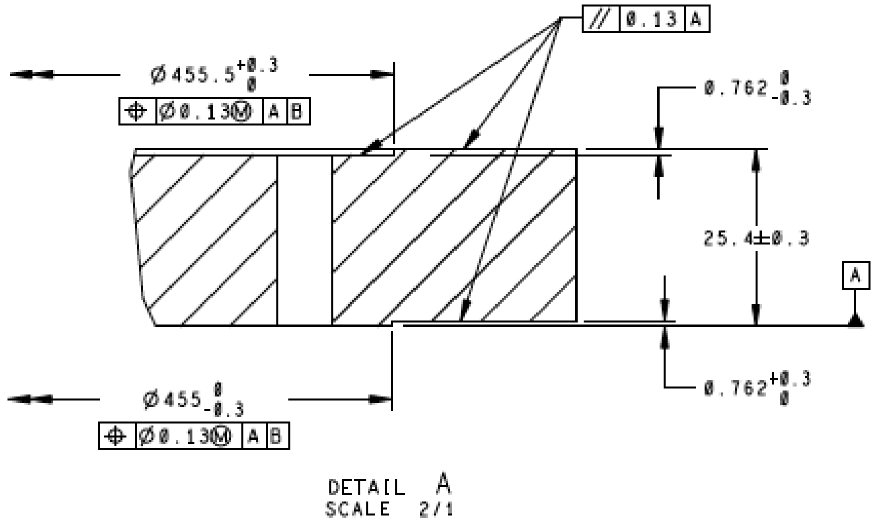

Figure 3.18: Detail of Step Joint on Nickel Reflector Plates for Composite Reflector Experiments. The 5" and 1" thick nickel plates will have a 0.030" step joint that will be machined around the outside of the plates to facilitate stacking, as shown in this detail.

The nickel reflectors have yet to be fabricated. The nominal density of Nickel 200 assumed for final design was 8.9 g/cm^3. Nickel 200 is considered to be commercially pure nickel, with > 99% purity. The density and impurity content of the Nickel 200 will be quantified during fabrication of the nickel parts.

3.5 Description of Experimental Configurations

Four critical configurations have been designed to investigate the composite HDPE/Nickel reflection effect around the BERP Ball. Each configuration differs in the thickness of HDPE reflector used, with Experiment 1 using 1 cm HDPE, Experiment 2 using 1.25 cm HDPE, Experiment 3 using 1.5 cm HDPE, and Experiment 4 using 1.75 cm HDPE. The number of nickel reflector plates was varied to obtain a critical configuration with each HDPE thickness.

Cross section views of the four configurations are shown in Figures 3.18 through 3.21. For all pictures, the BERP ball is shown as purple. Polyethylene is shown as light blue, nickel is shown as green, and the aluminum support structure is shown in gray.

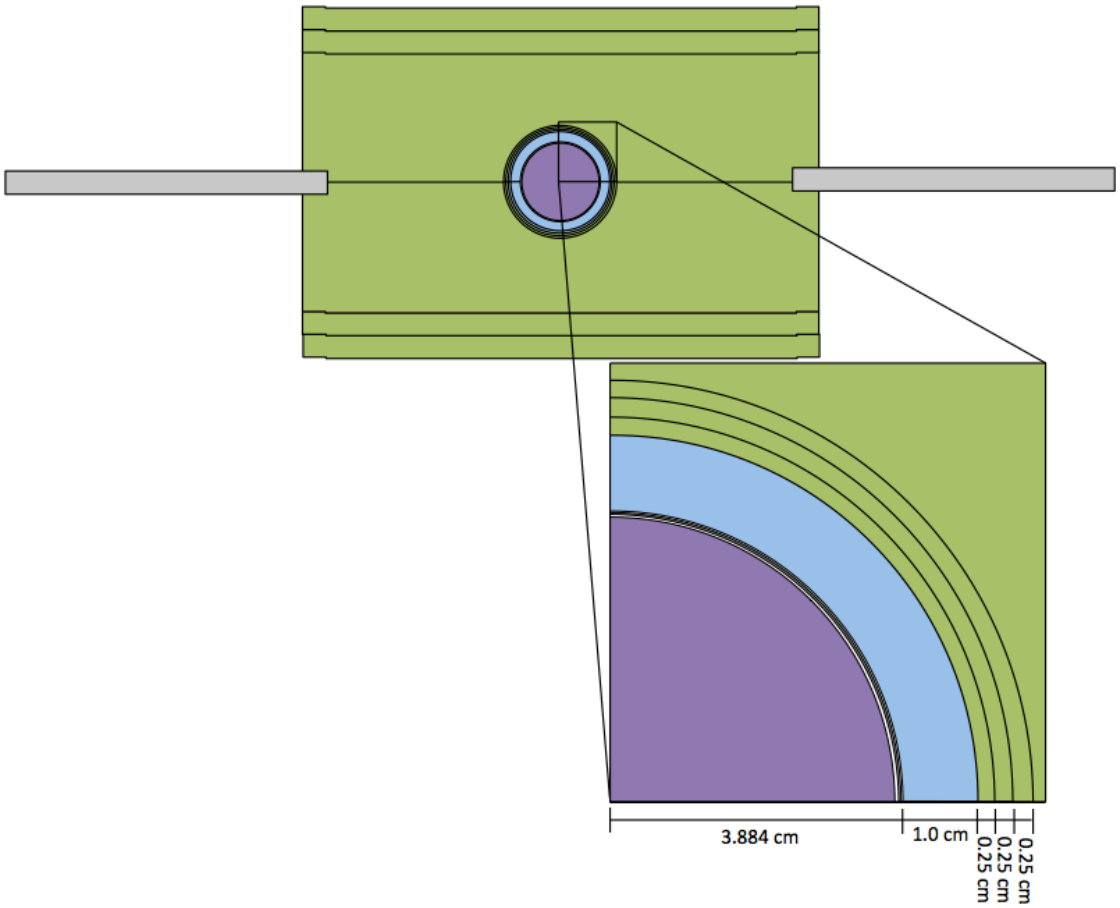

Figure 3.18. Experimental Configuration for Experiment 1: BERP Ball Reflected by 1 cm of Polyethylene Backed by Nickel Reflection. This experiment uses the thinnest polyethylene reflector shell and three 0.25 cm thick nickel shells to fill the inner cavity of the large cylindrical nickel reflectors. To achieve criticality, the two 5” thick cylindrical reflectors are supplemented with four additional 1” nickel reflector discs on top and bottom of the assembly.

