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Revision 0

UO_2 HALEU Transportation Package Evaluation and Recommendations

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SUMMARY

This M3FT-19IN030205042 milestone report presents the current status on investigations related to the development of HALEU transportation capabilities in the U.S. The report initially reviews potential short-term HALEU production options and describes an expected HALEU composition. It then discusses the regulatory bases for HALEU transportation and identifies two compliant packaging designs: (1) the TN Americas TN-LC and (2) the NAC International OPTIMUS™-L. To modify these designs for HALEU transportation, an inner canister concept, and modular metal and foam basket concepts were developed, and this is described in the report. The expected activity, criticality tendency, radiation level, and decay heat of the package content are evaluated considering the specific system characteristics.

Based on the results of the investigations, the research team consisting of INL, PNNL, and ORNL staff concluded that, given the anticipated source material composition, the OPTIMUS™-L, or a comparable design, is the preferred candidate. This is due to its larger HALEU payload per LWT, lighter weight, and simpler handling procedures compared to the TN-LC. Thus, ongoing research efforts for the scope of this project will focus on more thorough evaluations of the OPTIMUS™-L packaging for HALEU transportation. A tentative timeline is presented for the remaining work that is planned for FY 2020. The goal is the development of F&Rs that provide guidance to a potential HALEU transportation package vendor on critical specifications by August 2020.

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ACRONYMS

ANSI	American National Standards Institute
CNSC	Canadian Nuclear Safety Commission
CFR	Code of Federal Regulations
CoC	Certificate of Compliance
DOE	Department of Energy
DR	dose rate
DU	depleted uranium
EBR-II	Experimental Breeder Reactor-II
ENDF	Evaluated Nuclear Data Library
F&R	Functions and Requirements
FY	fiscal year
GNF-A	Global Nuclear Fuels-America
HAC	hypothetical accident conditions
HALEU	high-assay low-enriched uranium
HEU	high-enriched uranium
ID	inner diameter
INL	Idaho National Laboratory
LC	Long Cask
LEU	low-enriched uranium
LCT	low-enriched uranium, compound fuel form, thermal neutron spectrum
LWR	light water reactor
LWT	legal weight truck
NAC	Nuclear Assurance Corporation
NCT	normal conditions of transport
NE	Office of Nuclear Energy
NEI	Nuclear Energy Institute
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
OPTIMUS-L	Optimal Modular Universal Shipping for low activity contents
ORNL	Oakridge National Laboratory
OD	outer diameter
PCF	pounds per cubic foot
PNNL	Pacific Northwest National Laboratory

RG	Regulatory Guide
R&D	research and development
SARP	Safety Analysis Report for Packaging
UNF	used nuclear fuel
TN	Transnuclear
VF	volume fraction

UO_2 HALEU Transportation Package Evaluation and Recommendations

1. INTRODUCTION

Currently, operating commercial light water reactor (LWR) nuclear power plants (NPPs) in the U.S. utilize low-enriched uranium (LEU) fuel with a higher (up to 5%) enrichment of the isotope ^{235}U than the ^{235}U concentration found in natural uranium (≈0.72%). In the production process of fuel for thermal NPP reactors, the ^{235}U content is increased in an enrichment process using gas centrifuges. However, many of the proposed advanced nuclear reactor designs plan for high-assay low-enriched uranium (HALEU) as the main fuel component (Tschiltz 2018). Exceeding the 5% ^{235}U enrichment limit of LWR LEU fuel, the ^{235}U enrichment of HALEU fuel ranges from 5 to 20% (Tschiltz 2018). Besides raising the ^{235}U enrichment in gas centrifuges to HALEU levels, the desired enrichment in the fuel can be achieved by other means, e.g., via down-blending of available high-enriched uranium (HEU) with a ^{235}U enrichment above 20%.

The higher enrichment of HALEU compared to LEU leads to new technical and regulatory challenges regarding transportation (Tschiltz 2018). For instance, the enrichment process in a gas centrifuge typically yields uranium in a fluoride form (i.e., UF_6) as the final product. The transportation of UF_6 is regulated under Title 49 of the Code of Federal Regulations (CFR) Part 173.420. These regulations permit the transportation of UF_6 in standard cylinders listed in American National Standards Institute (ANSI) code ANSI.14-2001. However, the payloads of the ANSI-approved cylinders decrease with increasing enrichment of the cylinder content. Currently, only small amounts of UF_6 with an enrichment above 5% can be transported using these cylinders. This complicates economical HALEU transportation practices, which are necessary for large-scale fuel production (Tschiltz 2018). On the other hand, down-blending of HEU yields HALEU in the form of uranium metal or in oxidized form (i.e., UO_2), which can be transported in Type B packages, but require assurance of content subcriticality under most credible moderation scenarios of the package (10 CFR 71.55).

With an eye on the anticipated growth in demand for HALEU in the upcoming years, the Department of Energy (DOE), Office of Nuclear Energy (NE) provided funding to a research collaboration among Idaho National Laboratory (INL), Pacific Northwest National Laboratory (PNNL), and Oak Ridge National Laboratory (ORNL) to investigate technically sound, regulation-compliant solutions for economical transportation of HALEU. The extent of this research effort was determined as: (1) support of industrial research and development (R&D) by conducting a feasibility study on HALEU transportation utilizing existing package concepts, and (2) the development of a detailed Functions and Requirement (F&R) document that can be used to provide critical HALEU transportation package specifications to potential vendors.

As a first step, a workshop was organized in Washington, D.C. in August 2018 to gather the input from the regulatory and industrial stakeholders on HALEU-related issues (Jarrell 2018). Some of the technical and regulatory topics on transportation that were discussed at this workshop are summarized below:

- Timely availability of HALEU transportation concepts
- Expected composition of HALEU and production capabilities
- Regulatory basis of HALEU transportation
- Availability of criticality benchmarks for HALEU transportation

- Criticality issues related to HALEU transportation package content.

This report provides a status update on the research and investigations that have been conducted within the scope of this project to date. It presents the composition and activity limits of short-term available HALEU, reviews the regulatory basis for HALEU transportation, and evaluates the availability of criticality benchmarks for HALEU package assessments. Two available, promising package designs that have the potential to be adapted for HALEU transportation are reviewed and discussed. Additionally, the report provides an outlook on the activities scheduled for fiscal year (FY) 2020.

2. PURPOSE

This report was generated in fulfillment of milestone *M3FT-19IN030205042-UO_2 HALEU Transportation Package Evaluation and Recommendations* and summarizes the current progress in UO_2 HALEU Transportation Package Evaluation and Recommendations.

3. BACKGROUND

3.1 U.S. HALEU Production Capabilities

High-assay low-enriched uranium is a uranium blend characterized by a ^{235}U enrichment above 5% and below 20%. It is needed for many of the proposed U.S. advanced reactor designs (Tschiltz 2018). Currently, two options for U.S. HALEU production are considered:

1) Down-blending of available HEU to a ^{235}U enrichment between 5 and 20%. Available sources for HEU are the Experimental Breeder Reactor II (EBR-II), located at the INL Site, or used nuclear fuel (UNF) from other federally owned stocks. After down-blending, the yielded HALEU can be transported, for example, in an oxidized form (i.e., UO_2).
2) Increasing the ^{235}U enrichment in LEU to levels between 5 and 20% is accomplished using advanced gas centrifuges, gaseous diffusion, or laser separation. After the enrichment, the generated HALEU can be transported, for example, in a fluoride form (UF_6) or as elemental uranium (Tschiltz 2018).

Developing HALEU production capabilities that include enrichment of uranium above 5% ^{235}U would require the design of a new Category II site or the relicensing of the only commercial uranium enrichment facility currently existing in the U.S. (URENCO USA in Eunice, NM) with the U.S. Nuclear Regulatory Commission (NRC) (Mann 2019, Tschiltz 2018) from a Category III to a Category II site. On a short-term basis, neither of these two options appear feasible. For instance, the U.S. NRC guidance document for designing a Category II site is currently still under development (Tschiltz 2018, Mann 2019). Another restraining factor is the significant financial risks for the industry involved in HALEU fuel production, given the uncertainties in demand for the product. Furthermore, the Nuclear Energy Institute (NEI) estimates that the time required to establish a complete HALEU fuel production cycle in the U.S., including gas centrifuge-based uranium enrichment, is at least seven to nine years (Tschiltz 2018).

Thus, for a short-term, interim HALEU supply, which is needed for the development of advanced reactor technologies, down-blending of HEU recovered from EBR-II or other federally owned UNF appears to be the only practicable HALEU production option (Tschiltz 2018). The preferred uranium form of the final product of such processes would be UO_2, which can be converted to other forms if deemed necessary for advanced reactor fuel production.

3.2 HALEU Composition

The different HALEU sources and their corresponding extraction processes yield products with different uranium isotope compositions (i.e., uranium vectors) and with different amounts and types of impurities. The HALEU composition affects the design of transportation package concepts regarding demands on package shielding capabilities and in terms of maintaining content subcriticality.

The following section describes the composition of HALEU, produced via extraction and down-blending of HEU recovered from EBR-II. The composition of HALEU yielded from other federally owned stocks is not yet publicly available, but an information release process has already been set in motion.

3.2.1 Extraction of HALEU from EBR-II UNF

The EBR-II UNF available as source material for HALEU production consists of two general types of fuel: (1) sodium-bonded HEU (i.e., > 97% ^{235}U content) driver fuel and (2) blanket fuel that was manufactured from depleted uranium (DU) with a ^{235}U content below the concentration typically found in natural uranium (i.e., < 0.72%) (Benedict, McFarlane and Goff 2001).

Before down-blending, the HEU is extracted from the driver fuel using electrometallurgical treatment (EMT) based on molten salt refinement: In an air-filled hot cell, the fuel is separated from the assembly hardware, transferred to an argon-filled hot cell, and chopped into segments. Subsequently, the segments are transferred into an electrorefiner, which is an apparatus that dissolves the UNF and uses molten salts, liquid metals, and an anodic basket to separate the fission products and transuranic elements from the uranium in the UNF. A cathode in the refiner attracts and collects the uranium. The following uranium refinement includes the distillation of remaining salts. Finally, the enrichment of the final uranium blend can be adjusted by mixing the HEU gathered from the driver fuel with the DU extracted from the blanket fuel (Benedict, McFarlane and Goff 2001).

Vaden (2018) summarizes the average, minimum, and maximum isotopic contents of the EBR-II HALEU blend. The final form is anticipated to be UO_2 powder.

Table 1. Material composition of EBR-II HALEU (Vaden 2018).

Analyte	Units	Average	Minimum	Maximum
Total U	wt%	99.95	99.89	99.97
U232	ppb U	0.66	0.07	5.04
U233	ppb U	49.12	4.88	318.43
U234	iso% U	0.17	0.16	0.21
U235	iso% U	19.39	18.97	19.99
U236	iso% U	0.58	0.50	1.22
U237	ppt U	0.06	0.00	0.22
U238	iso% U	79.86	79.05	80.36
Zr	ppm	101.45	59.80	146.50
Si	ppm	77.6	40.00	130.00
Y	ppm	6.05	5.00	10.00
Fe	ppm	133.13	39.90	574.00
Cr	ppm	28.15	15.00	115.00
Ni	ppm	43.14	30.00	68.80
Mo	ppm	40.21	10.00	75.00
Mn	ppm	79.47	13.80	190.00
Ru	ppm	77.23	40.00	130.00
Cd	ppm	12.17	5.00	20.00
Al	ppm	101.24	20.00	285.00

Table 1 (continued). Material composition of EBR-II HALEU (Vaden 2018).

Analyte	Units	Average	Minimum	Maximum
Tc	ppm	75.00	65.00	85.00
Li	ppm	15.60	5.00	40.00
K	wt%	0.05	0.01	0.15
Na	ppm	82.29	35.00	200.00
Ba	ppm	5.00	5.00	5.00
Sr	ppm	5.00	5.00	5.00
Sr90	ppb	15.77	0.31	62.50
Nd	ppm	95.92	25.00	200.00
Sm	ppm	56.82	20.00	160.00
Tc99	ppm	0.15	0.06	0.28
Cs135	ppm	2.67	2.00	3.00
Mn54	ppt	3.04	0.04	12.52
Co60	ppt	27.81	0.27	176.99
Sb125	ppt	102.51	2.88	480.77
Cs134	ppt	24.99	0.23	153.85
Cs137	ppb	8.00	0.55	22.38
Ce144	ppt	67.11	1.88	313.48
Eu154	ppb	0.22	0.00	1.11
Eu155	ppb	0.22	0.00	1.04
Am241	ppb	61.23	2.92	291.55
Np237	ppm	17.11	13.90	21.40
Pu239	ppm	83.57	58.73	103.00
Pu240	ppm	2.24	1.46	2.71

3.3 Regulatory Basis for Transportation of Enriched Uranium

In this report and in line with the codified regulatory requirements, “packaging” refers to the assembly of components necessary to ensure compliance with the packaging requirements of 10 CFR 71. The definition may include spacing structures, radiation shielding, criticality control features, devices for absorbing mechanical shock, and the tie-down system. The “transport package” refers to the packaging together with its radioactive contents as presented for transport. Accordingly, the “containment boundary” refers to the enclosure formed by the packaging inner shell or vessel, the top flange, the top closure lid and associated bolts, and their inner seals.

Transportation of radioactive material is regulated under 49 CFR 173, Subpart I and 10 CFR 71. Further recommendations on the fracture toughness of the transportation package containment boundary are provided in the U.S. NRC Regulatory Guide (RG) 7.11 (U.S. NRC 1991).

3.3.1 Transportation of Enriched UF_6

Specific transportation requirements for fissile materials like UF_6 are provided in 49 CFR 173.420. This section of regulations requires transportation of UF_6 in packages designed according ANSI.N14-2001, which lists a set of approved standard cylinder designs. In the U.S., enriched uranium that is meant for fuel production is typically transported using the ANSI-approved 30B cylinder (Tschiltz 2018). This specific cylinder model has a maximum payload of 5,020 lbs of UF_6 with an enrichment of up to 5% (INMM 2001).

Transportation of LEU with a ^{235}U enrichment below 5% in the form of UF_6 (and not in any other form, like UO_2) is addressed in 10 CFR 71.55 (g) (4), which exempts a fissile material package from the requirement of maintaining subcriticality under water intrusion if the content is LEU UF_6. However, the ^{235}U enrichment in HALEU exceeds the 5% limit; thus, subcriticality under water intrusion needs to be maintained.

Another obstacle when transporting HALEU in the form of UF_6 is the limited payloads of the cylinders listed in ANSI.N14-2001, which decrease with the increase of approved UF_6 enrichment. For instance, the payload of cylinder type 8A, which was designed for transportation of UF_6 with an enrichment of up to 12.5%, is limited to 255 lbs. The cylinder types with the next higher approved UF_6 enrichment payload are 5A and 5B. Both can be used for transportation of up to 54.9 lbs. of UF_6 with an enrichment of up to 100% (INMM 2001). None of the available approved cylinder types permit the transportation of HALEU in large enough amounts to establish an economical fuel production cycle (Tschiltz 2018).

3.3.2 Transportation of Enriched UO_2

Unlike UF_6 that was enriched using a gas centrifuge, the form of the final HALEU product after down-blending of HEU that was recovered from EBR-II or other federally owned stocks can be either uranium metal or UO_2. Transportation of HALEU in forms other than UF_6 does not fall under the regulations stated in 49 CFR 173.420; thus, package designs other than the standardized cylinders listed in ANSI.N14-2001 can be used. However, the utilized package design still needs to meet appropriate 49 CFR, 173 Subpart I and 10 CFR 71 requirements, as well as the recommendations of U.S. NRC RG 7.11.

Generally, 49 CFR 173.417 permits transportation of fissile material in Type AF, B(U)F or Type B(M)F packages, if the transported quantities do not exceed the activity limits A_1 and A_2 as defined in 49 CFR 173.435 and the fissile material meets the applicable standards in 10 CFR 71. The preferred uranium form for this program is UO_2 powder, which would be shipped as normal form material (i.e., not small-size dual-encapsulated special form material). As such, the quantities to be transported would be characterized in quantities of fissile materials that exceed an A_2, which can be transported in Type B(U) or Type B(M) packages.

Preliminary activity assessments (see Section 3.4) of HALEU in sufficiently large amounts (from an economical perspective) indicate that the proposed package content does not meet any of the fissile exemptions listed in 10 CFR 71.15, and that a Type B package is required to meet 49 CFR 173.417. Furthermore, to provide flexibility regarding U.S. NRC RG 7.11 activity thresholds, a Category I containment design is recommended. However, a variety of Type B, Category I packaging designs for UO_2 UNF transportations are available, and the industry has gained extensive experience during the last couple of years in shipping them. Some of the existing packaging should also provide enough payload for the development of an economical fuel cycle for advanced reactors.

3.3.3 Compliance of HALEU Transportation Package with CFR

In Section 4 of this report, the compliance potential of two promising Type B package concepts with the regulations listed in 49 CFR 173 Subpart I and 10 CFR 71 is reviewed. For instance, the potential for criticality of the fissile package content is evaluated. If not exceptionally approved otherwise by the U.S. NRC, the fissile package content needs to remain subcritical under most credible water intrusion. Furthermore, the selected package designs are evaluated according to whether they are capable of providing enough shielding to comply with the external radiation standards according 10 CFR 71.47, and whether the package design is capable of withstanding normal conditions of transport (NCT) and hypothetical accident conditions (HAC) as defined in 10 CFR 71.71 and 10 CFR 71.73. Note that the review and the presented results in this report are of a preliminary nature. More comprehensive evaluations and results are anticipated for FY 2020 (See Section 6, Project Outlook FY 2020).

3.4 Activity Limits of Fissile Material in HALEU Package

Safe transportation of EBR-II HALEU demands packaging features such as engineered containment, criticality safety features, and shielding. This is due to the inventory of radioactive isotopes that reside in the material balance itself. Using the ORIGEN-S computer code (ORNL 2005), an evaluation of the source material and associated average isotopes weight fractions as listed in Table 1 was performed to determine the required package type (i.e., Type A or Type B) and to determine the packaging category based on the radioactive inventory.

By definition, a Type B package is required if it contains normal form radionuclides with an activity that exceeds one A_2 quantity (49 CFR 173.431). The evaluations in Appendix A show that only 3.375 kg or more of EBR-II HALEU are required to exceed one A_2 (Table A.1). The decay heat source for this source material is 5.56E-4 W/kg (Table A.2), which is relatively benign and can be considered negligible.

The three package categories I, II, and III indicate the ASME B&PV design requirements imposed on the package (see Section 4.5.1). As identified during the August 2018 HALEU workshop (Jarrell 2018), in order to maintain economic viability of transport, it would be preferable to develop the capacity to transport larger amounts of HALEU powder on the order of 1,600 kg or more per package. According to the evaluations performed in Appendix A, such an amount of EBR-II HALEU is equivalent to an activity limit of 474 A_2, which is below the 3,000 A_2 or 30,000 Ci limit of U.S. NRC RG 7.11 that would lead to Category I packaging requirements. A HALEU amount of 10,125 kg would be necessary to reach these limits. However, according to U.S. NRC RG 7.11, only 30 A_2 or greater are required to elevate the associated packaging requirements from Category III to Category II. This activity limit is reached by 101 kg of EBR-II HALEU. This leads to the conclusion that the transportation of 1,600 kg of HALEU requires a Category II containment.