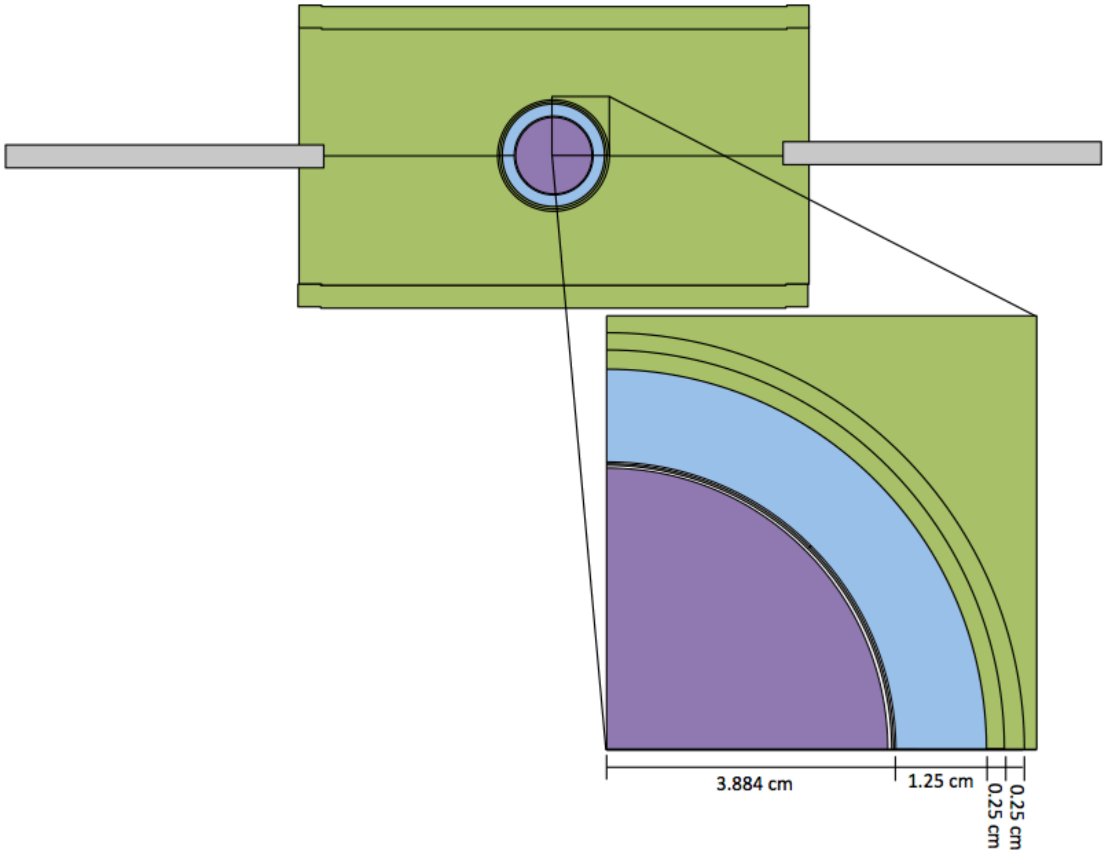

Figure 3.19. Experimental Configuration for Experiment 2: BERP Ball Reflected by 1.25 cm of Polyethylene Backed by Nickel Reflection. This experiment uses the 1.25 cm thick polyethylene reflector shell and two 0.25 cm thick nickel shells to fill the inner cavity of the large cylindrical nickel reflectors. To achieve criticality, the two 5" thick cylindrical reflectors are supplemented with two additional 1" nickel reflector discs on the top and bottom of the assembly.

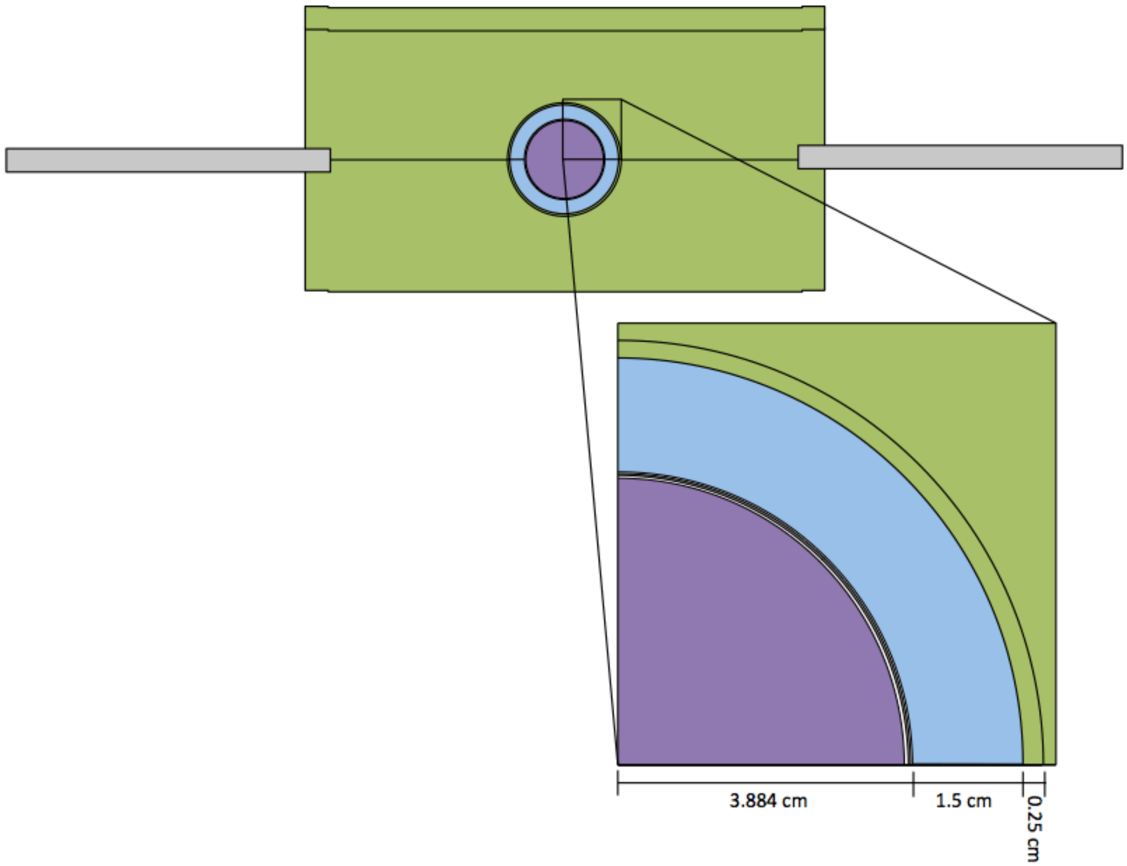

Figure 3.20. Experimental Configuration for Experiment 3: BERP Ball Reflected by 1.5 cm of Polyethylene Backed by Nickel Reflection. This experiment uses the 1.5 cm thick polyethylene reflector shell and one 0.25 cm thick nickel shell to fill the inner cavity of the large cylindrical nickel reflectors. For this case, the polyethylene is closest to optimal thickness requires only one 1” nickel reflector disks beyond the 5” thick cylindrical reflectors are required to achieve criticality.

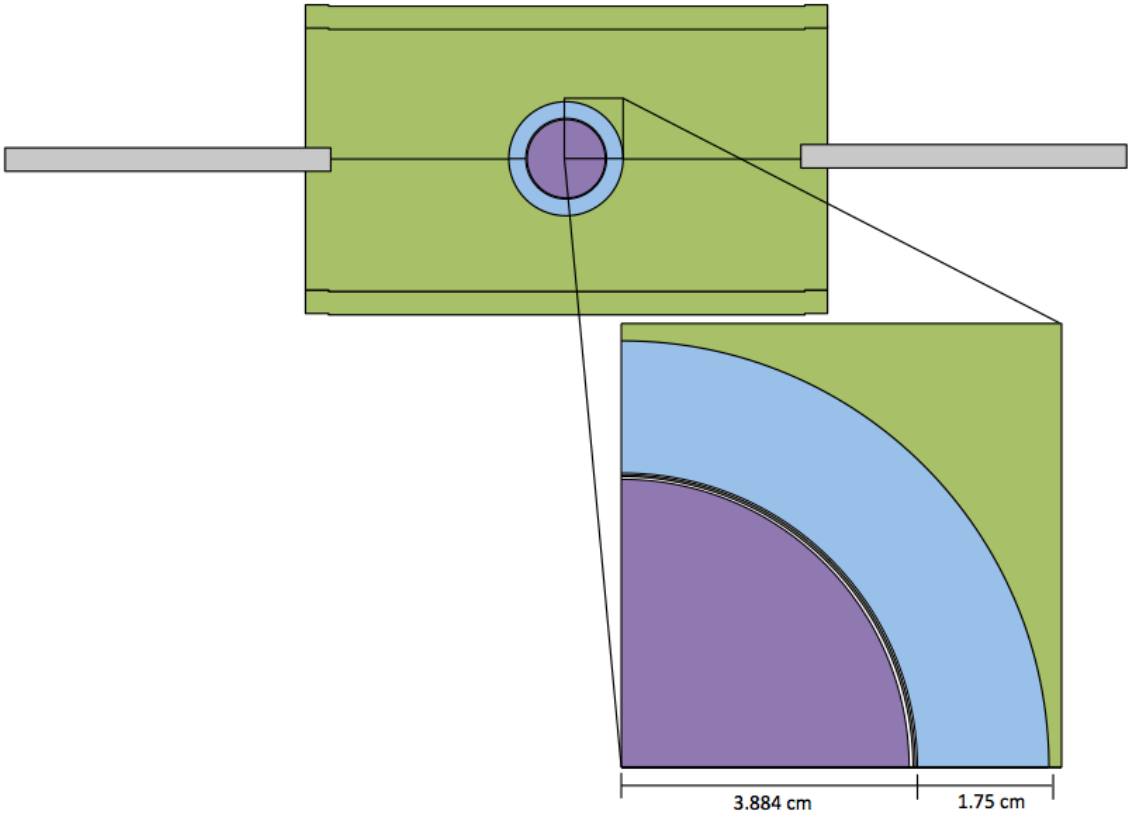

Figure 3.21. Experimental Configuration for Experiment 2: BERP Ball Reflected by 1.25 cm of Polyethylene Backed by Nickel Reflection. This experiment uses the thinnest polyethylene reflector shell and three 0.25 cm thick nickel shells to fill the inner cavity of the large cylindrical nickel reflectors. To achieve criticality, the two 5" thick cylindrical reflectors are supplemented with two additional 1" nickel reflector discs on top and bottom of the assembly.