Very little difference exists between Category I and Category II packaging design criteria per the applicable sections of the ASME B&PV Code as discussed in Section 4.5.1. To provide flexibility in case the cleanliness of EBR-II HALEU is less ideal than anticipated, the program has opted to adopt Type B, Category I packaging design criteria. The packaging selected for application will also be configured to meet the dose rate (DR) requirements as established in 49 CFR 173.441 and 10 CFR 71.47.

3.5 Criticality Benchmarks

Criticality safety evaluations require validation of the computational methods with critical benchmark experiments that are as similar as possible to the safety analysis models for which the effective neutron multiplication factor k_{eff} values are known. One of the conditions that has a controlling effect on criticality is the prevalence of a moderator (e.g., water) in the package. The HALEU transportation concepts reviewed in this report utilize multiple canisters inside one single larger outer cask shell (see drawings in Appendix B). The UO_2 payload is equally distributed and encapsulated in the inner canisters. For the evaluation of package content criticality, the goal is to confirm subcriticality with most reactive credible moderation (10 CFR 71.55). This includes evaluations of the effect of package moderation by water between the canisters (for NCT according 10 CFR 71.71) and hydrogenous moderation of the considered content itself (for HAC according 10 CFR 71.73).

One of the concerns voiced by industry representatives at the August 2018 workshop was a potential lack of criticality benchmarks applicable for the criticality assessments of HALEU transportation packages (and HALEU fuel facility and equipment). Computer codes used for criticality assessments must be benchmarked against criticality experiments (Fard 2011). Consequently, the evaluation of k_{eff} is dependent on the availability of benchmark critical experiments that are considered relevant for a specific criticality analysis. A lack of applicable criticality benchmarks obtained from relevant experiments could lead to unfavorably conservative safety margins in criticality assessments of HALEU transportation package designs. The criticality assessments presented in Section 4.3 of this report include identification of appropriate benchmark critical experiments using the TSUNAMI code suite (Clarity, Marshall and Saylor 2019) to determine if existing readily available experiments will be sufficient for HALEU transportation package analyses. The TSUNAMI calculations are based on preliminary application models and limiting conditions. The ultimate selection of benchmark experiments will be part of a more detailed analysis of the final package design selected.

4. Review and Application of Existing Packaging Designs

Multiple available packaging designs that could be used as a starting point for development of a HALEU transportation package concept were considered in the preliminary phase of this project, but after an extensive search in the RAMPAC database (U.S. DOE 2015) and thorough review of available packaging that could be easily handled and readily transported by truck, it was concluded that very few would meet programmatic needs as well as all regulatory requirements after adaptation.

Two promising packaging designs were identified that could be adapted for HALEU transportation, as well as readily transported by truck. These are the Transnuclear (TN) Americas Long Cask (TN-LC) and the Nuclear Assurance Corporation (NAC) International Optimal Modular Universal Shipping for low-activity contents (OPTIMUS™-L) packaging. Although both designs are Type B, Category I packaging, these two designs show vastly different shielding capacities. The TN-LC has significant gamma and neutron shielding boundaries, whereas the OPTIMUS™-L offers only modest shielding capacity (see Section 4.4 for details) with the option of additional shield inserts.

At this juncture, both designs are reviewed regarding their potential for transporting HALEU with a composition as listed in Table 1. The ultimate concept selection process needs to consider information on the cleanliness of the final HALEU blend, since it could affect the required shielding capabilities of the package, and the package requirements to remain subcritical (see Section 4.4).

4.1 Transport Packaging Options and Descriptions

One of the objectives of this initiative is to identify transportation packaging designs that offer reasonable HALEU payload capacities (on the order of 1,600 kg or more), can be readily transported by truck, and maintain enough adaption flexibility to meet the programmatic needs for material handling and processing. To assure flexibility in case process cleanliness of EBR-II HALEU is less ideal than expected, the program has opted to adopt Type B, Category I packaging design requirements and criteria. The following sections provide general descriptions of the TN Americas TN-LC and the NAC International OPTIMUS™-L packaging designs, a proposed adaptation concept to augment the designs for programmatic material handling and processing, and a discussion of the types of regulatory requirements that have to be met by the package configuration.

4.1.1 TN Americas TN-LC Description

The TN Americas TN-LC is a Type B(U)F NRC-licensed package (Certificate of Compliance [CoC] 9358) originally developed for transporting a variety of moderate to high-burnup UNF assemblies. The TN-LC is shown in Figure 1. If this design were selected by the program for HALEU transportation, TN Americas would be required to perform supporting safety basis evaluations that incorporate HALEU in the form of UO_2 powder as possible content. They would then need to amend the Safety Analysis Report for Packaging (SARP) to reflect the new package content and subsequently apply for approval and revision of the CoC by the U.S. NRC. This is estimated to be roughly a two-year process at the most, given its prior certification history.

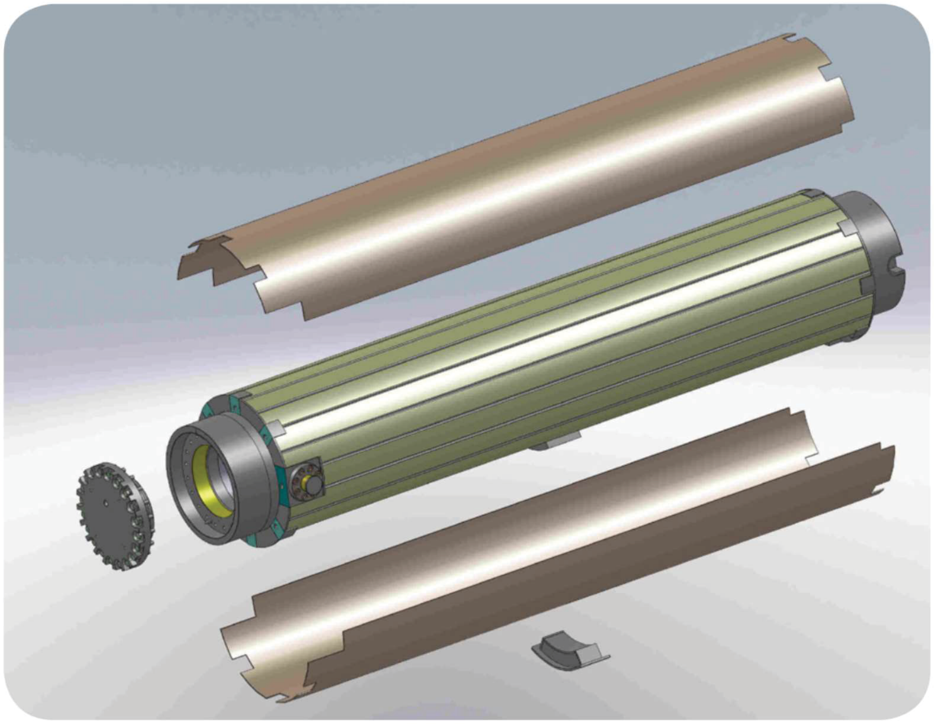


Figure 1. TN Americas TN-LC. Photo used with permission of TN Americas, LLC.

Presented below is a summary of some important design specifications of the TN-LC. Because of its size and weight, only one package (i.e., loaded packaging with its payload/contents) can be transported at a time without exceeding legal weight truck (LWT) limits.

TN-LC Specifications:

Dimensions:
- Cavity size: 18" (inner diameter [ID]) × 182.5"
- Outer dimensions: 66" (outer diameter [OD]) × 230"

Mass:
- Empty mass: 43,900 lbs
- Maximum content mass: 7,100 lbs
- Packages per LWT shipment: 1

Materials and components:
- Overpack
  - Gamma shielding layer constructed from B29 copper lead
    - Gamma shield thickness: 3.50"
    - Encased by inner and outer stainless-steel shells
      - Inner shell wall thickness: 1.00"
      - Outer shell wall thickness: 1.50"
  - Neutron shielding layer constructed from VYAL B
    - Neutron shield thickness: 3.75"
    - Resin is subdivided into channels constructed from 6063 aluminum
      - Resin channels (neutron shield boxes) surround contents region
      - Neutron shield box wall thickness: 0.125"
    - Encased by neutron shield shell on outer circumferential region
      - Neutron shield shell wall thickness: 0.25"
  - Bolted closure lid constructed from stainless steel (F304)
    - Requires 20 1-8UNC × 4 hex bolts to secure
  - Bottom and top flanges constructed from FXM019 SS
    - Flanges welded to inner, outer, and neutron shield shells
  - Lifting trunnions located at top end of package
- Impact limiters
  - Constructed from multi-layer wooden impact limiting material
    - Layers consist of a combination of balsa and redwood with differing grain directions
    - Wooden impact limiting material encased in 304 stainless steel shell
      - Impact limiter shell wall thickness: 0.375"
    - Support angle feet for stability when resting on flat surfaces
    - Hoist rings included on both the upper and lower impact limiters

4.1.2 NAC International OPTIMUS™-L Packaging Description

The NAC International OPTIMUS™-L is also a Type B(U)F packaging; however, it is not yet NRC certified. This design was originally developed by NAC to handle a wide variety of radioactively contaminated content types that typically need to be shipped in Type A(F) of Type B packages, like contact-handled transuranic or low-activity wastes. Nuclear Assurance Corporation International applied to the Canadian Nuclear Safety Commission (CNSC) in March of 2019 and anticipates receiving Canadian certification/approval in early 2020 for Type B(U)F capacity. The Canadian regulatory body relies on IAEA regulations that closely mimic the regulatory requirements enforced by the U.S. NRC for U.S. application certification. The OPTIMUS™-L packaging and its nonexclusive use related conveyance configuration is depicted in Figure 2. If this design were selected by the program for HALEU transportation, NAC International would be required to perform supporting safety basis evaluations that incorporate HALEU in the form of UO_2 powder as possible content. It would then need to amend the SARP to reflect the new package content and subsequently apply for approval and revision of the CoC by the U.S. NRC. This is estimated to be roughly a two- to three-year process at the most, given its current Canadian certification process history.

Figure 2. NAC International OPTIMUS™-L packaging and nonexclusive use conveyance configuration.

Presented below is a summary of some important design specifications of the OPTIMUS™-L. Because of its small size and light weight, up to ten packages, depending on payload weight (i.e., loaded packaging with its payload/contents), can be transported at a time without exceeding LWT limits.

<u>OPTIMUS™-L Specifications:</u>

<u>Dimensions:</u>
- Cavity size: 32.5” (ID) × 47”
- Outer dimensions: 49” (OD) × 70”

<u>Mass:</u>
- Empty mass: 6,050 lbs
- Maximum content mass: 3,150 lbs
- Packages per LWT shipment: 10

<u>Materials and components:</u>
- Package containment vessel: Innermost container
  - Stainless steel
  - Containment vessel wall thickness: 1.00”
  - Bolted closure with elastomeric O-rings and captured lid bolts
  - Lid porting for inerting containment cavity
  - Lifting attachments on lid
- Outer packaging: Outermost confinement and containment barrier
  - Fully encases packaging containment vessel for impact and fire protection
  - Constructed from stainless-steel shells and foam
  - General plastics 24 pounds per cubic foot (PCF) foam is used as the impact limiting material
    - Foam wall thickness: 6.875”
  - Outer stainless-steel encases foam layer
    - Outer stainless-steel shell wall thickness: 0.1875”
    - Lifting and tiedown points located on outer shell immediately below outer packaging lid assembly

4.2 Transport Packaging Adaptation Concept

A need was identified to integrate a modular confinement system that augments safe material (HALEU UO_2 powder) handling and processing to support advanced reactor development programs. The confinement system refers to the assembly residing within the containment boundary of the packaging that maintains confinement and configuration of the radioactive material in order to maintain subcriticality during transport. The confinement system is envisioned to be comprised of generic HALEU UO_2 powder canisters and a complementary basket intended to maintain a subcritical reactivity configuration. The canisters must be small enough to allow remote handling, yet large enough to maintain efficiency and economic viability during handling and processing operations.

Both foam and metal basket concepts were selected for review. Although metal basket designs are very common, a foam basket has the significant advantage of providing a lower-weight structure. Furthermore, foam could facilitate maintaining content subcriticality through judicious material property selection (e.g., through selecting high-density foams with high hydrogen and high carbon contents).

The PNNL and ORNL development teams established the confinement system iteratively while considering structural robustness, payload capacity, and operations viability. Furthermore, the package must confine its content, maintain a subcritical content state, and constrain the HALEU from adverse reconfiguration under postulated regulatory evaluation conditions as defined in 10 CFR 71. Presented below are details regarding the proposed generic canister and complimentary modular basket designs.

4.2.1 Generic HALEU Canister

4.2.1.1 Canister Design Overview

The proposed canister design, in conjunction with a modular basket, must satisfy the requirements to maintain an adequate subcritical margin within the package containment vessel. Several possible subcritical configurations were identified, and the canister wall thicknesses and center-to-center pitch dimensions of the canister cross-sectional layouts of these configurations were outlined in an interim ORNL deliverable (Scaglione 2019). Of these configurations, the 7-Pipe, Option 2 was chosen for the preliminary canister design due to the greater payload capacity associated with this option.

4.2.1.2 Canister Design Specifications

As provided by J. Scaglione (2019), in order to maintain subcritical reactivity, the radial dimensions of the generic HALEU canisters will be as follows: Each canister will be constructed of stainless steel, have a wall thickness of 0.375", and have an OD of approximately 5". The outer surface of the canister will be coated with a thin outer layer of neutron poisoning material (Al_2B_4). Furthermore, the canister components will be welded together to ensure adequate structural integrity of the canister (when integrated within the proposed packaging options) under postulated NCT and HAC loading as specified in 10 CFR 71.71 and 10 CFR 71.73.

In addition to satisfying criticality requirements, the canister design must also satisfy the anticipated operational requirements for the transportation of UO_2, which include reusability for multiple loading and unloading cycles and compatibility with both the TN-LC and OPTIMUS™-L transport packaging systems. To satisfy the reusability requirements, a threaded lid and self-energizing seal configuration have been incorporated into the canister design, allowing site personnel to easily load and unload material while also providing a reliable confinement boundary. Additional safeguards and refinements of the lid design will be added to prevent accidental opening of the canisters in the future.

The overall length of the canister design was chosen as 19", which has been determined to be a practicable length for canister use in both the TN-LC and NAC OPTIMUS™-L packaging and will be optimized in future design refinements to maximize package payloads. A sketch of the generic HALEU canister is featured in the drawings in Appendix B.

Based on the current proposed generic canister design, the mass of each canister is 35 lbs. The HALEU content mass of each canister volume (249 in^3), when entirely filled with HALEU in the form of UO_2 powder at a 63% compaction ratio, would be 62 lbs. As such, each canister loaded with UO_2 powder is estimated to weigh approximately 97 lbs.

4.2.2 OPTIMUS™-L and TN-LC Basket Design Concepts

4.2.2.1 Basket Design Overview

The necessary requirements for the HALEU transportation package concepts include maintaining the canister spacing as outlined by J. Scaglione (2019). Thus, basket designs were developed to keep the HALEU canisters in their respective configuration within the packaging cavity. Two modular basket designs were envisioned, which permit use in both the OPTIMUS™-L and TN-LC. The goal was to maintain flexibility in the current stage of the program without the need to develop packaging-specific basket designs.

The preliminary designs satisfy the currently identified requirements on the basket; however, additional refinements will be made to optimize the structural and thermal behavior, in addition to payload of the baskets, during the coming phases of this project.

4.2.2.2 Basket Design Specifications

Metal Basket Concept:

In a first step, a modular metal basket design was developed. The TN-LC canister cavity fits a combination of two male and two female sections, as shown in Figure 3. Each section of basket assembly can hold two HALEU canisters on top of each other in each of the seven storage locations, which adds up to a total capacity of 56 canisters.

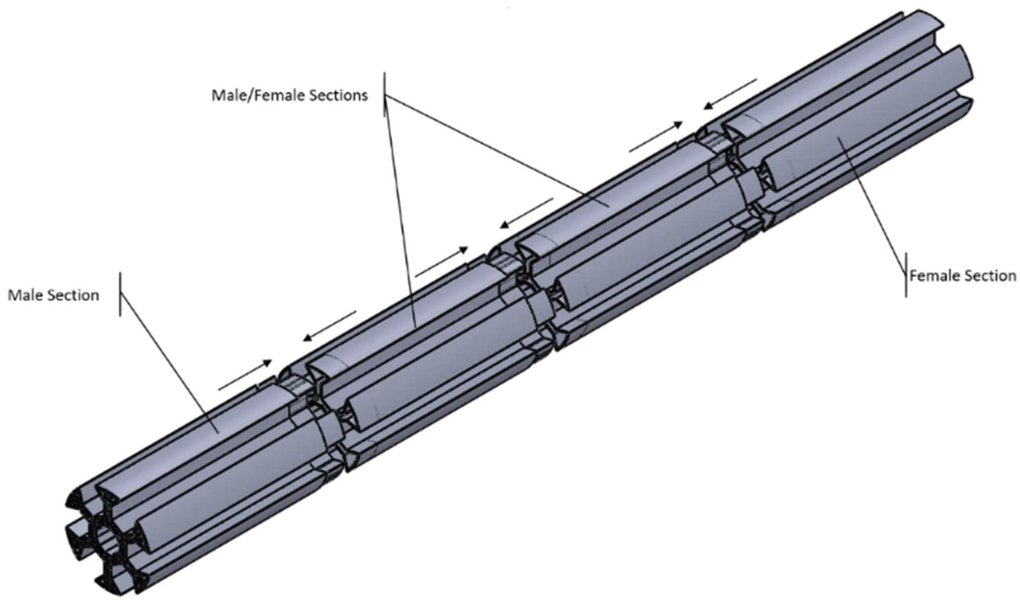


Figure 3. TN-LC metal canister basket.

The OPTIMUS™-L basket concept is shown in Figure 4. It includes a neutral section and an outer ring. Each storage location in the OPTIMUS™-L basket can hold two HALEU canisters on top of each other for a total capacity of 38 canisters.

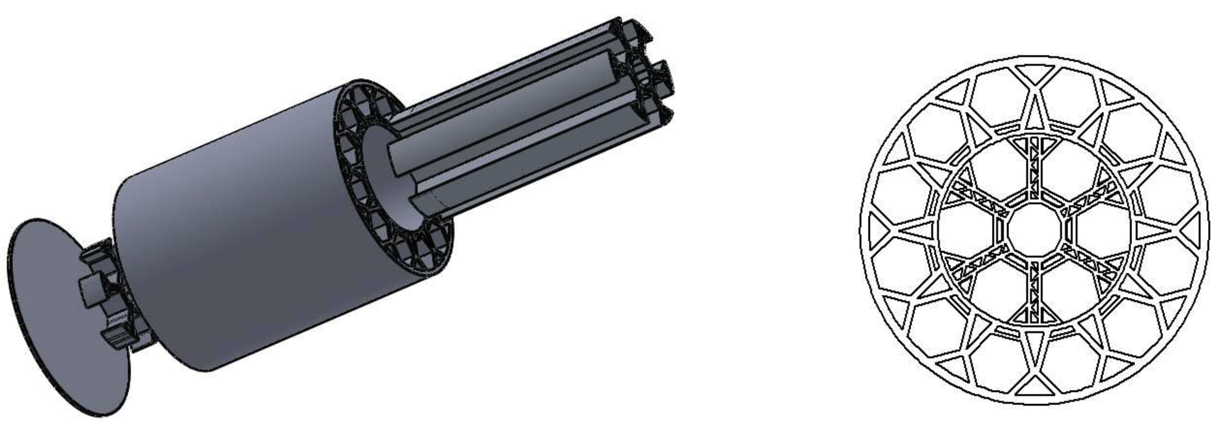


Figure 4. OPTIMUS™-L metal canister basket.