3.6 Diagnostic Probes and Reaction Rate Foils

This experiment will surround the BERP ball with thin polyethylene reflectors backed by thick nickel reflection. Polyethylene is an insulating material with a relatively low melting/deformation point (approximately 120 C) and a low recommended temperature for long-term service of 80 C. However, the nickel reflector also serves as a large heat sink that will transfer heat away from the warmer center of the assembly. Based on historical data of the BERP ball reflected by various materials, the temperature is expected to remain well under 80 C. The measured temperature of the subcritical BERP ball encased in 3 inches of polyethylene was 55 C and encased in 3 inches of nickel was 33.7 C, as reported in ICSBEP evaluations[5,6].

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[5] Valentine, T. SUB-PU-MET-FAST-001, *Polyethylene-Reflected Plutonium Metal Sphere Subcritical Noise Measurements.* International Handbook of Evaluated Criticality Safety Benchmark Experiments. NEA/NSC/DOC(95)03/I. September 2015 Edition.

The temperature the assembly achieves is an important piece of data for accurate experimental modeling and potential cross section adjustment. A 1/16" diameter cylindrical hole will be machined at the pole of hemispherical reflectors and through the center of the large nickel cylindrical reflectors to allow a thermocouple to be inserted into the assembly to measure the temperature of the outer cladding of the BERP ball.

Consideration was made concerning the inclusion of locations to place reaction rate foils inside the assembly to aid in determination of the neutron spectrum of the experiment. However, since the BERP ball lacks a central cavity, any foils would need to be located outside the core and thus outside the highest neutron fluence zone. Due to concerns about keeping the cladding intact around the BERP ball, the experimenters do not plan on keeping the assembly at or above critical for the length of time required to accumulate sufficient neutron interactions in foils located in the reflector. Thus, reaction rate foils are not included as part of the final design for the experiment.

4.0 Calculational Models of the Experiments

Final design of the IER 203 experiments required calculations to address criticality and weight stress analysis for the aluminum diaphragm. A discussion of the methodologies used for these calculations and their results is provided in the following sections.

4.1 Criticality and Spectrum Calculations

4.1.1 Methodology and Code Used

The Monte Carlo neutron transport code, MCNP5, version 1.60, developed at Los Alamos National Laboratory, was used to calculate critical configurations and the corresponding neutron fission spectrum for the TEX configurations with ZPPR plates. Continuous energy ENDF/B-VII.1 cross sections (.80c) were used in all MCNP5 calculations, save for a few minor constituents where ENDF/B-VII cross sections were unavailable. All materials were modeled using room temperature (293 K) cross sections. The non-default parameters used for the MCNP5 runs are listed in Table 4-1.

Table 4-1: Parameters Used in MCNP5 v 1.60 Calculations

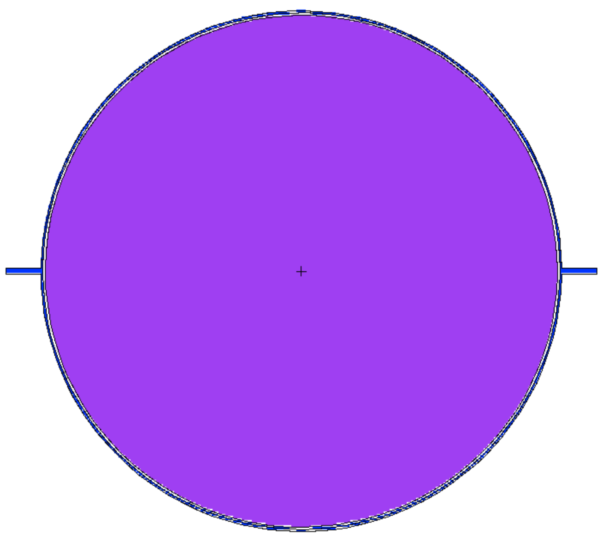
Parameter	Description	Value
gen	Number of generations run	500
npg	Number of neutrons started per generation	10^4
nsk	Number of generations skipped (not included in k_{eff} calculation)	50

4.1.2 MCNP5 Model of BERP Ball

[6] Richard, B. and J. Hutchinson. FUND-NCERC-PU-HE3-MULT-001, *Nickel-Reflected Plutonium Metal Sphere Subcritical Measurements.* International Handbook of Evaluated Criticality Safety Benchmark Experiments. NEA/NSC/DOC(95)03/I. September 2015 Edition.

A computational model of the BERP Ball was developed for MCNP based on the historical information described in Section 3.0, as reported in FUND-NCERC-PU-HE3-MULT-001.

The BERP ball is comprised of two materials: alpha phase plutonium metal and a SS-304 stainless steel cladding with a ring around the waist. Figure 4.1 shows a 2D representation of the 3D MCNP model of the BERP Ball and presents a chart showing the pertinent dimensions. The material densities as reported in FUND-NCERC-PU-HE3-MULT-001 were used for the model: 19.604 g/cm^3 for the alpha phase plutonium and 8.87 g/cm^3 for the SS-304.



Description	Dimension (cm)
Pu Radius	3.7938
SS Clad Inner Radius	3.82778
SS Clad Outer Radius	3.85826
Ring Outer Radius	4.37642
Ring Thickness	0.09144

Figure 4.1: MCNP5 Model of the BERP Ball with Cladding. Plutonium is shown in purple and cladding is shown in blue.

As reported in FUND-NCERC-PU-HE3-MULT-001, nearly 0.35 wt.% of the plutonium is unknown because it was not identified during chemical analysis. Based on the judgment of experts in analytical chemistry, the remainder would likely consist of tantalum and tungsten. Therefore, this unknown mass was defined in the BERP Ball benchmark model as a mixture composed of half tantalum/half tungsten by weight proportion. Additionally, the initial composition of the plutonium alloy has been aged over a period of 32 years using CINDER. Table 4-2 reports the composition of the plutonium used in the BERP Ball model.

Table 4-2: BERP Ball Isotopics Used in MCNP Model

Element/ Isotope	Atom density (atoms/(b-cm))	Element/ Isotope	Atom density (atoms/(b-cm))	Element/ Isotope	Atom density (atoms/(b-cm))
Be	6.550E-07	Zn	4.512E-07	^{234}U	2.204E-06

B	5.460E-07	Ga	5.672E-05	^{235}U	4.233E-05
C	2.261E-04	Zr	6.471E-06	^{236}U	9.819E-06
Na	1.284E-05	Mo	1.108E-06	^{238}U	8.067E-10
Mg	2.428E-07	Ag	5.474E-08	^{237}Np	4.593E-06
Al	1.094E-06	Cd	5.251E-07	^{238}Pu	7.665E-06
Si	1.051E-06	Sn	2.486E-07	^{239}Pu	4.603E-02
Ca	8.837E-07	Ta	1.160E-04	^{240}Pu	2.902E-03
Cr	5.676E-07	W	1.142E-04	^{241}Pu	2.792E-05
Fe	2.114E-06	Pb	1.424E-07	^{242}Pu	1.359E-05
Ni	5.029E-07	Bi	2.825E-08	^{241}Am	1.256E-04
Cu	9.289E-08	^{230}Th	1.036E-10		

As described in FUND-NCERC-PU-HE3-MULT-001, the composition of the SS-304 stainless steel cladding around the BERP ball has not been measured. Therefore, a standard composition from The Metals Handbook Desk Edition[7] was used for the MCNP5 model. The composition is given in Table 4-3.