The predicted masses of the metal basket concepts for the TN Americas TN-LC and NAC International OPTIMUS™-L packages are approximately 1,241 lbs and 1,430 lbs, respectively. Based on the capacities of each basket and the content capacity for each canister, the total payload masses of UO_2 powder in the TN-LC and OPTIMUS™-L are 3,472 lbs and 2,356 lbs, respectively. As such, the total mass (including metal basket, canister, and powder content) within the TN-LC is estimated to be 6,672 lbs. Likewise, the total mass (including metal basket, canister, and powder content) within the OPTIMUS™-L is estimated to be 5,116 lbs.

Foam Basket Concept:

The foam basket design consists of cylindrical foam sections that slide into the containment vessel cavities of the transportation packages. The foam sections have circular tube cutouts, which the canisters slide into under loading operations. Polycarbonate endcaps will be placed above and below the axial ends of the foam basket sections to provide a means of basket removal and installation, in addition to providing shoring/dunnage between the generic canisters and containment vessel inner surface. These endcaps also serve to distribute structural loads during the postulated NCT and HAC loading as prescribed by 10 CFR 71.71 and 10 CFR 71.73. The center-to-center pitch of these tube cutouts satisfies the spacing requirements to maintain subcriticality as outlined by J. Scaglione (2019).

To maintain modularity, the foam basket system consists of two independent parts: (1) a central section, and (2) an outer ring. Both the central and outer sections have the same length. The TN-LC cavity can accommodate four central sections with five polycarbonate end caps placed between the foam sections and at the top and bottom of the TN-LC inner containment cavity. Like the metal basket concept, the foam basket allows transportation of up to 56 HALEU canisters in the TN-LC.

The NAC OPTIMUS™-L cavity accommodates one central foam section, which slides inside one outer foam ring. The inner and outer sections are separated by a polycarbonate liner, and polycarbonate end caps are placed at the bottom and top of the containment vessel inner cavity.

Conceptual sketches of both packaging-specific foam basket configurations are featured in Appendix B.

Both the central and outer foam sections of the basket will be constructed using blow molding of a rigid polyurethane foam. Possible foam candidates include DUNA CORRADINI RTS 320 and General Plastics FR Series Last-A-Foam and could range between 10 and 24 PCF. Preliminary structural evaluations were performed with 10 PCF. Further structural and criticality evaluations will be performed to determine the optimal material and associated density for the basket configuration. Like the metal basket concept, the foam basket allows transportation of up to 38 HALEU canisters in the OPTIMUS™-L packaging.

The predicted masses of the foam basket concepts for the TN Americas TN-LC and NAC OPTIMUS™-L packaging are approximately 436 lbs and 462 lbs, respectively. These foam basket masses are essentially 1/3 of the masses of the metal basket and can accommodate identical payload masses of UO_2 powder. Based on the capacities of each basket and the content capacity for each canister, the total payload masses of UO_2 powder for the TN-LC and OPTIMUS™-L are 3,472 lbs and 2,356 lbs, respectively. As such, the total mass (including basket, canister, and powder content) within the TN-LC is estimated to be 5,868 lbs. Likewise, the total mass (including basket, canister, and powder content) within the OPTIMUS™-L is estimated to be 4,148 lbs.

4.3 Preliminary Package Subcriticality Assessment

The program has opted to adopt Type B, Category I packaging design requirements and criteria. Per 10 CFR 71.55 and other corroborating code sections, maintenance of subcriticality reactivity is required under most reactive credible package moderation.

Criticality control is demonstrated for the two basket designs (metal and foam) as a function of the areal density of the neutron absorber layer (modeled as a thin layer on the outside of the canister) and the neutron absorber's reactivity worth as a function of moderation between canisters (from water, steel, and foam). Analysis results for both package designs show that combinations of neutron absorber and foam can provide acceptable criticality control.

For the TN-LC package criticality calculations, the metal basket is omitted, and the space between the canisters is treated as a void. Modeling the metal basket as a void conservatively neglects patristic neutron absorptions in the metal. For the foam basket calculations, the space between the canisters is filled with foam. Because the density of the basket foam is not known, a range of foam density is considered.

For the OPTIMUS™-L package criticality calculations, the metal basket model approximates the layout of the basket shown in Figure 4. Calculations include configurations with and without foam filling the gaps between basket segments. A few selected all-foam basket cases without metal are performed to confirm the effect of replacing metal with foam.

4.3.1 TN Americas TN-LC Subcriticality

Criticality calculations for the TN-LC package are performed using the SCALE version 6.2.3 CSAS6 sequence, which performs k_{eff} calculations with KENO-VI. The Evaluated Nuclear Data Library (ENDF) version 7.1 252 group cross sections are used for the preliminary HALEU package assessment (Rearden and Jessee 2018). A cross section and a cutaway view of the simplified KENO model of the TN-LC package containing 56 HALEU canisters is shown in Figure 5.

The TN-LC package is modeled as an outer cylinder of 304 stainless steel, a layer of lead inside the outer steel cylinder, and an inner steel cylinder inside the lead layer. The basket and HALEU canisters reside inside the inner steel cylinder. Except for boundary condition sensitivity cases, reflective boundary conditions are used to bound an array of packages. The external neutron shield resin, aluminum shield boxes, and impact limiters are not modeled. The HALEU is assumed to be UO_2 at 20 wt% ^{235}U and 80 wt% ^{238}U with a nominal packing fraction of 62%. This generic HALEU enrichment bounds the HALEU compositions specified in Table 1. It is assumed that all reactivity trends evaluated are applicable to lower-enrichment HALEU.

Neutron poison may be required to maintain the packages in a subcritical condition. Previous studies have determined that an effective approach includes a poison layer on the outside of the canisters. Preliminary model calculations assume there is a thin layer of poison material, which coats the outside of each canister. In this configuration, some neutron moderating material between canisters makes the neutron poison more effective. The metal basket model has no added moderating material. Foam provides moderation in the foam basket model. Other arrangements of neutron poison and moderating material may also be acceptable but have not been investigated in the scoping calculations. The neutron poison material is assumed to be present on the full length of each canister. The moderating material, if present in the model, is also assumed to cover the full length of the canister.

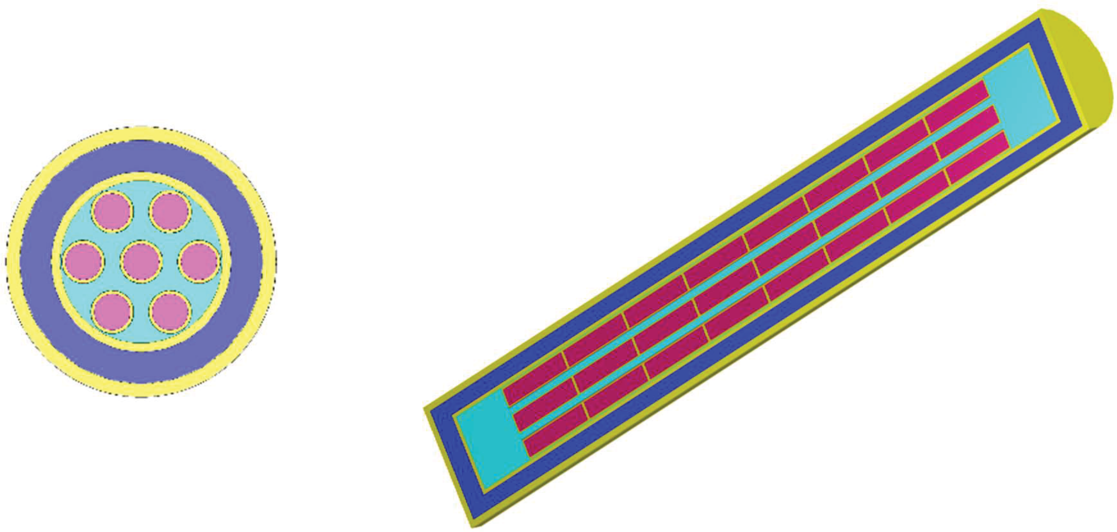


Figure 5. Cross section and cutaway view of TN-LC KENO criticality model.

Calculations are performed to establish reactivity trends, associated neutron absorber thickness and loading (areal density) in the layer around the canister, and the density of the basket foam (if present in the model). Water intrusion is assumed to occur. The effect of water in differing amounts and in different portions of the package include these conditions:

- **Dry conditions:** Both the canister and the basket are assumed to be dry. This is the expected normal condition. For trending, UO_2 volume fractions (VFs) (i.e., densities) of 100% and 62% are considered.
- **Wet canister with dry basket:** This scenario assumes water intrusion in the fuel canisters but dry (or drained) conditions in the packaging cavity. For these cases, a range of water and UO_2 volume fractions are considered. Previous scoping studies show the bounding UO_2 volume fraction is around 0.2; therefore, calculations consider a range from about 0.15 to 0.25 to establish the peak reactivity.
- **Wet canister with wet basket (metal basket model):** This scenario assumes water intrusion in the fuel canisters and the package cavity. These calculations establish the reactivity effect of moderator in the basket with no basket foam present.

4.3.1.1 TN-LC Criticality Results

Table 2 provides the results of the dry basket/dry canister scoping calculations for the metal basket model. Package reactivity increases with decreasing ^{10}B areal density and increasing UO_2 VF.

Table 2. TN-LC dry basket/dry canister cases, metal basket model.

Areal Density (g $^{10}B/cm^2$)	0.0007	0.0017	0.0028	0.0091	0.0228	0.0365	0.0176	0.0439	0.0702
Neutron Poison Layer Thickness (cm)	0.01			0.132			0.254		
Neutron Poison Layer Loading (wt% B)	5	12.5	20	5	12.5	20	5	12.5	20
UO_2 VF = 1, k_{eff}	1.1059	1.0997	1.0949	1.0576	1.0078	0.9690	1.0182	0.9434	0.8877
UO_2 VF = 0.62, k_{eff}	0.9799	0.9632	0.9491	0.8764	0.7989	0.7469	0.8168	0.7178	0.6560

Table 3 provides results for the dry basket/dry canister scoping calculations with varying densities of basket foam. Package reactivity increases with decreasing ^{10}B areal density, decreasing foam density, and increasing UO_2 VF.

Table 3. TN-LC dry basket/dry canister cases, foam basket model.

Areal Density (g $^{10}B/cm^2$)	0.0007	0.0017	0.0028	0.0091	0.0228	0.0365	0.0176	0.0439	0.0702
Basket Foam Density (g/cm^3)	0.12								
Neutron Poison Layer Thickness (cm)	0.01			0.132			0.254		
Neutron Poison Layer Loading (wt% B)	5	12.5	20	5	12.5	20	5	12.5	20
UO_2 VF = 1, k_{eff}	1.1039	1.0939	1.0860	1.0365	0.9774	0.9325	0.9902	0.9067	0.8487
UO_2 VF = 0.62, k_{eff}	0.9814	0.9677	0.9556	0.8936	0.8208	0.7699	0.8377	0.7412	0.6780
Basket Foam Density (g/cm^3)	0.22								
Neutron Poison Layer Thickness (cm)	0.01			0.132			0.254		
Neutron Poison Layer Loading (wt% B)	5	12.5	20	5	12.5	20	5	12.5	20
UO_2 VF = 1, k_{eff}	1.0987	1.0834	1.0716	1.0129	0.9460	0.9009	0.9618	0.8751	0.8176
UO_2 VF = 0.62, k_{eff}	0.9807	0.9613	0.9454	0.8715	0.7937	0.7411	0.8113	0.7125	0.6505
Basket Foam Density (g/cm^3)	0.32								
Neutron Poison Layer Thickness (cm)	0.01			0.132			0.254		
Neutron Poison Layer Loading (wt% B)	5	12.5	20	5	12.5	20	5	12.5	20
UO_2 VF = 1, k_{eff}	1.0890	1.0699	1.0541	0.9858	0.9149	0.8679	0.9317	0.8444	0.7878
UO_2 VF = 0.62, k_{eff}	0.9741	0.9498	0.9305	0.8462	0.7636	0.7124	0.7834	0.6840	0.6252

Tables 4 through 9 (in increasing ^{10}B areal density order) provide results for the wet/dry basket and wet/dry canister scoping calculations for the metal basket model. Package reactivity increases with increasing amounts of water in the canisters, decreasing amounts of water in the basket, and decreasing ^{10}B areal density. Peak reactivity occurs between 20% and 25% VF UO_2 for limiting cases.

Table 4. TN-LC wet/dry basket and canister cases, metal basket model.

Canister Water Density (g/cm^3)	0			0.5			1		
Basket Water Density (g/cm^3)	0	0.5	1	0	0.5	1	0	0.5	1
Neutron Poison Layer Thickness (cm)	0.01								
Areal Density (g $^{10}B/cm^2$)	0.0021								
UO_2 VF	k_{eff}								
0.1	0.4260	0.3923	0.3220	0.9352	0.6377	0.5034	1.1585	0.8529	0.7158
0.116	0.4648	0.4184	0.3412	0.9556	0.6565	0.5194	1.1766	0.8669	0.7286
0.133	0.5000	0.4401	0.3577	0.9697	0.6715	0.5315	1.1864	0.8779	0.7360
0.15	0.5324	0.4604	0.3726	0.9823	0.6834	0.5413	1.1948	0.8855	0.7420
0.166	0.5619	0.4781	0.3852	0.9922	0.6934	0.5499	1.1995	0.8898	0.7467
0.1833	0.5890	0.4949	0.3985	0.9983	0.7024	0.5585	1.2013	0.8951	0.7489
0.2	0.6146	0.5105	0.4110	1.0039	0.7103	0.5664	1.2038	0.8972	0.7501
0.216	0.6382	0.5240	0.4197	1.0095	0.7163	0.5713	1.2026	0.8981	0.7517
0.2333	0.6599	0.5371	0.4304	1.0143	0.7222	0.5778	1.2028	0.8992	0.7514
0.25	0.6815	0.5492	0.4399	1.0172	0.7281	0.5817	1.2011	0.8985	0.7506

Table 5. TN-LC wet/dry basket and canister cases, metal basket model.

Canister Water Density (g/cm^3)	0			0.5			1		
Basket Water Density (g/cm^3)	0	0.5	1	0	0.5	1	0	0.5	1
Neutron Poison Layer Thickness (cm)	0.0588								
Areal Density (g $^{10}B/cm^2$)	0.0124								
UO_2 VF	k_{eff}								
0.1	0.3412	0.1822	0.1293	0.7918	0.4733	0.3547	1.0581	0.7418	0.6152
0.116	0.3789	0.2019	0.1432	0.8126	0.4863	0.3646	1.0747	0.7525	0.6228
0.133	0.4126	0.2206	0.1562	0.8297	0.4987	0.3739	1.0857	0.7591	0.6279
0.15	0.4444	0.2380	0.1678	0.8438	0.5077	0.3803	1.0914	0.7619	0.6296
0.166	0.4744	0.2535	0.1799	0.8554	0.5162	0.3876	1.0975	0.7652	0.6315
0.1833	0.5020	0.2688	0.1907	0.8652	0.5228	0.3939	1.1002	0.7664	0.6307
0.2	0.5273	0.2832	0.2013	0.8738	0.5294	0.3985	1.1025	0.7662	0.6295
0.216	0.5520	0.2972	0.2109	0.8830	0.5344	0.4024	1.1034	0.7647	0.6286
0.2333	0.5753	0.3098	0.2202	0.8900	0.5400	0.4063	1.1027	0.7641	0.6268
0.25	0.5964	0.3217	0.2293	0.8960	0.5432	0.4112	1.1014	0.7631	0.6247

Table 6. TN-LC wet/dry basket and canister cases, metal basket model.

Canister Water Density (g/cm³)	0			0.5			1		
Basket Water Density (g/cm³)	0	0.5	1	0	0.5	1	0	0.5	1
Neutron Poison Layer Thickness (cm)	0.1076								
Areal Density (g $^{10}B/cm^2$)	0.0226								
UO_2 VF	k_{eff}								
0.1	0.2939	0.1419	0.0974	0.7315	0.4295	0.3214	1.0156	0.7098	0.5938
0.116	0.3290	0.1593	0.1097	0.7525	0.4414	0.3307	1.0304	0.7214	0.5991
0.133	0.3618	0.1760	0.1208	0.7686	0.4514	0.3389	1.0404	0.7254	0.6032
0.15	0.3923	0.1909	0.1316	0.7820	0.4613	0.3452	1.0478	0.7302	0.6057
0.166	0.4207	0.2057	0.1421	0.7957	0.4687	0.3521	1.0513	0.7320	0.6066
0.1833	0.4478	0.2195	0.1521	0.8048	0.4752	0.3566	1.0545	0.7311	0.6057
0.2	0.4735	0.2332	0.1618	0.8144	0.4805	0.3608	1.0558	0.7306	0.6040
0.216	0.4970	0.2458	0.1714	0.8225	0.4865	0.3671	1.0574	0.7296	0.6019
0.2333	0.5201	0.2580	0.1806	0.8293	0.4912	0.3705	1.0561	0.7275	0.6010
0.25	0.5417	0.2699	0.1887	0.8366	0.4957	0.3734	1.0552	0.7257	0.5967

Table 7. TN-LC wet/dry basket and canister cases, metal basket model.

Canister Water Density (g/cm³)	0			0.5			1		
Basket Water Density (g/cm³)	0	0.5	1	0	0.5	1	0	0.5	1
Neutron Poison Layer Thickness (cm)	0.1564								
Areal Density (g $^{10}B/cm^2$)	0.0329								
UO_2 VF	k_{eff}								
0.1	0.2625	0.1251	0.0860	0.6916	0.4074	0.3052	0.9866	0.6958	0.5838
0.116	0.2954	0.1408	0.0971	0.7114	0.4195	0.3151	1.0006	0.7042	0.5893
0.133	0.3265	0.1561	0.1072	0.7285	0.4284	0.3220	1.0107	0.7098	0.5940
0.15	0.3551	0.1703	0.1179	0.7425	0.4374	0.3298	1.0161	0.7119	0.5943
0.166	0.3828	0.1838	0.1277	0.7534	0.4451	0.3362	1.0215	0.7142	0.5941
0.1833	0.4090	0.1970	0.1373	0.7642	0.4505	0.3410	1.0246	0.7131	0.5938
0.2	0.4333	0.2100	0.1462	0.7732	0.4566	0.3439	1.0247	0.7122	0.5931
0.216	0.4566	0.2221	0.1549	0.7830	0.4604	0.3485	1.0254	0.7104	0.5913
0.2333	0.4791	0.2336	0.1638	0.7904	0.4659	0.3518	1.0248	0.7089	0.5873
0.25	0.5004	0.2446	0.1725	0.7972	0.4699	0.3562	1.0238	0.7063	0.5854

Table 8. TN-LC wet/dry basket and canister cases, metal basket model.