Table 4-3: BERP Ball Isotopics Used in MCNP Model

Element	Atom density (atoms/(b-cm))
C	2.362E-04
Si	1.271E-03
P	5.184E-05
S	3.338E-05
Cr	1.956E-02
Mn	1.299E-03
Fe	6.674E-02
Ni	8.434E-03

4.1.3 Aluminum Support Structure

Based on the drawing presented as Figure 3.2, the aluminum upper support platen was modeled in MCNP as shown in Figure 4.2. The outer dimensions are 45" by 45" (114.3 cm by 114.3 cm) and the outer plate thickness is 1" (2.54 cm). An 18" (48.26 cm) diameter circular hole is located in the center of the platen. The entire platen, including the diaphragm, was modeled as Al-6061. The 1" (2.54 cm) aluminum platform that supports the lower, movable half of the experiment was modeled as shown in Figure 4.3. The platform was modeled as Al-6061.

[7] J. R. Davis, ed., *The Metals Handbook Desk Edition* , 2nd Edition (American Society for Metals, Materials Park, Ohio, 1998).

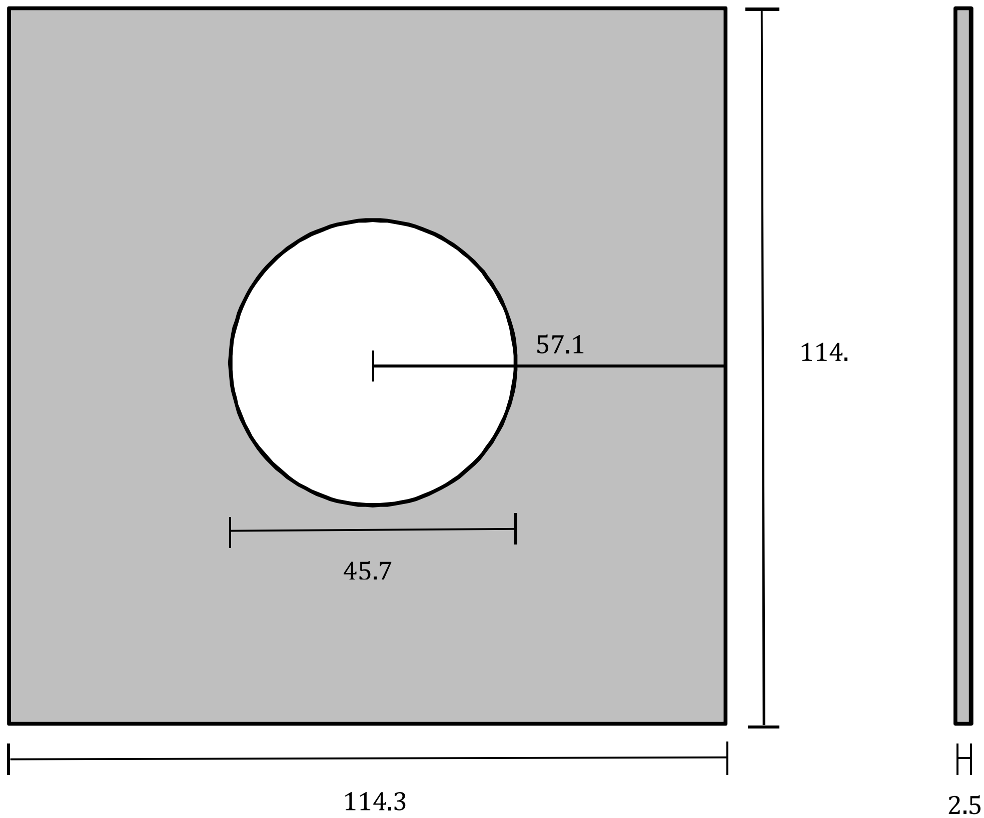


Figure 4.2. Upper Support Platen for BERP Composite Experiments as Modeled in MCNP

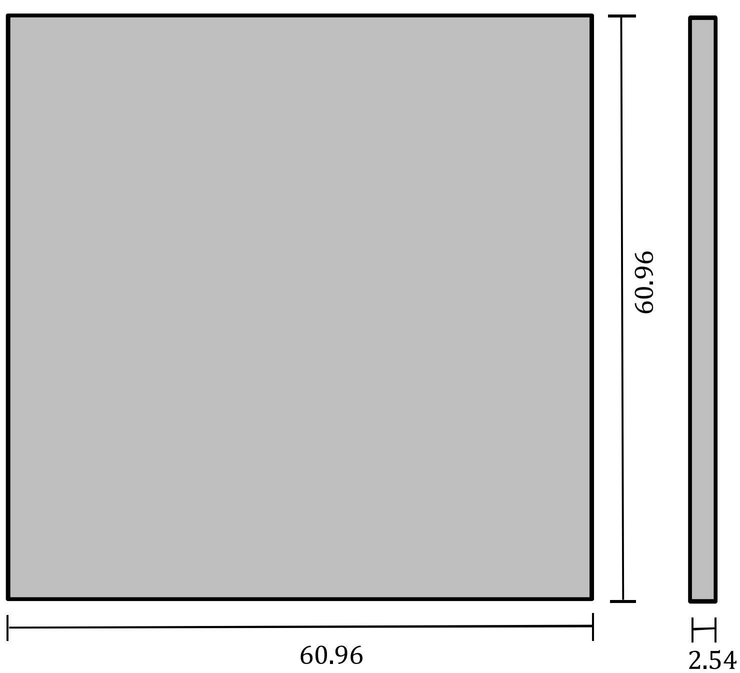


Figure 4.3. Lower Support Platform for BERP Composite Experiments as Modeled in MCNP.

4.1.4 MCNP5 Model of Experimental Configurations

Using the MCNP5 model of the BERP Ball described in Section 4.1.2, four experimental composite polyethylene/nickel reflected configurations were modeled using one of four thicknesses of polyethylene inner shells: 1 cm, 1.25 cm, 1.5 cm, or 1.75 cm. Figure 4.4 shows an MCNP5 screen capture illustrating the model geometry for the cases with 1.0 cm of polyethylene. As shown in the figure, the BERP ball (purple) is surrounded by the 1.0 cm thick polyethylene shells (light blue), followed by three sets of 0.25 cm nickel shells (green). The outermost nickel shell mates up with the cavity in the two large 5" (12.7 cm) nickel reflector cylinders (also in green). If additional nickel reflection is needed, 1" (2.54 cm) plates of nickel can be stacked on top and bottom of the 5" cylinders. Figure 4.4 shows two 1" plates on top and two 1" plates on bottom of the assembly. The total height of the reflector, H, for this assembly would be obtained by adding two 5" cylindrical reflectors plus 4 1" plate reflectors, for a total of 14" (35.56 cm) of reflection.

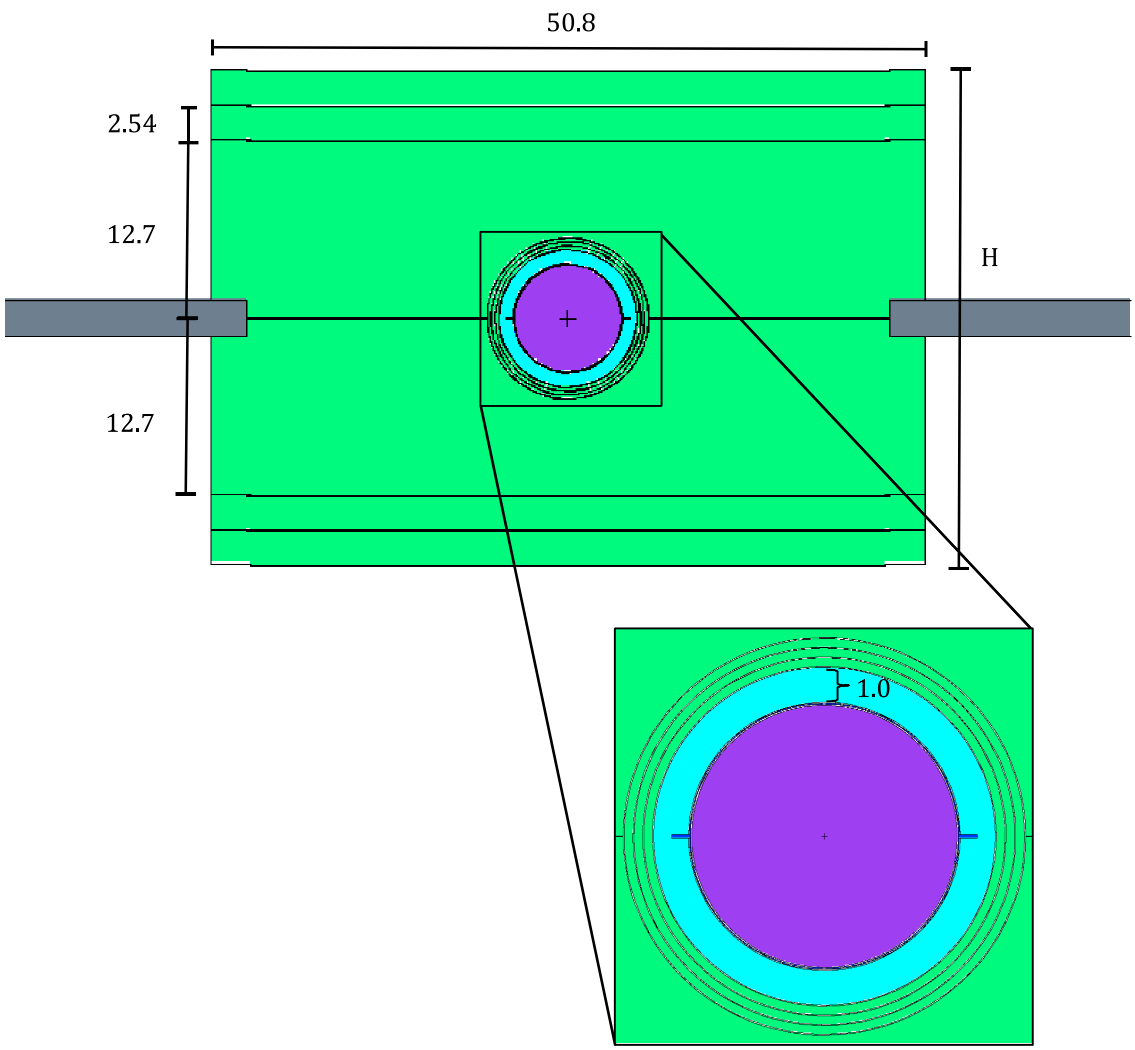


Figure 4.4: MCNP5 Model of Experiment 1, the BERP Ball reflected by 1 cm of Close-Fitting Polyethylene Reflection backed by Nickel. This picture is a screen capture from the interactive plotter function in MCNP5. The plutonium shown in purple, the stainless steel cladding is shown in blue, the polyethylene is shown in light blue, and the nickel is shown in green. The aluminum support structure is shown in gray. In the top figure, the picture was cut off and does not show the full width of the upper aluminum platen (gray) in the interest of showing more detail in the assembly region. Dimensions are given in centimeters.

The model geometry for the other three cases is similar, although the thickness of the polyethylene shell in the center changes, as illustrated in Figure 4.5. The 0.25" thick nickel shells are removed as the polyethylene thickness increases.

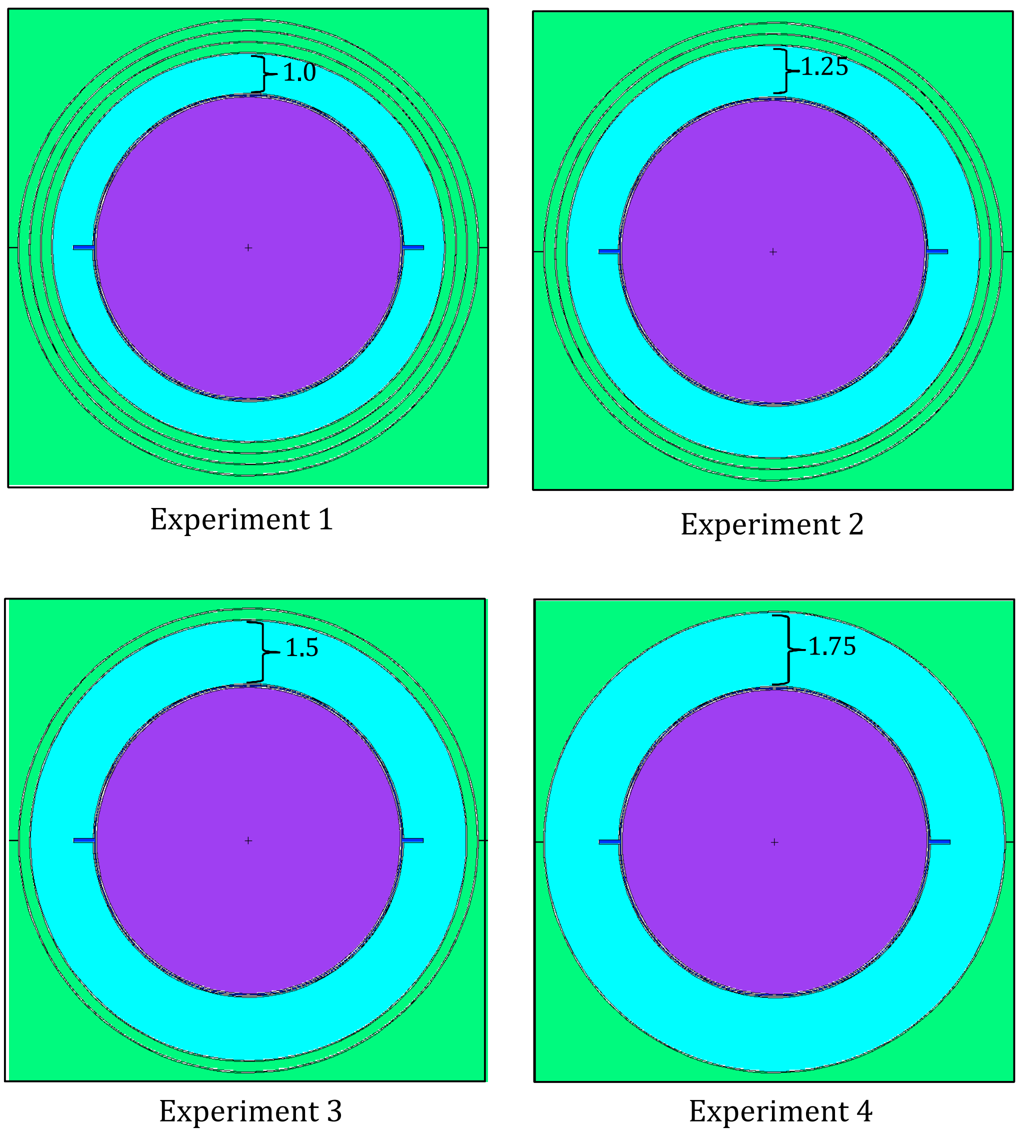


Figure 4.5: Close-Up of the MCNP5 Models of Experiments 1-4, Showing the Inner Polyethylene Reflector Configurations for Each Experiment. This picture is a screen capture from the interactive plotter function in MCNP5. The plutonium shown in purple, the stainless steel cladding is shown in blue,

the polyethylene is shown in light blue, and the nickel is shown in green. Dimensions are given in centimeters.

Gaps were modeled between individual components of the assembly to take into account real world tolerances and the fact that the nickel reflector cylinders and discs will not be completely flat. Figure 4.6 highlights the gaps modeled in the MCNP5 geometry for the central nesting shells of the reflector. For the Nickel plates, gaps between the plates were modeled as 0.005 cm.