Canister Water Density (g/cm^3)	0			0.5			1		
Basket Water Density (g/cm^3)	0	0.5	1	0	0.5	1	0	0.5	1
Neutron Poison Layer Thickness (cm)	0.2052								
Areal Density (g ^{10}B/cm^2)	0.0431								
UO_2 VF	k_{eff}								
0.1	0.2389	0.1146	0.0799	0.6620	0.3924	0.2973	0.9651	0.6853	0.5780
0.116	0.2702	0.1294	0.0903	0.6816	0.4038	0.3074	0.9778	0.6932	0.5849
0.133	0.2992	0.1440	0.1003	0.6991	0.4136	0.3133	0.9874	0.6979	0.5870
0.15	0.3272	0.1577	0.1100	0.7117	0.4211	0.3196	0.9955	0.7004	0.5893
0.166	0.3536	0.1709	0.1195	0.7234	0.4284	0.3257	0.9991	0.7019	0.5887
0.1833	0.3785	0.1831	0.1284	0.7342	0.4341	0.3307	1.0026	0.7016	0.5875
0.2	0.4022	0.1951	0.1376	0.7436	0.4400	0.3348	1.0043	0.7007	0.5863
0.216	0.4254	0.2070	0.1460	0.7524	0.4441	0.3387	1.0011	0.6991	0.5837
0.2333	0.4469	0.2181	0.1543	0.7589	0.4494	0.3420	1.0012	0.6964	0.5811
0.25	0.4677	0.2289	0.1630	0.7660	0.4539	0.3452	1.0009	0.6941	0.5780

Table 9. TN-LC wet/dry basket and canister cases, metal basket model.

Canister Water Density (g/cm^3)	0			0.5			1		
Basket Water Density (g/cm^3)	0	0.5	1	0	0.5	1	0	0.5	1
Neutron Poison Layer Thickness (cm)	0.254								
Areal Density (g ^{10}B/cm^2)	0.0534								
UO_2 VF	k_{eff}								
0.1	0.2208	0.1076	0.0761	0.6403	0.3815	0.2914	0.9478	0.6769	0.5741
0.116	0.2504	0.1216	0.0859	0.6603	0.3926	0.3000	0.9615	0.6850	0.5796
0.133	0.2781	0.1351	0.0956	0.6747	0.4019	0.3077	0.9700	0.6907	0.5841
0.15	0.3048	0.1480	0.1046	0.6882	0.4102	0.3134	0.9769	0.6935	0.5856
0.166	0.3298	0.1609	0.1137	0.6998	0.4168	0.3195	0.9804	0.6936	0.5844
0.1833	0.3543	0.1726	0.1228	0.7104	0.4227	0.3237	0.9824	0.6931	0.5843
0.2	0.3774	0.1847	0.1310	0.7190	0.4280	0.3283	0.9835	0.6925	0.5832
0.216	0.3990	0.1958	0.1400	0.7265	0.4330	0.3321	0.9840	0.6907	0.5795
0.2333	0.4199	0.2069	0.1483	0.7342	0.4379	0.3366	0.9829	0.6882	0.5755
0.25	0.4406	0.2179	0.1560	0.7419	0.4415	0.3387	0.9811	0.6854	0.5735

Tables 10 through 12 (in increasing foam density order) provide results of the dry basket, wet canister (water density of 1 g/cm^3) scoping calculations for the foam basket model. Package reactivity increases with decreasing basket foam density and decreasing ^{10}B areal density. Peak reactivity occurs between 20% and 25% VF UO_2. These are the limiting cases.

Table 10. TN-LC dry basket/wet canister cases, foam basket model.

Basket Foam Density (g/cm^3)	0.12								
Neutron Poison Layer Thickness (cm)	0.01			0.132			0.254		
Neutron Poison Layer Loading (wt% B)	5	12.5	20	5	12.5	20	5	12.5	20
Areal Density (g ^{10}B/cm^2)	0.0007	0.0017	0.0028	0.0091	0.0228	0.0365	0.0176	0.0439	0.0702
UO_2 VF	k_{eff}								
0.1	1.1716	1.1422	1.1229	1.0502	0.9886	0.9547	1.0059	0.9409	0.9038
0.116	1.1894	1.1592	1.1395	1.0663	1.0040	0.9695	1.0196	0.9535	0.9162
0.133	1.2011	1.1724	1.1504	1.0771	1.0141	0.9789	1.0301	0.9624	0.9252
0.15	1.2080	1.1788	1.1590	1.0850	1.0209	0.9843	1.0385	0.9674	0.9303
0.166	1.2132	1.1841	1.1641	1.0895	1.0245	0.9877	1.0419	0.9726	0.9337
0.1833	1.2161	1.1888	1.1671	1.0931	1.0282	0.9913	1.0450	0.9735	0.9351
0.2	1.2172	1.1894	1.1688	1.0942	1.0277	0.9917	1.0464	0.9755	0.9354
0.216	1.2164	1.1888	1.1686	1.0947	1.0294	0.9917	1.0462	0.9752	0.9361
0.2333	1.2164	1.1896	1.1701	1.0948	1.0289	0.9913	1.0457	0.9747	0.9349
0.25	1.2143	1.1871	1.1676	1.0942	1.0288	0.9910	1.0449	0.9720	0.9334

Table 11. TN-LC dry basket/wet canister cases, foam basket model.

Basket Foam Density (g/cm^3)	0.22								
Neutron Poison Layer Thickness (cm)	0.01			0.132			0.254		
Neutron Poison Layer Loading (wt% B)	5	12.5	20	5	12.5	20	5	12.5	20
Areal Density (g ^{10}B/cm^2)	0.0007	0.0017	0.0028	0.0091	0.0228	0.0365	0.0176	0.0439	0.0702
UO_2 VF	k_{eff}								
0.1	1.1550	1.1238	1.1024	1.0309	0.9688	0.9354	0.9860	0.9206	0.8854
0.116	1.1707	1.1409	1.1185	1.0461	0.9826	0.9498	0.9998	0.9351	0.8969
0.133	1.1827	1.1524	1.1321	1.0565	0.9928	0.9583	1.0097	0.9421	0.9059
0.15	1.1910	1.1610	1.1387	1.0634	0.9998	0.9638	1.0171	0.9487	0.9110
0.166	1.1956	1.1666	1.1446	1.0684	1.0033	0.9674	1.0205	0.9525	0.9138
0.1833	1.1979	1.1694	1.1475	1.0723	1.0072	0.9693	1.0239	0.9543	0.9150
0.2	1.2005	1.1718	1.1494	1.0730	1.0076	0.9709	1.0243	0.9543	0.9173
0.216	1.2010	1.1715	1.1496	1.0741	1.0077	0.9705	1.0251	0.9553	0.9158
0.2333	1.1994	1.1711	1.1508	1.0744	1.0080	0.9708	1.0251	0.9537	0.9145
0.25	1.1980	1.1700	1.1490	1.0729	1.0070	0.9694	1.0242	0.9529	0.9131

Table 12. TN-LC dry basket/wet canister cases, foam basket model.

Basket Foam Density (g/cm^3)	0.32								
Neutron Poison Layer Thickness (cm)	0.01			0.132			0.254		
Neutron Poison Layer Loading (wt% B)	5	12.5	20	5	12.5	20	5	12.5	20
Areal Density (g ^{10}B/cm^2)	0.0007	0.0017	0.0028	0.0091	0.0228	0.0365	0.0176	0.0439	0.0702
UO_2 VF	k_{eff}								
0.1	1.1348	1.1043	1.0820	1.0111	0.9494	0.9164	0.9668	0.9031	0.8679
0.116	1.1534	1.1215	1.0991	1.0258	0.9638	0.9295	0.9801	0.9162	0.8790
0.133	1.1640	1.1336	1.1109	1.0366	0.9727	0.9384	0.9901	0.9238	0.8875
0.15	1.1734	1.1408	1.1192	1.0425	0.9800	0.9442	0.9964	0.9291	0.8925
0.166	1.1782	1.1456	1.1244	1.0477	0.9826	0.9480	1.0012	0.9330	0.8955
0.1833	1.1805	1.1497	1.1277	1.0514	0.9868	0.9497	1.0033	0.9335	0.8961
0.2	1.1822	1.1519	1.1289	1.0526	0.9862	0.9497	1.0051	0.9351	0.8966
0.216	1.1819	1.1528	1.1301	1.0541	0.9870	0.9497	1.0043	0.9353	0.8958
0.2333	1.1826	1.1518	1.1293	1.0532	0.9861	0.9497	1.0040	0.9337	0.8956
0.25	1.1819	1.1513	1.1290	1.0512	0.9860	0.9472	1.0028	0.9328	0.8933

4.3.1.2 TN-LC Boundary Condition Sensitivity

Assessment of TN-LC package criticality in the preceding section assumes reflective boundary conditions at the outer surface with no credit for spacing between packages due to neutron absorber boxes, impact limiters, or shipment configuration. The reflective boundary condition essentially models a large number of packages in contact with each other. This is conservative for NCT and bounding for HAC involving multiple packages. However, 10 CFR 71 (c) (3) allows for exclusive use conveyance, which can be limited to a single package. For a single package, the transportation model reflective boundary condition may be relaxed.

Table 13 provides results of the TN-LC model for the highest reactivity case from Table 4 (20% UO_2 VF, 80% water VF in the canister, dry basket) with all neutron poison removed using three different boundary conditions:

- Reflective at the package outer wall
- Vacuum outside of a 50-cm-thick air region around the package
- Vacuum outside of a 50-cm-thick full density water region around the package.

The boundary condition relaxation reduces k_{eff} by about 0.25 Δk. The need for neutron absorber and foam in the TN-LC package could be greatly reduced by use of a vacuum boundary if exclusive use conveyance is considered.

Table 13. TN-LC boundary condition effect (no basket foam or neutron absorber).

Boundary Condition	k_{eff}
Reflective at package outer surface	1.259
Vacuum at surface of 50-cm-thick air region outside package outer surface	0.997
Vacuum at surface of 50-cm-thick water region outside package outer surface	1.013

4.3.1.3 TN-LC TSUNAMI Results

TSUNAMI calculations are performed to identify critical experiments with cross section uncertainty sensitivity that is similar to an application model (J. M. Scaglione 2012). Application model sensitivity depends on design features, as well as conditions modeled, so TSUNAMI results are of primary interest for the most limiting criticality analysis cases (limiting conditions). Similarity is quantified in a single term, the correlation coefficient c_k, which relates the degree to which the uncertainties in the critical benchmarks are coupled with the uncertainties in the application of interest. A value of 0.8 or higher is desirable in order to consider a critical experiment highly relevant for benchmarking.

Two application models are considered for the TN-LC: One from the leftmost column of Table 10 (wet fuel, dry basket, low-density foam, and low ^{10}B areal density) and one from the rightmost column of Table 11 (wet fuel, dry basket, mid-density foam, and high ^{10}B areal density). These models will be designated Case 1 and Case 2, respectively.

Figure 6 shows the c_k values for 1,584 available critical experiments evaluated for Case 1. TSUNAMI identified 130 critical experiments with $c_k \geq 0.8$, all of which are from the "LEU-comp-therm" (LCT; low-enriched uranium, compound fuel form, thermal neutron spectrum) group. The correlation coefficient c_k is weakly inversely correlated to ^{235}U enrichment (Figure 7), which indicates that enrichment is not, in and of itself, indicative of similarity between the application model and a critical experiment. Figure 8 shows that normalized k_{eff} shows little bias versus c_k and that the group of experiments most closely correlated to the TN-LC design are clustered near $k_{eff} = 1$. This application model has a sufficient number of neutronically similar critical experiments for criticality analysis benchmarking.

For Case 2, TSUNAMI identified no critical experiments with $c_k \geq 0.8$. Figure 9 shows the c_k values for the 1,584 critical experiments evaluated. As in the first case, c_k is weakly inversely correlated to ^{235}U enrichment (Figure 10). Figure 11 shows that normalized k_{eff} shows little bias versus c_k and that the group of experiments most closely correlated to the TN-LC design are clustered near $k_{eff} = 1$.

Benchmarking calculations for the TN-LC with this set of design features and conditions would require determination of an appropriate k_{eff} penalty due to the lack of experiments with $c_k \geq 0.8$. The SCALE 6.2.3 implementation of TSUNAMI includes a method for determining a subcritical margin penalty for applications with inadequate experiment coverage based on c_k. The penalty method relaxes the global c_k requirement and determines whether adequate sensitivity coverage exists at the individual reaction and individual energy group level within the population of near-similar experiments. For group-wise nuclide-reaction-specific sensitivity coefficients for the application that are not fully covered by the experiments, the uncovered portion of the sensitivity coefficient is used to compute an uncertainty in k_{eff} though the cross section covariance data. For TN-LC Case 2, there are 258 experiments with $c_k \geq 0.7$ that are candidates for the penalty method.

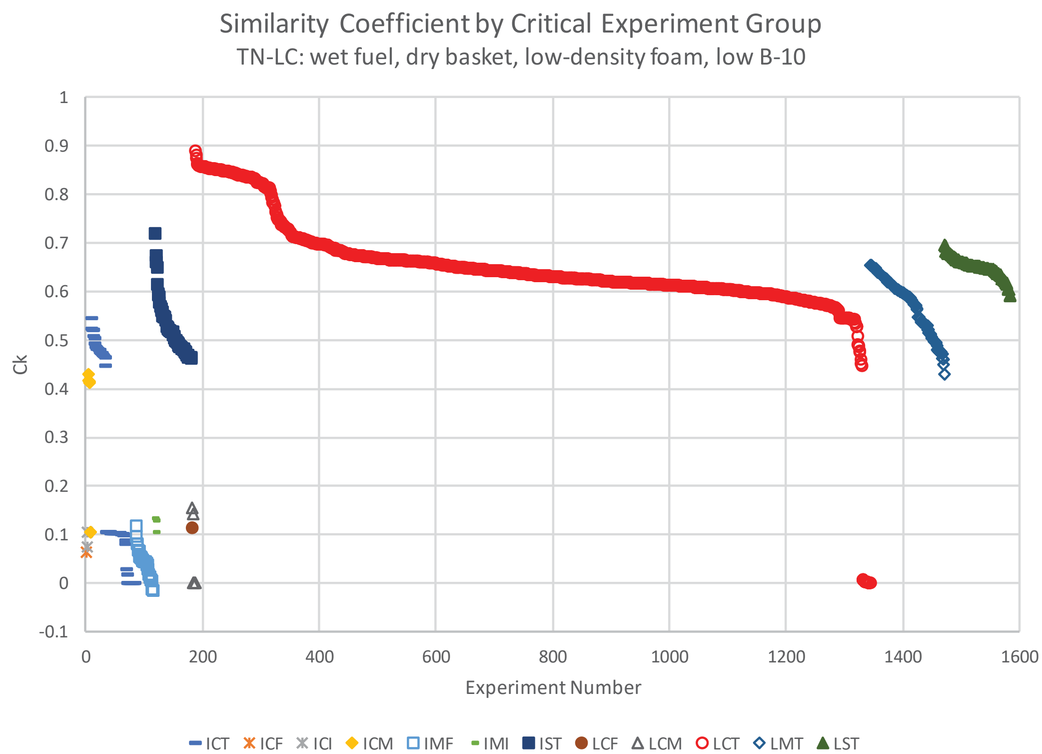


Figure 6. TN-LC Case 1 c_k.

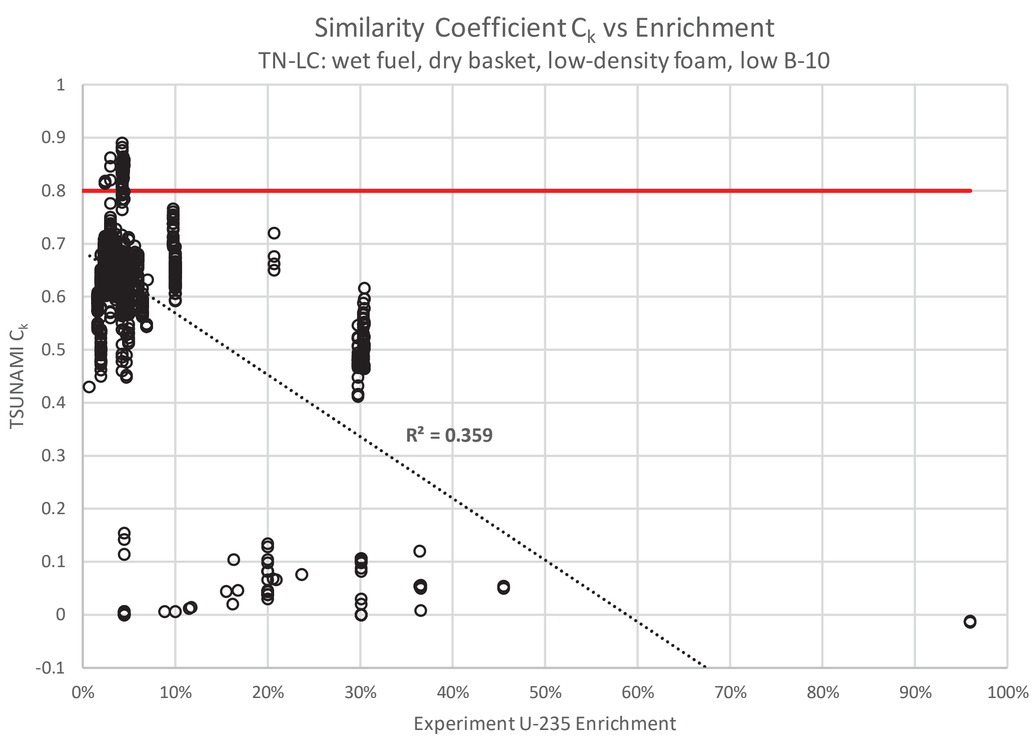


Figure 7. TN-LC Case 1 c_k versus ^{235}U enrichment.

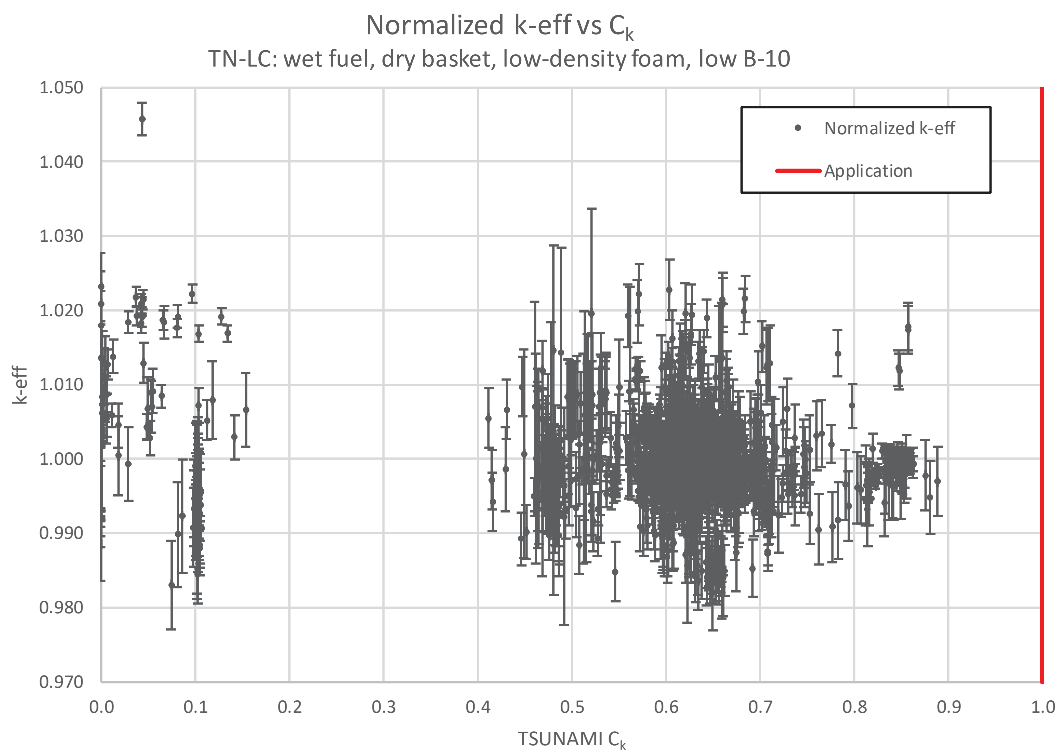


Figure 8. TN-LC Case 1 normalized k_{eff} versus c_k.

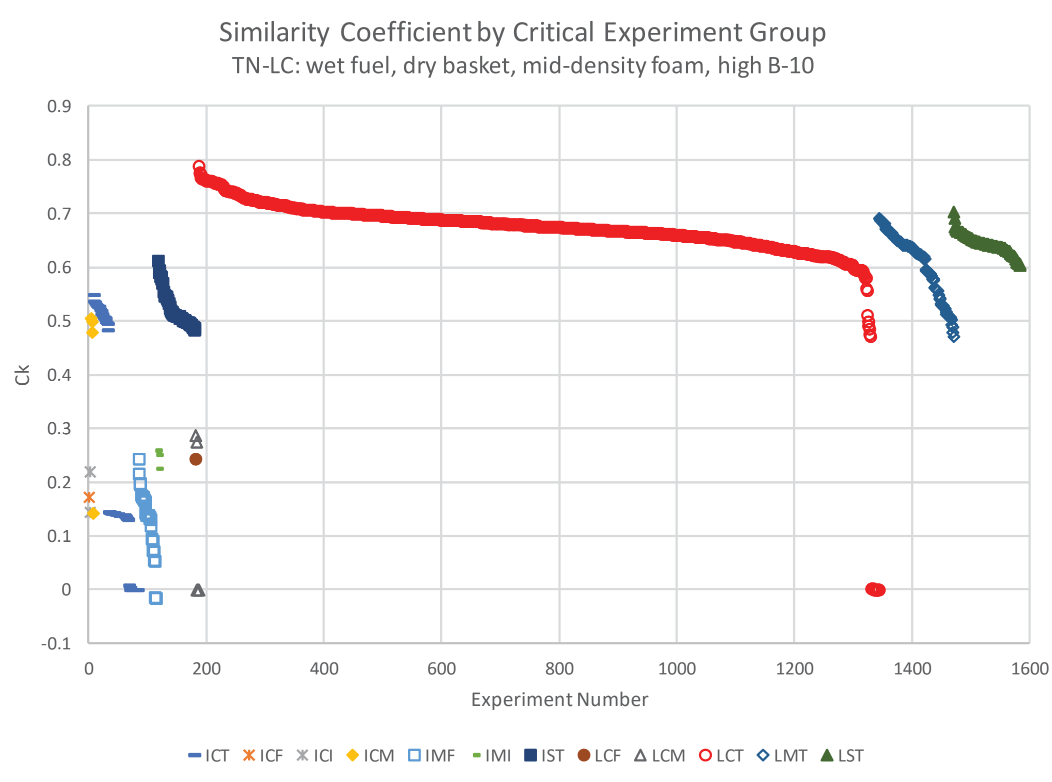


Figure 9. TN-LC Case 2 c_k.

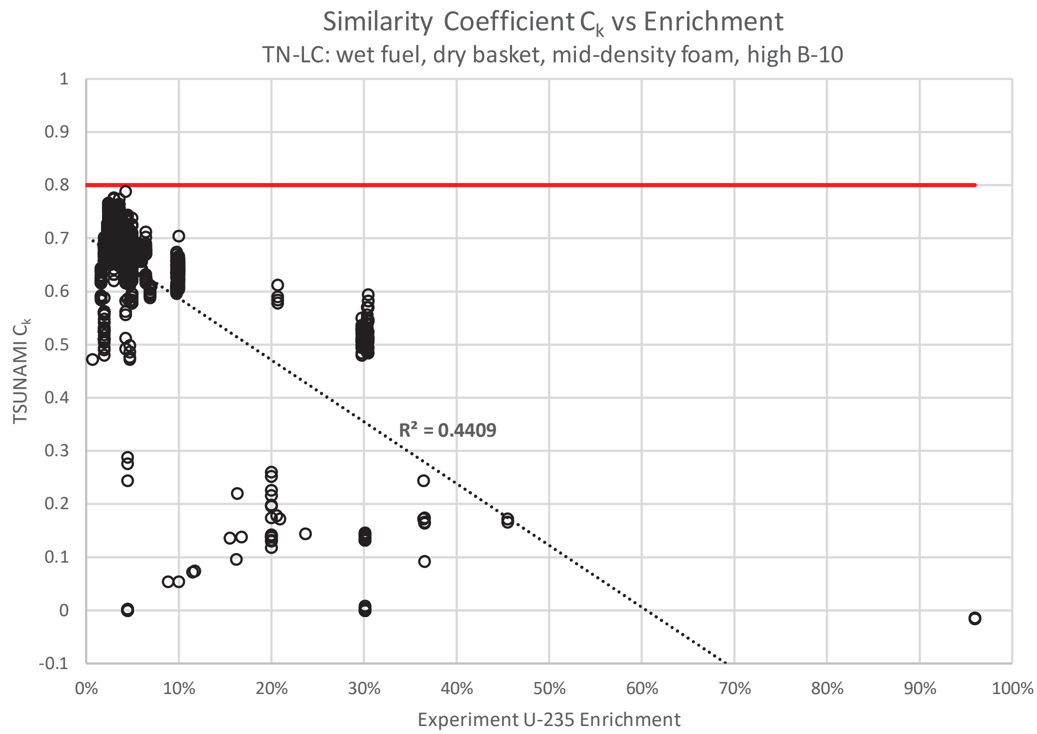


Figure 10. TN-LC Case 2 c_k versus ^{235}U enrichment.

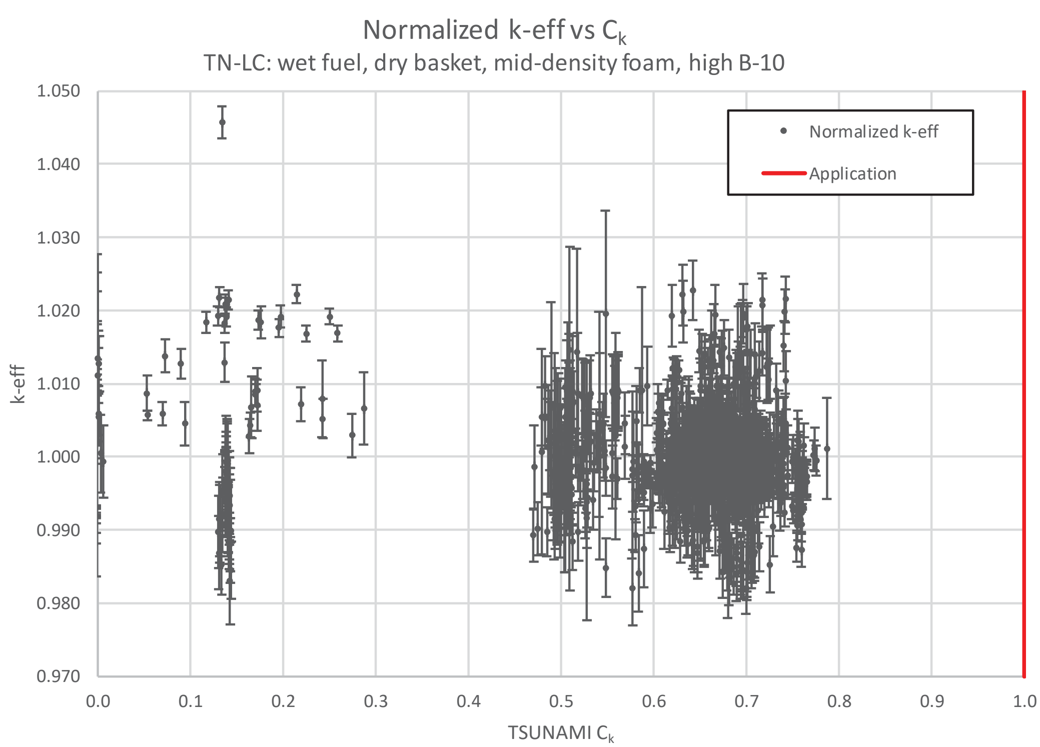


Figure 11. TN-LC Case 2 normalized k_{eff} versus c_k.

4.3.2 OPTIMUS™-L Subcriticality

Criticality calculations for the OPTIMUS™-L package are performed using the SCALE version 6.2.3 CSAS6 sequence, which performs k_{eff} calculations with KENO-VI. The ENDF version 7.1 252 group cross sections are used for the preliminary HALEU package assessment (Rearden and Jessee 2018). A cross section and a cutaway view of the simplified KENO model of the OPTIMUS™-L package containing 38 HALEU canisters is shown in Figure 12. Some basket details are omitted for simplicity.

The design and size of the OPTIMUS basket necessitates additional criticality control features. As in the TN-LC analysis, borated metal coating is added to the outer surface of the canisters. Analysis cases with no foam represent the metal basket design. For most of the analysis cases, foam (white space in the cross-sectional view in Figure 12) is placed in the metal basket spaces between canister storage holes to serve as a moderating material that enhances the flux trap effect of the borated metal surfaces. These cases conservatively bound the all-foam basket design. Select all-foam basket cases are provided to confirm the effect of replacing the basket steel with foam. Dark shading around the canisters in Figure 12 is void (dry basket cases) or water (wet basket cases).

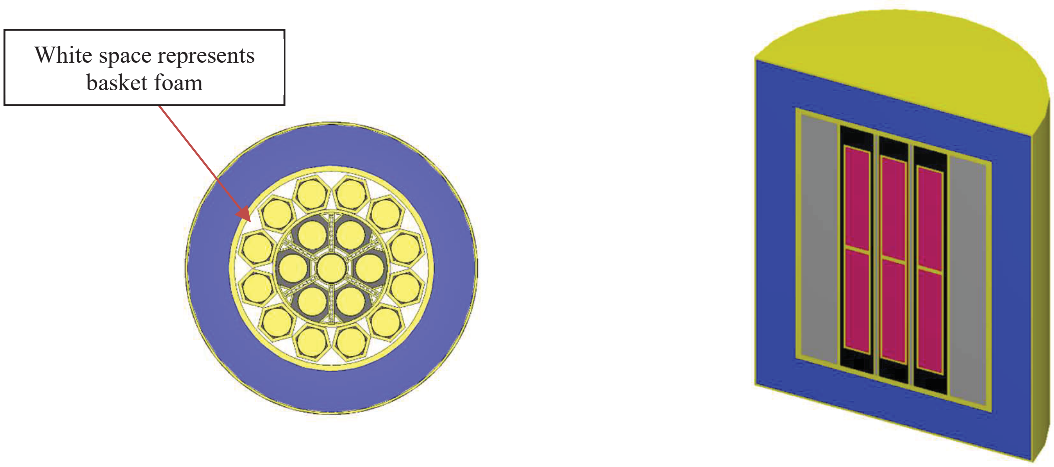


Figure 12. Cross section and cutaway view of OPTIMUS™-L KENO criticality model.

The OPTIMUS™-L package is modeled as an outside cylinder of 304 stainless steel with a layer of foam impact limiter inside. The impact limiter is modeled as balsa. Sensitivity cases indicate that k_{eff} is higher with balsa impact limiter than with higher-density foam. A cylinder of steel is inside the impact limiter. The basket with HALEU canisters resides inside this inner steel cylinder. Reflective boundary conditions are used to bound an array of packages. Fuel is assumed to be UO_2 at 20 wt% ^{235}U with a nominal packing fraction of 62%.

Calculations are performed to establish reactivity trends, associated neutron absorber thickness and loading (areal density) in the layer around the canister, and the density of the basket foam (if present in the model). Water intrusion is assumed to occur. The effect of water in differing amounts and in different portions of the package include these conditions:

- **Dry conditions.** Both the canister and the basket are assumed to be dry. This is the expected normal condition. For trending, UO_2 VFs of 100% and 62% are considered.
- **Wet canister with dry basket.** This scenario assumes water intrusion in the fuel canisters but dry (or drained) conditions in the packaging cavity. For these cases, a range of water and UO_2 volume fractions are considered. Previous scoping studies show the bounding UO_2 volume fraction is around 0.2; therefore, calculations consider a range from about 0.15 to 0.25 to establish the peak.
- **Wet canister with wet basket.** This scenario assumes water intrusion in the fuel canisters and the package cavity. These calculations establish the reactivity effect of moderator in the basket with no basket foam present.

Trends determined from combinations of wet/dry basket and wet/dry canister TN-LC cases with no basket foam are not expected to change for the OPTIMUS™-L and are not repeated.

4.3.2.1 OPTIMUS™-L Criticality Results

Table 14 provides results of the dry basket/dry canister scoping calculations for the metal basket model. Package reactivity increases with decreasing ^{10}B areal density and increasing UO_2 VF.

Table 14. OPTIMUS™-L dry basket/dry canister cases, metal basket model.

Areal Density (g $^{10}B/cm^2$)	0.00069	0.00912	0.01755	0.00173	0.02280	0.04388	0.00276	0.03649	0.07021
Neutron Poison Layer Thickness (cm)	0.01			0.132			0.254		
Neutron Poison Layer Loading (wt% B)	5	12.5	20	5	12.5	20	5	12.5	20
UO_2 VF = 1, k_{eff}	0.8840	0.8739	0.8666	0.8621	0.8425	0.8246	0.8478	0.8184	0.7941
UO_2 VF = 0.62, k_{eff}	0.7113	0.7008	0.6917	0.6850	0.6634	0.6457	0.6662	0.6366	0.6137

Table 15 provides results of the dry basket/dry canister scoping calculations with varying densities of foam in the metal basket segment spaces. Package reactivity increases with decreasing ^{10}B areal density, decreasing foam density, and increasing UO_2 VF.

Table 15. OPTIMUS™-L dry basket/dry canister cases, foam in basket spaces.

Areal Density (g $^{10}B/cm^2$)	0.00069	0.00912	0.01755	0.00173	0.02280	0.04388	0.00276	0.03649	0.07021
Basket Foam Density (g/cm^3)	0.12								
Neutron Poison Layer Thickness (cm)	0.01			0.132			0.254		
Neutron Poison Layer Loading (wt% B)	5	12.5	0.32						
UO_2 VF = 1, k_{eff}	0.8846	0.8737	0.8641	0.8634	0.8378	0.8191	0.8462	0.8120	0.7861
UO_2 VF = 0.62, k_{eff}	0.7160	0.7028	0.6923	0.6882	0.6620	0.6423	0.6684	0.6332	0.6092
Basket Foam Density (g/cm^3)	0.22								
Neutron Poison Layer Thickness (cm)	0.01			0.132			0.254		
Neutron Poison Layer Loading (wt% B)	5	12.5	0.32						
UO_2 VF = 1, k_{eff}	0.8851	0.8709	0.8599	0.8603	0.8336	0.8131	0.8439	0.8060	0.7792
UO_2 VF = 0.62, k_{eff}	0.7177	0.7022	0.6900	0.6880	0.6592	0.6385	0.6680	0.6284	0.6032
Basket Foam Density (g/cm^3)	0.32								
Neutron Poison Layer Thickness (cm)	0.01			0.132			0.254		
Neutron Poison Layer Loading (wt% B)	5	12.5	0.32						
UO_2 VF = 1, k_{eff}	0.8832	0.8669	0.8549	0.8584	0.8279	0.8062	0.8410	0.7996	0.7708
UO_2 VF = 0.62, k_{eff}	0.7174	0.7003	0.6864	0.6874	0.6547	0.6325	0.6671	0.6236	0.5974

Tables 16 through 18 (in increasing foam density order) provide results for the dry basket/wet canister (water density of 1 g/cm^3) scoping calculations with foam in the metal basket segment spaces. Results for select all-foam basket cases are also provided. Replacing the mixed metal and foam basket with an all-foam basket reduces k_{eff}. Package reactivity increases with decreasing amounts of basket foam and decreasing ^{10}B areal density. Peak reactivity occurs near 20% VF UO_2. These are the limiting cases.

Table 16. OPTIMUS™-L dry basket/wet canister cases, foam in basket spaces.

Basket Foam Density (g/cm^3)	0.12								
Neutron Poison Layer Loading (wt% B)	5			12.5			20		
Neutron Poison Layer Thickness (cm)	0.01	0.132	0.254	0.01	0.132	0.254	0.01	0.132	0.254
Areal Density (g ^{10}B/cm^2)	0.0007	0.0091	0.0176	0.0017	0.0228	0.0439	0.0028	0.0365	0.0702
UO_2 VF	k_{eff}								
0.15	1.0688	1.0190	0.9990	1.0327	0.9660	0.9428	1.0099	0.9356	0.9115
0.16	1.0708	1.0228	1.0005	1.0352	0.9677	0.9445	1.0118	0.9359	0.9118
0.17	1.0729	1.0233	1.0032	1.0369	0.9697	0.9455	1.0134	0.9390	0.9146
0.18	1.0740	1.0247	1.0039	1.0379	0.9716	0.9476	1.0161	0.9401	0.9152
0.19	1.0742	1.0261	1.0053	1.0385	0.9720	0.9478	1.0165	0.9404	0.9162
0.2	1.0750	1.0272	1.0058	1.0382	0.9724	0.9488	1.0158	0.9397	0.9159
0.2*			0.9944			0.9332			0.8995
0.21	1.0751	1.0266	1.0050	1.0387	0.9721	0.9485	1.0152	0.9404	0.9158
0.22	1.0739	1.0256	1.0047	1.0388	0.9722	0.9482	1.0148	0.9405	0.9150
0.23	1.0728	1.0265	1.0036	1.0366	0.9704	0.9473	1.0137	0.9395	0.9146
0.24	1.0712	1.0247	1.0040	1.0365	0.9711	0.9465	1.0137	0.9395	0.9132
0.25	1.0704	1.0238	1.0018	1.0346	0.9697	0.9443	1.0125	0.9382	0.9129
**Basket is all foam*									

Table 17. OPTIMUS™-L dry basket/wet canister cases, foam in basket spaces.