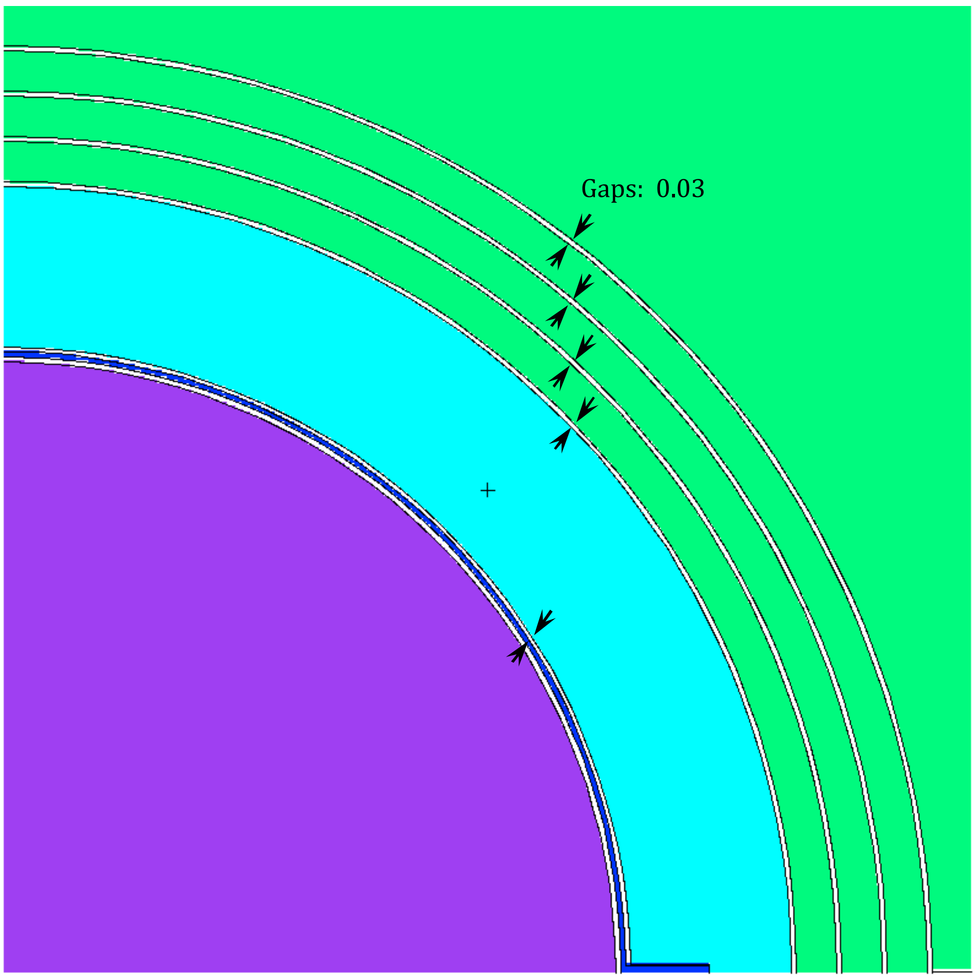


Figure 4.6: Close-Up of the Gaps Modeled Between the Nesting Shells Around the BERP Ball in the MCNP5 Model. The arrows point to the gap locations and dimensions are in cm.

4.1.5 MCNP5 Calculation Results

Iterative MCNP calculations were performed to determine critical configurations for the four polyethylene reflector thicknesses. The total reflector height, H (described in Figure 4.4), was varied to determine critical configurations. Figure 4.7 displays the results of the iterative calculations, presenting k_{eff} as a function of total reflector height. The first points on the graph, at a nickel reflector height of 25.4 cm, correspond to the BERP ball and shell reflectors reflected by the two 5" (12.7 cm) cylindrical nickel reflectors, for a total reflector height of 10" (25.4 cm). Nickel height is increased in the model by adding additional 1" nickel plate reflectors, alternating adding to the top and bottom of the stack, as shown in Figure 4.8.

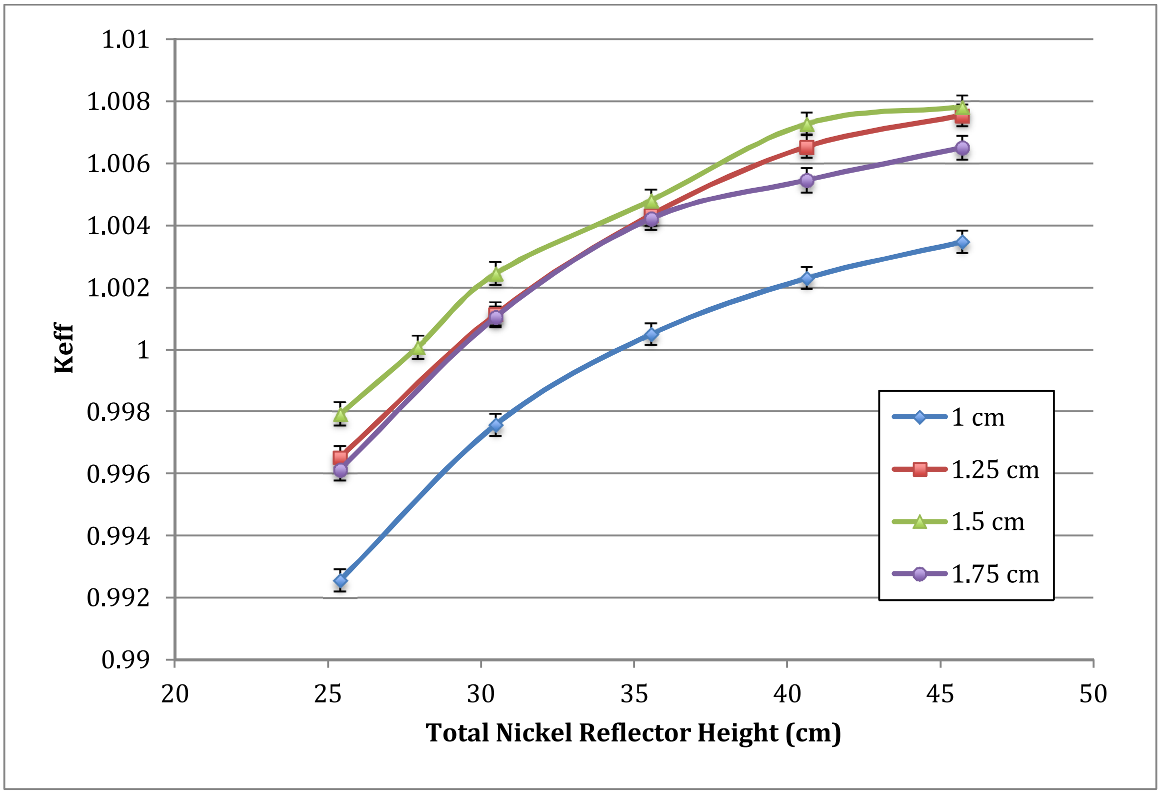


Figure 4.7: Keff as a Function of Nickel Reflector Height for Four Thicknesses of Inner Polyethylene Radial Reflector.