Basket Foam Density (g/cm^3)	0.22								
Neutron Poison Layer Loading (wt% B)	5			12.5			20		
Neutron Poison Layer Thickness (cm)	0.01	0.132	0.254	0.01	0.132	0.254	0.01	0.132	0.254
Areal Density (g ^{10}B/cm^2)	0.0007	0.0091	0.0176	0.0017	0.0228	0.0439	0.0028	0.0365	0.0702
UO_2 VF	k_{eff}								
0.15	1.0615	1.0120	0.9909	1.0267	0.9585	0.9339	1.0035	0.9275	0.9023
0.16	1.0644	1.0144	0.9929	1.0285	0.9615	0.9365	1.0060	0.9294	0.9047
0.17	1.0660	1.0166	0.9954	1.0302	0.9621	0.9379	1.0082	0.9317	0.9071
0.18	1.0675	1.0180	0.9975	1.0318	0.9633	0.9398	1.0088	0.9322	0.9078
0.19	1.0683	1.0187	0.9975	1.0321	0.9650	0.9408	1.0105	0.9332	0.9087
0.2	1.0683	1.0193	0.9984	1.0310	0.9645	0.9413	1.0095	0.9333	0.9080
0.21	1.0689	1.0202	0.9986	1.0311	0.9645	0.9404	1.0091	0.9330	0.9080
0.22	1.0673	1.0191	0.9974	1.0327	0.9644	0.9409	1.0094	0.9331	0.9076
0.23	1.0667	1.0183	0.9967	1.0324	0.9649	0.9401	1.0083	0.9327	0.9067
0.24	1.0661	1.0189	0.9963	1.0296	0.9632	0.9390	1.0072	0.9319	0.9052
0.25	1.0649	1.0174	0.9963	1.0294	0.9622	0.9375	1.0062	0.9307	0.9054

Table 18. OPTIMUS™-L dry basket/wet canister cases, foam in basket spaces.

Basket Foam Density (g/cm^3)	0.32								
Neutron Poison Layer Loading (wt% B)	5			12.5			20		
Neutron Poison Layer Thickness (cm)	0.01	0.132	0.254	0.01	0.132	0.254	0.01	0.132	0.254
Areal Density (g ^{10}B/cm^2)	0.0007	0.0091	0.0176	0.0017	0.0228	0.0439	0.0028	0.0365	0.0702
UO_2 VF	k_{eff}								
0.15	1.0554	1.0048	0.9841	1.0201	0.9509	0.9272	0.9974	0.9212	0.8962
0.16	1.0579	1.0076	0.9867	1.0222	0.9543	0.9298	0.9998	0.9231	0.8979
0.17	1.0598	1.0082	0.9876	1.0249	0.9548	0.9310	1.0026	0.9253	0.8997
0.18	1.0614	1.0104	0.9898	1.0254	0.9559	0.9331	1.0027	0.9251	0.9010
0.19	1.0620	1.0117	0.9896	1.0260	0.9573	0.9334	1.0039	0.9261	0.9011
0.2	1.0626	1.0121	0.9910	1.0267	0.9581	0.9335	1.0035	0.9262	0.9012
0.2*			0.9522			0.8905			0.8575
0.21	1.0618	1.0117	0.9905	1.0269	0.9578	0.9334	1.0044	0.9258	0.9003
0.22	1.0611	1.0115	0.9905	1.0264	0.9577	0.9332	1.0027	0.9267	0.9001
0.23	1.0611	1.0107	0.9899	1.0243	0.9574	0.9327	1.0019	0.9249	0.8992
0.24	1.0592	1.0106	0.9889	1.0250	0.9562	0.9318	1.0018	0.9244	0.8980
0.25	1.0582	1.0099	0.9867	1.0230	0.9553	0.9307	1.0010	0.9231	0.8980
*Basket is all foam									

4.3.2.2 OPTIMUS™-L Boundary Condition Sensitivity

Assessment of OPTIMUS™-L package criticality in the preceding section assumes reflective boundary conditions at the package body outer surface with no credit for spacing between packages due to impact limiters or shipment configuration. The reflective boundary condition essentially models a large number of packages in contact with each other. For a shipment of a known number of packages, the reflective boundary condition may be unnecessarily conservative.

Table 19 provides results of the TN-LC model for the highest reactivity case from Table 16 (21% UO_2 VF, 79% water VF in the canister, dry basket) with all neutron poison removed using three different boundary conditions:

- Reflective at the package outer wall
- Vacuum outside of a 50-cm-thick air region around the package
- Vacuum outside of a 50-cm-thick full density water region around the package.

The boundary condition relaxation reduces k_{eff} by about 0.11 Δk for a single package. The need for neutron absorber and basket foam in the OPTIMUS™-L package could be reduced by use of boundary conditions based on a pre-determined maximum number of packages.

Table 19. OPTIMUS™-L boundary condition effect (no basket foam or neutron absorber).

Boundary Condition	k_{eff}
Reflective at package outer surface	1.135
Vacuum at surface of 50-cm-thick air region outside package outer surface	1.017
Vacuum at surface of 50-cm-thick water region outside package outer surface	1.026

4.3.2.3 OPTIMUS™-L TSUNAMI Results

Two application models are considered for the OPTIMUS™-L: One from the leftmost column of Table 16 (wet fuel, dry basket, low-density foam, and low ^{10}B areal density) and one from the rightmost column of Table 17 (wet fuel, dry basket, mid-density foam, and high ^{10}B). These models will be designated Case 1 and Case 2, respectively.

Figure 13 shows the c_k values for the available 1,584 critical experiments evaluated for Case 1. TSUNAMI identified 163 critical experiments with $c_k \geq 0.8$, most of which are from the LCT group. The correlation coefficient c_k is weakly inversely correlated to ^{235}U enrichment (Figure 14), which indicates that enrichment is not, in and of itself, indicative of similarity between the application model and a critical experiment. Figure 15 shows that normalized k_{eff} shows little bias versus c_k and that the group of experiments most closely correlated to the OPTIMUS™-L design are clustered near $k_{eff} = 1$.

Figure 16 shows the c_k values for the 1,584 critical experiments evaluated for Case 2. TSUNAMI identified 74 critical experiments with $c_k \geq 0.8$, all of which are from the LCT group. As in the first case, c_k is weakly inversely correlated to ^{235}U enrichment (Figure 17). Figure 18 shows that normalized k_{eff} shows little bias versus c_k and that the group of experiments most closely correlated to the OPTIMUS™-L design are clustered near $k_{eff} = 1$.

Both application models considered have a sufficient number of neutronically similar critical experiments for criticality analysis benchmarking.

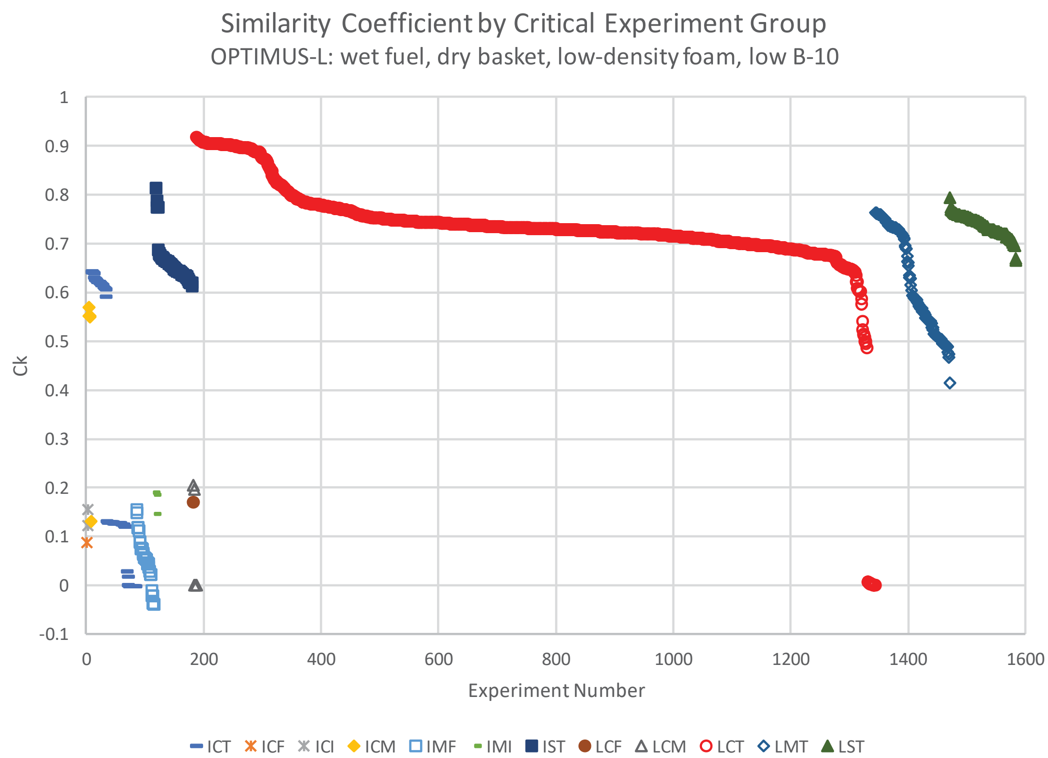


Figure 13. OPTIMUS™-L Case 1 c_k.

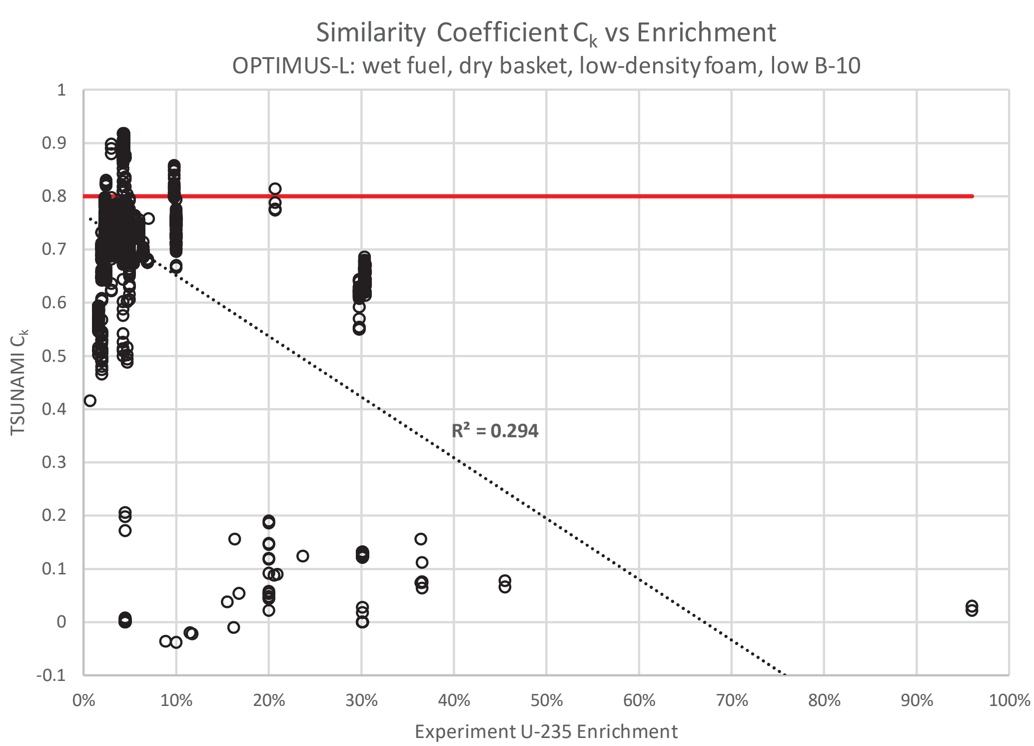


Figure 14. OPTIMUS™-L Case 1 c_k versus ^{235}U enrichment.

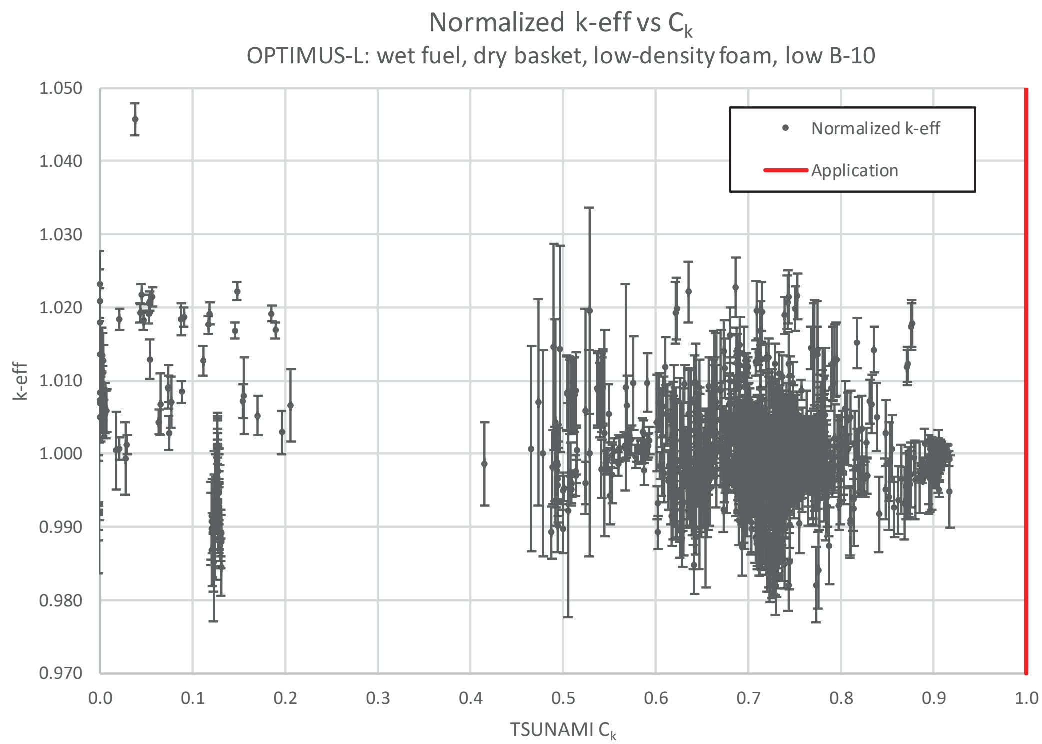


Figure 15. OPTIMUS™-L Case 1 normalized k_{eff} versus c_k.

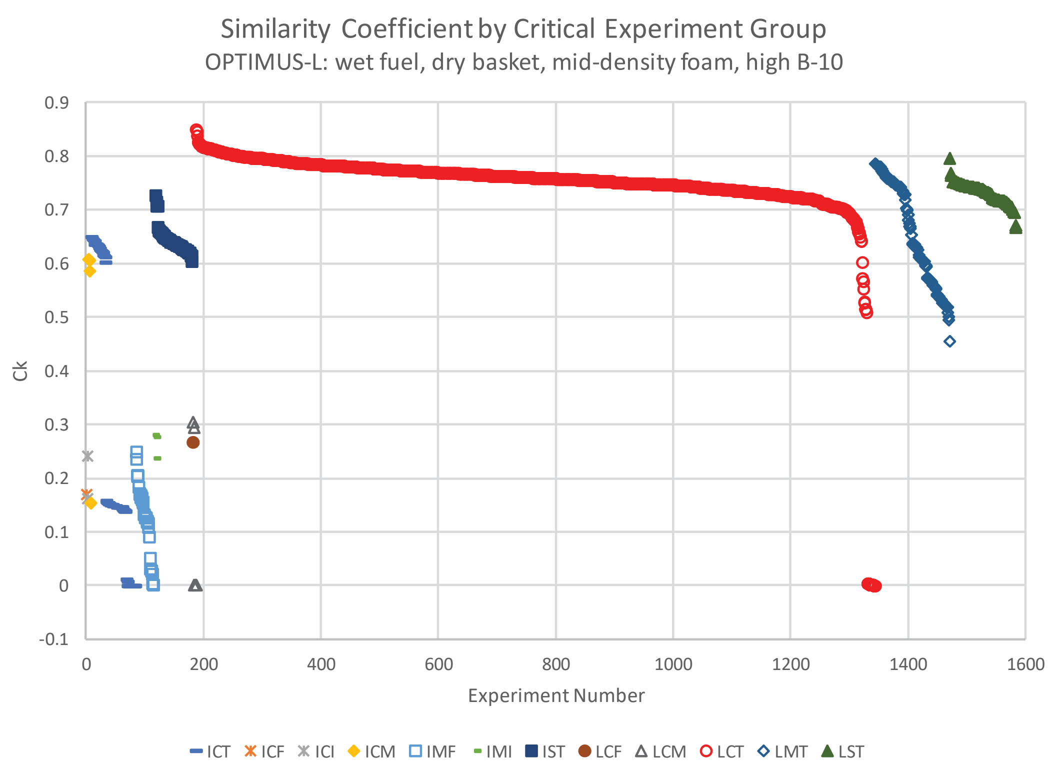


Figure 16. OPTIMUS™-L Case 2 c_k.

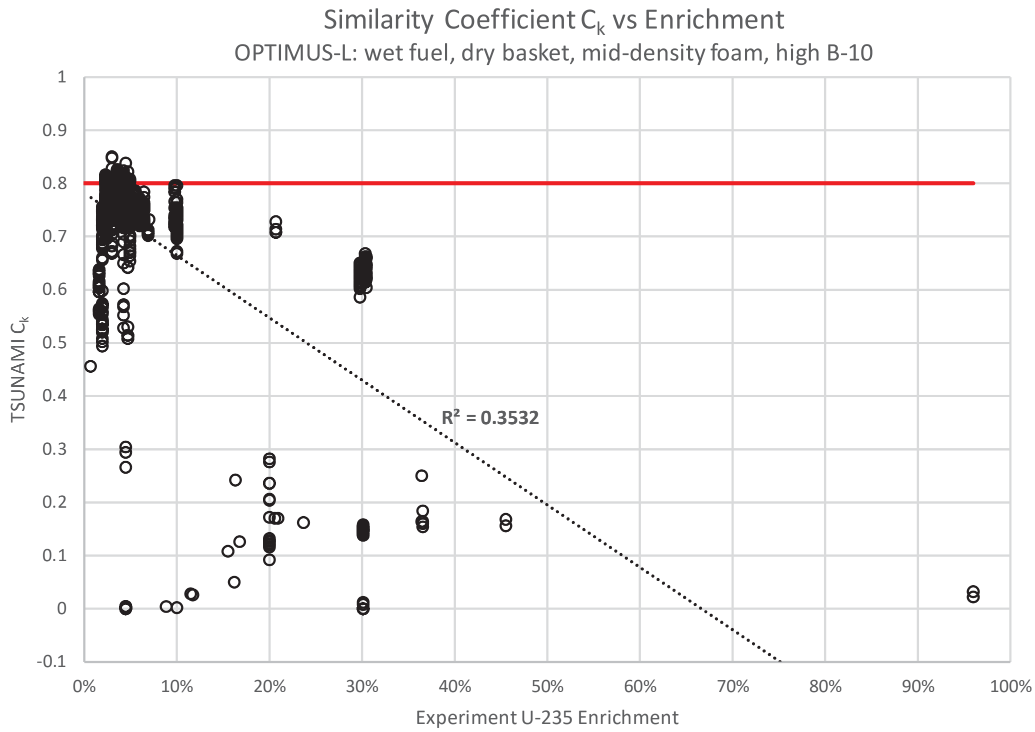


Figure 17. OPTIMUS™-L Case 2 c_k versus ^{235}U enrichment.

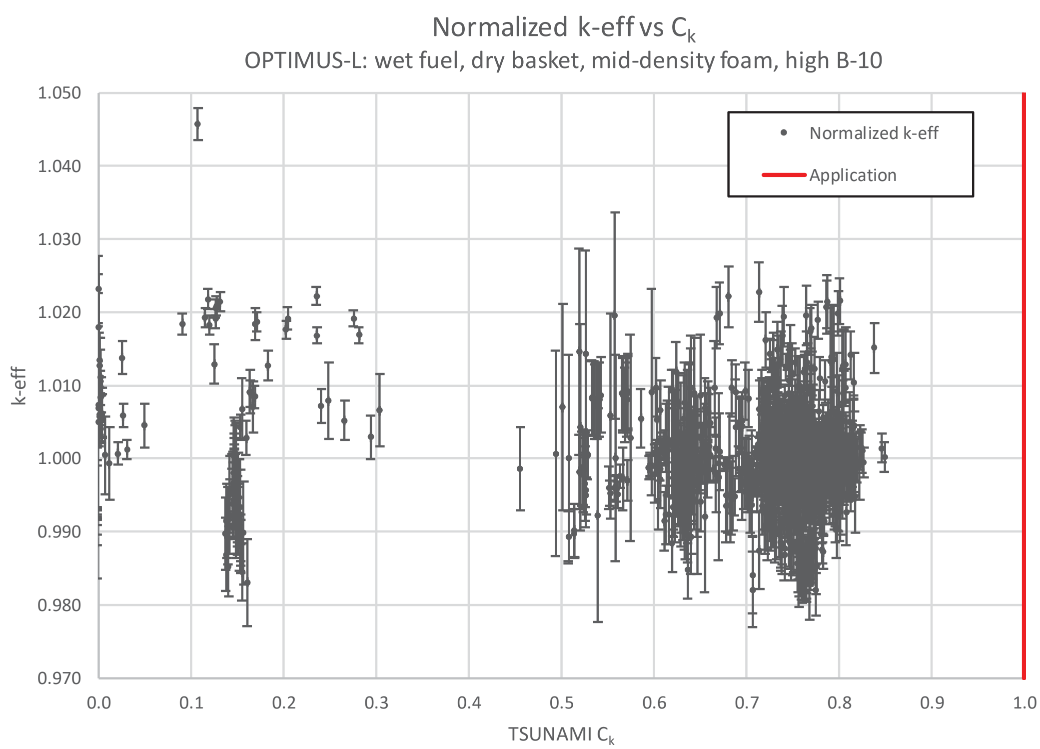


Figure 18. OPTIMUS™-L Case 2 normalized k_{eff} versus c_k.

4.4 Preliminary Package Shielding Assessment

Table 20 summarizes the regulatory compliance items considered in the preliminary review of shielding capability.

Table 20. Shielding compliance items.

Regulation	Condition	Limit	Evaluated?
10 CFR 71.47	NCT/Nonexclusive use shipment	200 mrem/hr @ surface 10 mrem/hr @ 1 m	Yes
10 CFR 71.47	NCT/Exclusive use shipment	200 mrem/hr @ surface 10 mrem/hr @ 2 m*	Yes
10 CFR 71.47	NCT/Exclusive use shipment	2 mrem/hr in an occupied space**	No
10 CFR 71.51	HAC	1000 mrem/hr @ 1 m	Yes

*Dose rate is conservatively assessed at 2 m from the package with no credit for additional distance provided by the position of the package on the vehicle.

**The occupied space limit is unlikely to be limiting and can be assessed when specific transportation configurations are known.

To provide flexibility depending on the cleanliness of the process for down-blended EBR-II HALEU, the program has opted to consider the application of two packaging displaying vastly different shielding capacities. The TN-LC has significant gamma and neutron shielding boundaries, whereas the OPTIMUS™-L offers only modest shielding capacity. In cases in which the HALEU cleanliness is less ideal than expected, the TN-LC would be the preferred packaging concept. This packaging is certified for high-burnup UNF and, as discussed below, and is not challenged by the anticipated payload of 1,600 kg when configured in the modular confinement system components. As also discussed, if the quality of the processed UO_2 powder is as anticipated, the OPTIMUS™-L provides enough shielding.

4.4.1 TN Americas TN-LC Shielding Capability

External DR calculations are performed using the MAVRIC code in SCALE 6.2.3 (Rearden and Jessee 2018). The TN-LC evaluation uses the v7-27n19g cross section library for the discrete ordinates portion of the calculation sequence and ENDF version 7.1 continuous energy cross sections coupled with ANSI/ANS-6.1.1-1991 flux-to-dose conversion factors for the DR calculations. The ORIGEN-S code is used to determine the neutron and gamma source strength based on the specified HALEU isotopic content. The DR calculation sequence, libraries, computer codes, and conversion factors are part of the SCALE 6.2.3 system.

For the evaluations, a simplified model assumes a TN-LC package loaded with the maximum anticipated amount of HALEU in 56 canisters. Figure 19 shows a cutaway view of the simplified SCALE/MAVRIC model.

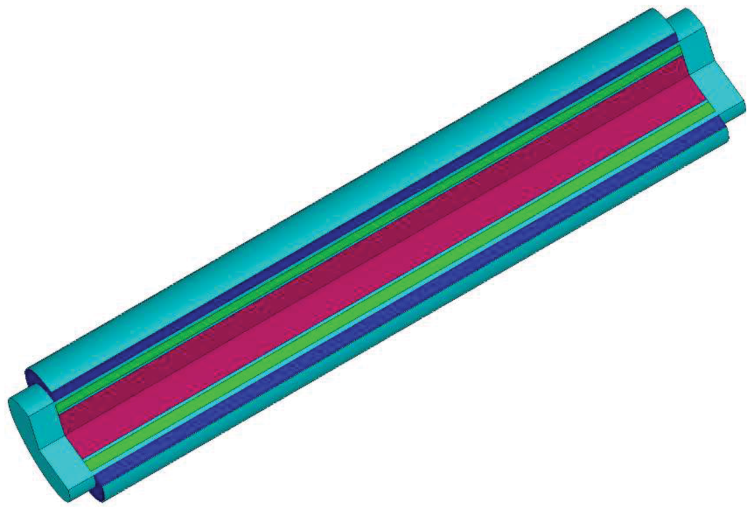


Figure 19. TN-LC SCALE/MAVRIC simplified model.

The HALEU source is assumed to be evenly distributed inside the package cavity. For simplicity, neutron absorber shielding boxes are modeled as aluminum. Two different MAVRIC cases were analyzed: one with the ORIGEN-S source for average EBR-II HALEU analyte (isotopic content) according to Table 1, and one for the maximum HALEU analyte according to Table 1. Both cases assume HALEU canisters fully loaded and one day of decay from the initial specified analyte content.

Normal conditions of transport DRs for the TN-LC scoping model cases are shown in Table 21. The maximum analyte DRs are 4-5 times higher than the average analyte DRs. Gamma DRs (γ) are much higher than neutron DRs (N), even though the neutron shielding material (borated resin) is not modeled. The scoping model combined N and γ are 2-3 orders of magnitude below 10 CFR 71.47 limits. Figure 20 shows the spatial distribution of γ (rem/hr) under NCT on a 10 cm/mesh grid.

Because the TN-LC metal (steel and lead) is much thicker than the OPTIMUS™-L metal (steel), HAC DRs are evaluated only for the OPTIMUS™-L package.

Table 21. TN-LC – γ and N under NCT.

Analyte	**DR @ Surface**	**DR Limit @ Surface**	**DR @ 1 m**	**DR Limit @ 1 m**
Average	0.023 mrem/hr (γ) 0.004 mrem/hr (N)	200 mrem/hr	0.003 mrem/hr (γ) < 0.001 mrem/hr (N)	10 mrem/hr
Maximum	0.12 mrem/hr (γ) 0.017 mrem/hr (N)	200 mrem/hr	0.015 mrem/hr (γ) 0.001 mrem/hr (N)	10 mrem/hr

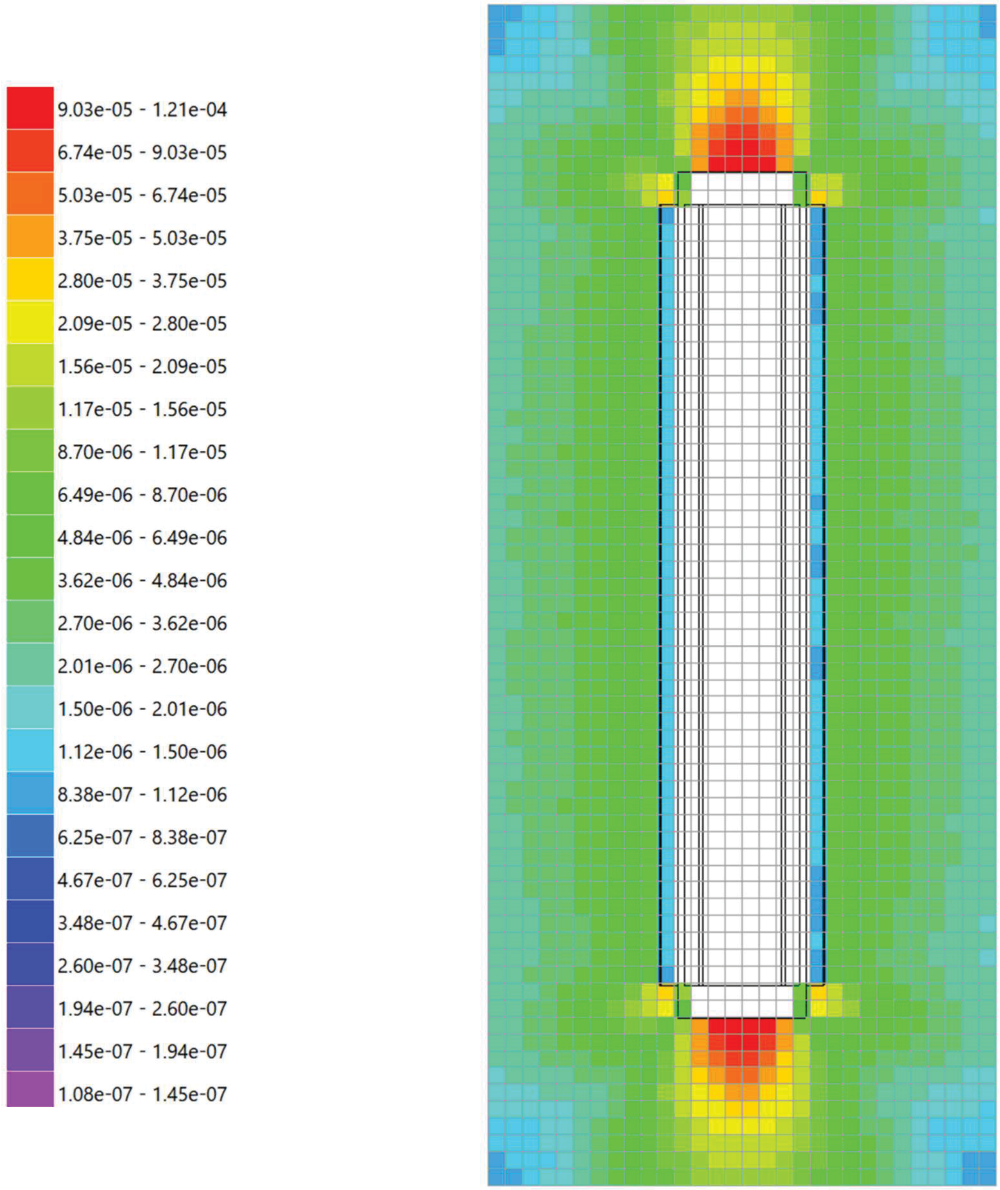


Figure 20. Spatial distribution of TN-LC NCT γ (rem/hr).

4.4.2 OPTIMUS™-L Shielding Capability

External DR scoping calculations are performed for the OPTIMUS™-L package in a similar manner to those for TN-LC. Because the OPTIMUS™-L DRs are much closer to the limits than TN-LC model DRs, the more conservative ANSI/ANS-6.1.1-1977 flux-to-dose conversions are used. The OPTIMUS™-L preliminary model contains the maximum anticipated amount of HALEU in 38 canisters.

Figure 21 shows a cutaway view of the simplified OPTIMUS™-L SCALE/MAVRIC model. The HALEU is evenly distributed inside 19 canisters. Each modeled canister represents two actual canisters stacked axially. The ORIGEN-S HALEU source for maximum analyte, according to Table 1, is used because the TN-LC cases showed that it produces the highest DR.

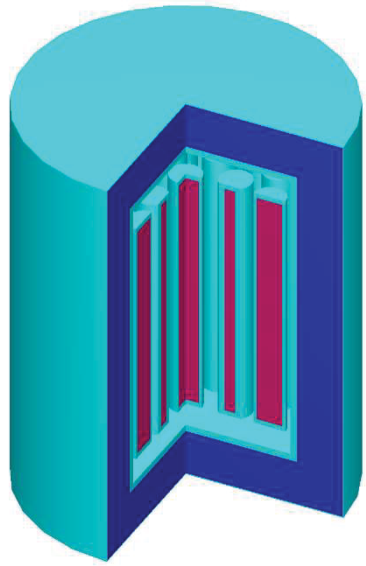


Figure 21. OPTIMUS™-L SCALE/MAVRIC simplified model.

Normal conditions of transport DRs for the OPTIMUS™-L scoping model cases are shown in Table 22. Gamma DRs are much higher than N. Table 22 results are for a single package with distances measured from the outer surface of the package. Multiple packages in a shipment will increase DRs. However, for exclusive use shipments, 10 CFR 71.47 specifies that the measurement for the 2-m limit be performed 2 m from the outer lateral surfaces of the vehicle rather than the outer surface of the package. The reduction in DR due to increased distance is expected to offset the increase in DR due to multiple packages. Dose rate calculations can be performed to directly confirm that regulatory limits will be met when the transportation configuration is better known.

Table 22. OPTIMUS™-L – γ and N under NCT.

Analyte	DR @ Surface	DR Limit @ Surface	DR @ 2 m	DR Limit @ 2 m
Maximum	52 mrem/hr (γ) 0.04 mrem/hr (N)	200 mrem/hr	3.6 mrem/hr (γ) 0.003 mrem/hr (N)	10 mrem/hr

Figure 22 shows the spatial distribution of NCT γ (rem/hr) on a 10-cm mesh grid.

The HAC DR is evaluated at the surface of the containment vessel with the outer packaging removed. The single package dose rate is ≈ 14 mrem/hr, which is well below the limit of 1,000 mrem/hr.

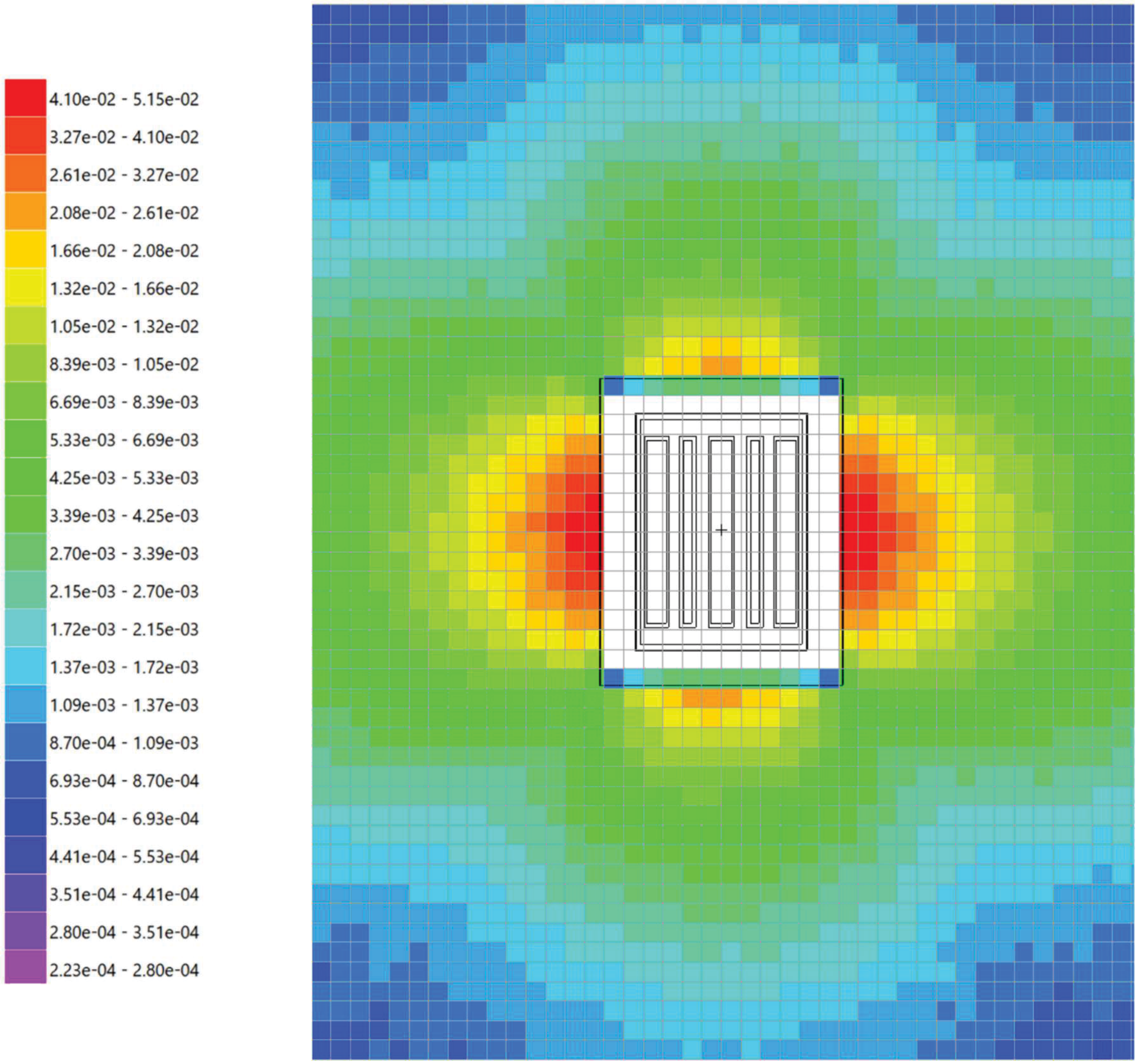


Figure 22. Spatial distribution of OPTIMUS™-L NCT γ (rem/hr).

4.5 Additional Required Regulatory Evaluations and Assessments

Gathering and reviewing acceptable Type B packaging configurations and information required more time than expected during the initial phase of this project. As such, the initiation of supporting evaluations was delayed. Remaining tasks are related to the review of structural, thermal, and containment capabilities, which are comparable for each of the two package configurations. Critical items to verify the safety bases are outlined below.