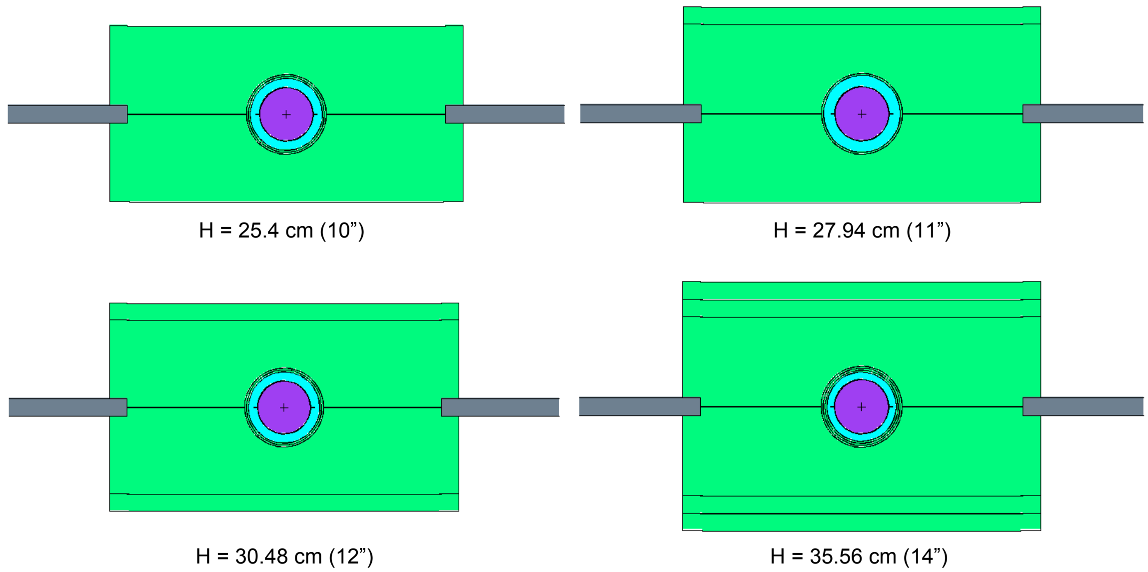


Figure 4.8: Illustration of the Nickel Reflector Configurations and their corresponding Heights (H).

As shown in Figure 4.7, the optimal polyethylene thickness for this configuration is 1.5 cm (green line), as those cases resulted in the highest k_{eff}s at each nickel reflector height. One cm of polyethylene was the least effective thickness of the four thicknesses studied. It does appear that critical configurations (k_{eff} equal to 1) are possible with each of the four polyethylene thicknesses. Details about critical configurations for each polyethylene thickness are given in Table 4-4, below.

Table 4-5: Critical Dimensions for Experiments 1-4, Including K_{eff}

Experiment Number	Thickness of PE Shell (cm)	Critical Ni Reflector Height, H (cm)	Number of 1" Ni Plates	Approximate Total Ni Weight (kg)	$k_{eff} \pm \sigma$
1	1	35.56	4	636.73	1.00050 ± 0.00034
2	1.25	30.48	2	544.39	1.00114 ± 0.00037
3	1.5	27.94	1	497.78	1.00008 ± 0.00037
4	1.75	30.48	2	542.72	1.00105 ± 0.00033

In addition to the 1" thick nickel plate used for reactivity adjustment by reflections, two 1/2" thick nickel plates will also be fabricated to allow for finer reactivity adjustment, if required.

4.2 Uncertainty and Bias Characterization

This section contains results of sensitivity calculations performed to determine the effects of various uncertainties in the reported data on the value of k_{eff}. MCNP5 with continuous-energy cross sections was used. All of the MCNP calculations used continuous-energy cross sections, employing 6,250 generations of neutrons with 200,000 histories per generation. The first 100 generations were excluded from the statistics for each case, producing 1.23 billion active histories in each calculation. The standard deviation in the calculated k_{eff} for the individual MCNP calculation was 0.00002. When the calculated effect is less than 0.00001 in Δk_{eff}, the case is considered to be insignificant.

4.2.1 Mass Uncertainties

A description of how the models were varied to determine mass uncertainties is provided in the following sections. The effects of uncertainties in the material mass are summarized in
Table 4-3.

4.2.1.1 BERP Ball Mass

The BERP ball mass used in the benchmark-model is 4483.884 g. The BERP ball mass uncertainty[8] is 0.058 g. The BERP ball mass was increased by 0.058 g, and the effect in Δk_{eff} was less than 0.0001 in Δk_{eff}, which is considered to be insignificant.

4.2.1.2 Stainless Steel Cladding Mass

In the benchmark model, the mass of the cladding used is 43.8 g. The standard uncertainty of the cladding mass[1] is 0.115 g. To observe the change in Δk_{eff}, the mass was increased by 0.115 g, and calculated effect was 0.00003 in Δk_{eff}, which is considered to be insignificant.

4.2.1.3 Nickel Plate Mass

The density of nickel plates used in the benchmark model is 8.9 g/cm^3. Densities of the nickel plates to be used in the experiments are not yet known. The density of these nickel plates was increased by 0.1 g/cm^3, and the effect in Δk_{eff} was 0.00142.

4.2.1.4 Polyethylene Shell Mass

The density of a polyethylene shell surrounding the BERP Ball used in the benchmark model is 0.967 g/cm^3. The density of HDPE was decreased by 0.017g/cm^3, and the change in Δk_{eff} was
-0.00134.

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[8] Richard, B., et. al., "Nickel-Reflected Plutonium-Metal-Sphere Subcritical Measurements," FUND-NCERC-PU- HE3-MULT-001, NEA/NSC/DOC (95)03, OECD, September 2014 Edition.

4.2.2 Dimensional Uncertainties

A description of how the models were varied to determine dimensional uncertainties is provided in the following sections. To see the geometry effect only, the component masses were maintained. The effects of uncertainties in the dimensions are summarized in Table 4-4.

4.2.2.1 BERP Ball Radius

The radius of the BERP ball used in the model is 1.4936". A tolerance of ± 0.001732"[9] was used to increase and decrease the radius. The maximum change in k_{eff} due to this variation is 0.00103. The distribution is equally probable everywhere within the interval, and the resulting uncertainty is ($\Delta k_{eff}/\sqrt{3}$) is ± 0.0006.

4.2.2.2 SS-304 Cladding Thickness

The thickness of the SS 304 cladding used in the benchmark model is 0.012". A tolerance[2] for the thickness is ±0.00082". The effect of the tolerance was calculated and the change was ±0.00004 Δk_{eff}, which is judged to be insignificant.

4.2.2.3 Polyethylene Thickness

The thickness of the SS 304 cladding used in the benchmark model is 1.56 cm. A tolerance for the thickness is assumed to be 0.005 cm. The effect of the tolerance was calculated and the change was -0.00008 Δk_{eff}, which is judged to be insignificant.

4.2.2.4 Inner Nickel Reflector Radius

The thickness of the inner nickel reflector is 0.25 cm. A tolerance for the radius is assumed to be 0.005 cm. The effect of the tolerance was calculated and the change was 0.00003 Δk_{eff}, which is judged to be insignificant.

4.2.2.5 Gap between Ni Reflectors

In the benchmark model, the gap between the two nickel reflectors surrounding the BERP ball were model as 0.02 cm void. Sensitivity calculation was performed assuming an increased gap thickness of 0.02 cm plus 0.127 cm (0.05") between reflectors. The gap effect was calculated and the effect was -0.00089 in Δk_{eff}.

4.2.3 Determination of Bias

Several calculations were completed to quantify the bias inherent in the models due to the exclusion of some model parameters. A summary of the sources of bias and their values is given in Table 4-4.

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[9] Richard, B., et. al., "Nickel-Reflected Plutonium-Metal-Sphere Subcritical Measurements," FUND-NCERC-PU- HE3-MULT-001, NEA/NSC/DOC (95)03, OECD, September 2014 Edition.

4.2.3.1 Positioning of the BERP Ball

There is a small gap, 0.03398 cm, between the BERP Ball and the SS304 cladding. In the benchmark model, this void region was modeled outside the surface of the BERP Ball. The BERP Ball will touch the bottom of the cladding when placed at the center of the assembly. To calculate the effect, the BERP Ball was moved down by 0.03398 cm in the model. Calculated effect was 0.00004 in Δk_{eff}, which is insignificant.

4.2.3.2 Impurities in Fuel

The impurities in the BERP Ball[10] is shown in Table 4-5. To observe the effect of the impurities, two MCNP calculations with and without the impurities were performed, and the change in Δkeff was calculated. The effect was -0.00027 in Δk_{eff}.

Table 4-5 Impurities in the α-phase Plutonium Sphere.

Element	PPM
Fe	10
Ga	335
Be	<1
Al	<5
Ni	<5
Mo	9
Pb	<5
B	<1
Si	<5
Cu	<1
Ag	<1
Bi	<1
Na	<50
Ca	3
Zn	<5
Cd	<10

[10] Richard, B., et. al., "Nickel-Reflected Plutonium-Metal-Sphere Subcritical Measurements," FUND-NCERC-PU- HE3-MULT-001, NEA/NSC/DOC (95)03, OECD, September 2014 Edition.

Mg	<1
Cr	<5
Zr	<100
Sn	<5
C	230
Unknown	3500[(a)]

(a) This value was derived from 100 wt.% minus the sum of the measured plutonium, americium, and impurity concentrations.

4.2.3.3 Impurities in Ni

The benchmark model used 99 wt% nickel plus 1 wt% of impurities (Nickel 200[11]) shown in Table 4-5. Reactivity effect of varying combination of nickel with impurities was calculated, and the maximum effect was 0.00063 in Δk_{eff}.

Table 4-5 Nickel 200 Composition.

Element	Weight percent
Ni	99
Fe	≤ 0.4
Si	≤0.35
Mn	≤0.35
C	≤0.15
Cu	≤0.25
S	≤0.01

4.2.3.4 Temperature

Temperature distribution of the BERP Ball during experiments is not known yet. The cross section data libraries used for the benchmark model are based on ENDF/B.VII.1 at a temperature of 293 K. Anticipated fuel temperature is 353 K. Available neutron cross section data based on 600 K were applied and adjusted for the temperature change of 60 degrees. The effect was -0.00021 in Δk_{eff}.

4.2.3.5 Room Return

Critical experiments are planned to be performed in the Planet experimental room at NCERC. The BERP Ball assembly is quite a distance away from any surrounding walls.

[11] Corrosion materials, http://www.corrosionmaterials.com/documents/dataSheet/nickel200And201DataSheet.pdf

The closest wall to the assembly is about 9' away. A detailed model of the experimental room was completed for a separate study[12] and is fully described in that report. The BERP assembly was modeled as offset in the experimental room and the calculated effect of the room return was 0.00073 in Δk_{eff}.

[12] Kim, S.S. *12-Rad Zone Anylsis for CAAS Placement at the Device Assembly Facility*. Lawrence Livermore National Laboratory. CSM 1531. September 30, 2008.

Table 4-6. Summary of Uncertainties for BERP Ball Assembly Calculations.

Source of Uncertainty	Parameter Value used	Parameter Variation in Calculation	Calculated Effect (Δk_{eff})	Standard Uncertainty of Parameter	Standard Uncertainty in Δk_{eff}
Material Mass					
BERP Ball	4483.884 g	0.058 g	<0.00002	0.058	Negligible
Stainless Steel Cladding	43.8 g	0.115 g	0.00003	0.115	Negligible
Ni Reflector	8.9 g/cm^3	0.1 g/cm^3	0.00142	0.1	0.00142
Polyethylene Shell	0.967 g/cm^3	-0.017 g/cm^3	-0.00134	-0.017	-0.00134
Geometry Dimensions					
BERP Ball Radius	1.4936”	± 0.001732”	±0.0006	±0.001732	±0.0006
SS-304 Cladding Thickness	0.012” thick	± 0.0008”	±0.00004	±0.0008”	Negligible
Polyethylene Thickness	1.56 cm	0.005 cm	0.00036	0.005	0.00036
Inner Ni Reflector Radius	0.25 cm	0.005 cm	0.00003	0.005	Negligible
Gaps between Ni Reflectors	0.02 cm	0.127 cm	-0.00089	0.127	-0.00089
Total Uncertainty	Quadrature Sum: 0.00226				

Table 4-7. Summary of Bias for BERP Ball Assembly Calculations.

Source of Bias	**Parameter Value used**	**Parameter variation in Calculation**	**Calculated Effect (Δk_{eff})**	**Standard Uncertainty of Parameter**	**Standard Bias in Δk_{eff}**
BERP Ball Positioning	No Cladding Touch	With Cladding Touch	0.00004	With Cladding Touch	Negligible
Fuel Impurities	No Impurities	With Impurities	-0.00027	With Impurities	-0.00027
Ni impurities	No Impurities	With Impurities	0.0006	With Impurities	0.0006
Temperature	293 K	60 degrees	-0.00021	60 degrees	-0.00021
Room Return	No Room	With Room	0.00073	With Room	0.00073
Total Uncertainty	Quadrature Sum: 0.00081				

4.2.4 Summary of Uncertainty and Bias Calculations

As shown in Table 4-6, the largest contributor to uncertainty is the uncertainty in the polyethylene and nickel reflector mass and dimensions. As the reflectors have yet to be fabricated, these perturbations were educated guesses and thus can be lessened through procurement specifications and piece-by-piece measurements. A concerted effort can also be made to lessen and quantify any gaps between plates in the assembly, which also have a relatively large effect on k_{eff}.

Fuel and nickel impurities, temperature, and room return were shown introduce a slight bias to the calculations. Temperature will be quantified during the experiment and nickel impurities will be determined before the experiment.

5.0 Cost Estimates for Fabrication

The highest-cost components of the described BERP Composite experiments with polyethylene and nickel are the fissile material (BERP Ball) and the nickel reflector. The BERP Ball is an existing NCSP asset that has been used in many critical experiments.

The parts to be fabricated are two 5" nickel reflector blocks, 6 1" nickel reflector plates, four sets of nickel nesting shells, and four sets of polyethylene nesting shells. In addition, an aluminum upper platen for use with the Planet critical assembly machine will need to be fabricated. Table 5-1 lists estimated material and fabrication costs associated with these parts.

Table 5-1: Estimated Costs for Fabricated Parts

Polyethylene Shells: P1A, P1B, P2A, P2B, P3A, P3B, P4A, P4B	
8 Polyethylene Blocks	$1000.00
Fabrication Costs	$2000.00
Nickel Shells: N1A, N1B, N2A, N2B, N3A, N3B, N4A, N4B	
Material and Fabrication Cost for 8 shells	$32,000
Nickel 5" Cylindrical Reflectors, 20" OD	
Material and Fabrication Cost for 2 parts	$45,000
Nickel 1" Plate Reflectors, 20" OD	
Material and Fabrication Cost for 6 parts	$15,000
Nickel 1/2" Plate Reflectors, 20" OD	
Material and Fabrication Cost for 2 parts	$4,000
Platen, 1" Aluminum Platen with 18" OD Hole	
45"x45"x1" Al-6061	$2000.00
Fabrication Costs	$1500.00
Total Costs for Materials	$102,500.00

LLNL recommends inspections of the parts once fabricated and constituent and impurity analysis (likely through mass spectroscopy) in order to reduce benchmark uncertainties. LLNL has conservatively estimated those costs to be $5,000, based on current costs and estimates of laboratory time.

A detailed inspection of all items (or at least a representative sample) is also recommended, including dimensional measurements and contour measurements, particularly of the fissile parts. LLNL estimates these costs to be $5000 for the non-fissile parts.

6.0 Conclusions and Recommended Schedule for CED-3

The following sections describe considerations for scheduling activities associated with CED-3A (Project Introduction) and CED-3B (Experiment Execution).

6.1 Scheduling Considerations

6.1.1 Fabrication of Reflectors and Fixturing

As described in Section 5.0, reflectors and aluminum fixturing for Comet will need to be fabricated. LLNL estimates that these items could be fabricated in Q3-Q4 of FY16.

6.2 CED-3 Schedule

FY 2016- Quarter 4 and FY 2017 Quarter 1

- **Project Introduction.** LLNL will work with NSTec and LANL personnel to prepare all facility documentation and reactor safety and experimental plans.
- **Procurements and Fabrication.** LLNL will procure materials and fabricate the associated experimental parts as detailed in Section 5.0.

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- **Experiment Execution.** Once the reflector parts are fabricated and the project paperwork is complete, the experiments can be executed at NCERC. LLNL will work with NCERC personnel to schedule and conduct these four experiments.

6.3 CED-4 Schedule

- **Laboratory Reports.** A laboratory report summarizing each critical configuration will be completed one month after the completion of each experiment. These laboratory reports will record the experimental details needed for the ICSBEP benchmark.
- **ICSBEP Evaluations.** ICSBEP evaluations for all four experiments will be completed in FY18, Q1 for review by the ICSBEP review group in May of 2018.