4.5.1 Structural Requirements

The primary objective is to verify that the structural performance of the package has been adequately evaluated for the postulated scenarios specified under NCT and HAC and that the package design has adequate structural integrity to meet the requirements of 10 CFR 71. The program has opted to adopt Type B, Category I packaging design requirements and criteria. Per RG 7.11, and other corroborating code sections, ASME B&PV Code Section III, Division 1, Subsection NB must be followed in assessing adequate structural integrity of the containment as it is defined. Both the TN Americas TN-LC and the NAC International OPTIMUS™-L have been previously developed and analyzed with appropriate codified regulatory requirements and corroborating code sections applicable to containment as part of their application for certification.

The confinement system (canister and basket) and HALEU content are new to both systems and would require additional evaluation for certification. The ASME B&PV Code Section III, Division 1, Subsection NG (and NF for Buckling) apply to the confinement system components which are required to maintain an appropriate subcritical reactivity margin for the canister content under postulated NCT and HAC loading (10 CFR 71).

Some of the confinement system components are comprised of polyurethane foam, polycarbonate, and aluminum. As such, they will have to be physically tested to be certified because consensus design guides/standards do not exist for these types of materials. Nevertheless, these items can be readily designed, modeled, analyzed, and developed to support prototyping and future testing for final assessment and certification.

As previously discussed, the foam basket masses are essentially 1/3 of the masses of the metal basket and accommodate identical payload masses of HALEU UO_2 powder. The TN-LC has the capacity of accommodating 56 loaded canisters, and the predicted mass of the metal basket concepts for the TN Americas TN-LC package is approximately 1,241 lbs. Based on this, the total mass (including metal basket, canister, and powder content) within the TN-LC is estimated to be 6,672 lbs. This is only 428 lbs below the maximum content weight limit for this packaging.

Also presented above, the proposed OPTIMUS™-L foam basket is predicted to weigh 462 lbs, and the 38 canisters loaded with UO_2 powder are predicted to weigh 3,686 lbs (38 x 97 lbs), for a total predicted package payload of 4,148 lbs. The permitted design payload of the OPTIMUS™-L is 3,150 lbs. This is roughly 1,000 lbs over the maximum content weight limit for this packaging without the additional weight of the metal basket. Compliance of the OPTIMUS™-L (including a foam basket) with the permitted payload limits can be readily achieved by simply reducing the number of generic UO_2 canisters residing in the basket/packaging by ten each to meet the prescribed maximum content weight limit of 3,150 lbs per packaging. With this in mind, besides the added manufacturing complexity that would stem from fabricating the metal baskets themselves, the program opted to pursue integration of the foam basket configurations instead of potentially exchanging payload capacity for parasitic basket mass.

The ASME B&PV Code Section VIII, Division 1, or Section III, Division 1, Subsection NF apply to assessing the successful maintenance of shielding (as well as other safety features) under NCT and HAC (10 CFR 71). Refinements and optimizations will be made during the next phase of this project via computational assessment. Subsequently, specific design recommendations through vetted F&Rs will be developed for a final proposed application.

4.5.2 Thermal Requirements

The objective of this review is to verify that the thermal performance of the package has been adequately evaluated for the tests specified under postulated NCT and HAC and that the package design satisfies the thermal requirements of 10 CFR 71. Both the TN Americas TN-LC and the NAC International OPTIMUS™-L have been previously developed and analyzed with appropriate codified regulatory requirements and corroborating code sections applicable to containment as part of their application for certification. These analyses primarily focus on the influence of temperature-sensitive items such as O-rings (defining part of the containment boundary) or other low service temperature items. As previously discussed in Section 3.4, the decay heat source for the anticipated material payload (UO_2 powder) is 5.56E-4 W/kg, which is relatively benign and can be considered negligible. However, the foam baskets for both TN-LC and OPTIMUS™-L confinement systems are temperature sensitive (glass transition of softening temperature) and must be evaluated and verified to maintain a subcriticality reactivity margin under postulated hypothetical accident fire conditions.

Refinements and optimizations will be made during the next phase of this project via computational assessment. After that, specific design recommendations through vetted F&Rs will be developed for a final proposed application.

4.5.3 Containment Requirements

The objective of this review is to verify that the package design satisfies the containment requirements of 10 CFR 71 under NCT and HAC conditions. Evaluations performed as part of the structural and thermal evaluations develop the basis by which to establish compliance and lead to certification. Refinements and optimizations will be made during the next phase of this project via computational assessment. Then, specific design recommendations through vetted F&Rs will be developed for a final proposed application.

5. Preliminary Concept Selection for Further Development

Program resources and available time are limited for this study and restrict the capacity to fully investigate and evaluate the application of both the TN-LC and OPTIMUS™-L at this time. As such, the design team had to make a programmatic decision and perform a down-selection to one of the available options. The following considerations were part of that down-selection process.

- The TN-LC can only be transported as a single package containing 56 generic UO_2 powder canisters per shipment with one LWT. Each generic UO_2 powder canister holds 62 lbs of powder. This equates to 3,472 lbs (1,574 kg) of total UO_2 powder that can be transported in the TN-LC on one LWT. The TN-LC package would likely weigh approximately 48,000 lbs in this configuration and remain transportable with an LWT without special permitting (which is not required below approximately 51,000 lbs).
- The OPTIMUS™-L can be transported in groups of 10 packages per shipment, provided LWT limits are not exceeded. However, as discuss previously, if each OPTIMUS™-L had all 38 generic canister compartments loaded, this proposed package configuration would be roughly 1,000 lbs overweight. The OPTIMUS™-L could be qualified by simply reducing the number of generic UO_2 powder canisters from the matrix residing in the basket/packaging by ten each to meet the prescribed maximum content weight limit of 3,150 lbs (1,429 kg) per packaging. This represents a reduction of loaded generic canisters to 28 per OPTIMUS™-L and a gross weight of roughly 9,228 lbs per OPTIMUS™-L package. If we were to then limit the entire load of the packages to 51,000 lbs to maintain LWT (comparable to the TN-LC shipment), only five OPTIMUS™-L packages would be allowed per shipment. This would equate to 8,680 lbs (3,937 kg) per OPTIMUS™-L shipment, which would still remain within LWT limits. Hence, the OPTIMUS™-L represents 2.5 times the transport capacity than that of the TN-LC for similar LWT payloads. The proposed TN-LC concept is limited to one package per shipment exclusively.
- The TN-LC has significant gamma and neutron shielding boundaries, whereas the OPTIMUS™-L offers only modest shielding capacity. As discussed in Section 4.4, if the processed UO_2 powder is as clean as anticipated, the OPTIMUS™-L shielding capabilities are more than adequate. As such, the TN-LC would provide unnecessary shielding and unnecessary associated mass.
- Additionally, OPTIMUS™-L provides operational advantages over the TN-LC. It is small enough for facilities with limited access and/or crane capacity, can be forklift handled to eliminate the need for higher-capacity cranes for lifting, and could be left on the conveyance during the loading and unloading processes within facilities.

Based on these details, the design team chose to proceed with the NAC International OPTIMUS™-L for the next phase of this project. Refinements and optimizations will be made during the next phase of this project via computational assessment. Then, specific recommendations through vetted F&Rs will be developed for a final proposed application to fulfill this project task.

6. Project Outlook FY 2020

Figure 23 provides an overview on a tentative schedule for FY 2020 tasks. A work meeting is going to be held in early December of 2019 at ORNL to discuss the preliminary HALEU transportation package design selection and the path forward. The next milestone is scheduled for February 3, 2020. It includes brief letter reports submitted by PNNL and ORNL on initial feasibility studies on the selected HALEU transportation package concept. In the beginning of April 2020, INL is going to submit a brief letter report that provides a rough cost estimate for the selected package concept and a list of potential packaging vendors. In May 2020, PNNL and ORNL are going to submit publicly releasable reports on a completed package feasibility study. These reports, in addition to the F&R document that describes the desired HALEU package, are meant to support the R&D efforts of potential HALEU transportation packaging vendors. On June 1, 2020, INL is going to provide ORNL and PNNL with preliminary package specifications for review. The final specifications are going to be returned to INL three weeks later (June 22, 2020). After receiving, INL is going to author the final F&R document, which is going to be submitted on August 31, 2020.

Work Meeting - December 2019 at ORNL

Agenda:
- **Path Forward**
- **Preliminary Design Selection**

Milestone - February 3, 2020

Selected Package Concept:
- **Initial Structural Feasability Study (PNNL)**
- **Initial Thermal Analysis (PNNL)**
- **Initial Containment Analysis (PNNL)**
- **Preliminary Shielding Analysis (ORNL)**
- **Preliminary Criticality Anlaysis (ORNL)**
- **Preliminary Package Operations Analysis (PNNL, supported by ORNL)**

Milestone - April 6, 2020

Preliminary Designs:
- **Rough Cost Estimation (INL)**
- **Potential Vendor Selection (INL)**

Milestone - May 4, 2020

Selected Package Concept:
- **Package Feasability Study: Structural Design (PNNL)**
- **Package Feasability Study: Thermal Analysis (ORNL)**
- **Package Feasability Study: Containment Analysis (PNNL)**
- **Package Feasability Study: Shielding Analysis (ORNL)**
- **Package Feasability Study: Criticality Anlaysis (ORNL)**
- **Package Feasability Study: Package Operations Analysis (PNNL, supported by ORNL)**

Milestone - June 1, 2020

Preliminary F&Rs:
- **Preliminary F&Rs (INL)**
- **Preliminary Specification Rationale (INL)**
- **Design Specification Matrix (INL)**

Milestone - June 22, 2020

Critical F&Rs:
- **Review F&Rs (ORNL and PNNL)**
- **Review Specification Rationale (ORNL and PNNL)**

Milestone - August 31, 2020

F&R Document (INL)

Figure 23. Potential project schedule for FY 2020.

7. Summary and Conclusions

This M3FT-19IN030205042 milestone report presents the current status on investigations related to the development of HALEU transportation capabilities in the U.S. The report initially reviews potential short-term HALEU production options and describes an expected HALEU composition. It then discusses the regulatory bases for HALEU transportation and identifies two compliant packaging designs: (1) the TN Americas TN-LC and (2) the NAC International OPTIMUS™-L. To modify these designs for HALEU transportation, an inner canister concept, and modular metal and foam basket concepts were developed, and this is described in the report. The expected activity, criticality tendency, radiation level, and decay heat of the package content are evaluated considering the specific system characteristics.

Based on the results of the investigations, the research team consisting of INL, PNNL, and ORNL staff concluded that, given the anticipated source material composition, the OPTIMUS™-L, or a comparable design, is the preferred candidate. This is due to its larger HALEU payload per LWT, lighter weight, and simpler handling procedures compared to the TN-LC. Thus, ongoing research efforts for the scope of this project will focus on more thorough evaluations of the OPTIMUS™-L packaging for HALEU transportation. A tentative timeline is presented for the remaining work that is planned for FY 2020. The goal is the development of F&Rs that provide guidance to a potential HALEU transportation package vendor on critical specifications by August 2020.

8. References

10 CFR 173.401 - 173.477. 1995. "Subpart I. Class 7 (Radioactive) Materials."

10 CFR 71. 1995. "Packaging and Transportation of Radioactive Material."

10 CFR 71.15. 2015. "Exemption from Classification as Fissile Material."

10 CFR 71.47. 2017. " External Radiation Standards for All Packages."

10 CFR 71.55. 2004. "General Requirements for Fissile Material Packages."

10 CFR 71.71. 2016. "Normal Conditions of Transport."

10 CFR 71.73. 2004. "Hypothetical Accident Conditions."

49 CFR 173.417. 2015. "Authorized Fissile Materials Packages."

49 CFR 173.420. 2015. "Uranium Hexafuoride (Fissile, Fissle Expected and Non-Fissile)."

49 CFR 173.431. 1995. "Activity Limits for Type A and Type B Packages."

49 CFR 173.435. 2015. "Table A1 and A2 Values for Radionuclides."

49 CFR 173.441. 1995. "Radiation Level Limitations and Exclusive use Provisions."

ANS. 1991. "Neutron and Gamma-Ray Fluence-to-Dose Factors." *ANSI/ANS-6.1.1-1991.* ANSI.

—. 1977. "Neutron and Gamma-Ray Flux-to-Dose Rate Factors." *ANSI/ANS-6.1.1-1977.* ANSI.

ASME.III.1.NB. 2019. "Section III Division 1 - Subsection NB Class 1 Components - Rules for Construction of Nuclear Facility Components." *ASME BPVC.III.1.NB-2019.* ASME.

ASME.III.1.NF. 2019. "Section III Division 1 - Subsection NF Supports - Rules for Construction of Nuclear Facility Components." *ASME BPVC.III.1.NF-2019.* ASME.

ASME.III.1.NG. 2019. "Section III Division 1 - Subsection NG Core Support Structures - Rules for Construction of Nuclear Facility Components." *ASME BPVC.III.1.NG-2019.* ASME.

ASME.III.3. 2019. "Section III Division 3 - Containment Systems for Transportation and Storage of Spent Nuclear Fuel and High-Level Radioactive Material." *ASME BPVC.III.3-2019.* ASME.

ASME.VIII.1. 2019. "Section VIII Division 1 Rules for Construction of Pressure Vessels." *ASME BPVC.VIII.1-2019.* ASME.

Benedict, R. W., H. F. McFarlane, and K. M. Goff. 2001. *Electrometallurgical Treatment of Sodium-Bonded Spent Nuclear Fuel.* INIS-FR-1353, Idaho Falls, ID: ANL.

Clarity, J. B., W. J. Marshall, and E. M. Saylor. 2019. "User Experiences with ICSBEP Distributed Sensitivity Data Profiles with the SCALE Sensitivity and Uncertainty Methods as of Winter 2019." *Transactions of the American Nuclear Society.* Minneapolis, MN: ANS.

Fard, M. R. 2011. *Nuclear Material Safety and Safeguards Issues - NMSS-0007. Criticality Bechmarks Greater than 5% Enrichment.* NUREG-0933 Section 6, Washington, D.C.: U.S. NRC.

INMM. 2001. "Uranium Hexafluoride - Packaging for Transport." *ANSI.N.14.1-2001.* ANSI, 2 1.

J. M. Scaglione, D. E. Mueller, J. C. Wagner, W. J. Marshall. 2012. *An Approach for Validating Actinide and Fission Product Burnup Credit Criticality Safety Analyses - Criticality (keff) Predictions.* NUREG/CR-7109, Oak Ridge, TN: ORNL.

Jarrell, Josh. 2018. *A Propsed Path Forward for Transportation of High-Assay Low-Enriched Uranium.* INL/EXT-18-51518, Idaho Falls, ID: INL.

Mann, Melissa. 2019. "INL-NEI Technical Workshop of Transportation of High Assay Low Enriched Uranium." Washington, D.C., 08 30.

ORNL. 2005. *SCALE System Module to Calculate Fuel Depletion, Actinide Transmutation, Fission Product Buildup and Decay, and Associated Radiation Source Terms.* ORNL/TM-2005/39, Oak Ridge, TN: ORNL.

Rearden, B. T., and M. A. Jessee. 2018. *Scale Code System.* ORNL/TM-2005/39, Oak Ridge, TN: ORNL.

Scaglione, J. M. 2019. *New HALEU Design Options.* Oak Ridge, TN: ORNL.

Tschiltz. 2018. *Addressing the Challenges with Establishing the Infrastructure for the Front-end of the Fuel Cycle for Advanced Reactors.* Whitepaper, Washington, D.C.: NEI.

U.S. DOE. 2015. *RAMPAC - Radioactive Matrial Packaging.* 7 29. Accessed 10 17, 2019. https://rampac.energy.gov/.

U.S. NRC. 1991. *Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Maxium Wall Thickness of 4 Inches.* Regulatory Guide 7.11, Washington, D.C.: U.S. NRC.

Vaden, D. 2018. *Isotopic Characterization of HALEU from EBR-II Drive Fuel Processing.* INL/EXT-18-51906, Idaho Falls, ID: INL.

Appendix A

Package Type Determination

Table A.1 – ORIGEN-S A_2 calculations.

Isotope	Unit	Average		Isotope	Weight fraction		ORIGEN Input Assumption					
Total U	wt%	99.95										
U232	ppbU	0.66		U232	6.5967E-10	gm	922320	2		Table 1	A2/g for mix:	0.000296283
U233	ppbU	49.12		U233	4.90954E-08	gm	922330	2				3375.153295
U234	iso% U	0.17		U234	0.00169915	gm	922340	2				
U235	iso% U	19.39		U235	0.19380305	gm	922350	2				
U236	iso% U	0.58		U236	0.0057971	gm	922360	2				
U237	pptU	0.06		U237	5.997E-14	gm	922370	2				
U238	iso% U	79.86		U238	0.7982007	gm	922380	2				
Zr	ppm	101.45		Zr	0.00010145	gm	400000	4				
Si	ppm	77.6		Si	0.0000776	gm	140000	4				
Y	ppm	6.05		Y	0.00000605	gm	390000	4				
Fe	ppm	133.13		Fe	0.00013313	gm	260000	4				
Cr	ppm	28.15		Cr	0.00002815	gm	240000	4				
Ni	ppm	43.14		Ni	0.00004314	gm	280000	4				
Mo	ppm	40.21		Mo	0.00004021	gm	420000	4				
Mn	ppm	79.47		Mn	0.00007947	gm	250000	4				
Ru	ppm	77.23		Ru	0.00007723	gm	440000	4				
Cd	ppm	12.17		Cd	0.00001217	gm	480000	4				
Al	ppm	101.24		Al	0.00010124	gm	130000	4				
Tc	ppm	75		Tc	0.000075	gm	430000	4				
Li	ppm	15.6		Li	0.0000156	gm	30000	4				
K	wt%	0.05		K	0.0005	gm	190000	4				
Na	ppm	82.29		Na	0.00008229	gm	110000	4				
Ba	ppm	5		Ba	0.000005	gm	560000	4				
Sr	ppm	5		Sr	0.000005	gm	380000	4				
Sr90	ppb	15.77		Sr90	1.577E-08	gm	380900	3				
Nd	ppm	95.92		Nd	0.00009592	gm	600000	4				
Sm	ppm	56.82		Sm	0.00005682	gm	620000	4				
Tc99	ppm	0.15		Tc99	0.00000015	gm	430990	3				
Cs135	ppm	2.67		Cs135	0.00000267	gm	551350	3				
Mn54	ppt	3.04		Mn54	3.04E-12	gm	250540	3				
Co60	ppt	27.81		Co60	2.781E-11	gm	270600	3				
Sb125	ppt	102.51		Sb125	1.0251E-10	gm	511250	3				
Cs134	ppt	24.99		Cs134	2.499E-11	gm	551340	3				
Cs137	ppb	8		Cs137	0.000000008	gm	551370	3				
Ce144	ppt	67.11		Ce144	6.711E-11	gm	581440	3				
Eu154	ppb	0.22		Eu154	2.2E-10	gm	631540	3				
Eu155	ppb	0.22		Eu155	2.2E-10	gm	631550	3				
Am241	ppb	61.23		Am241	6.123E-08	gm	952410	2				
Np237	ppm	17.11		Np237	0.00001711	gm	932370	2				
Pu239	ppm	83.57		Pu239	0.00008357	gm	942390	2				
Pu240	ppm	2.24		Pu240	0.00000224	gm	942400	2				
				Sum	**1.001141345**							

Table A.2 – ORIGEN-S decay-heat calculations.

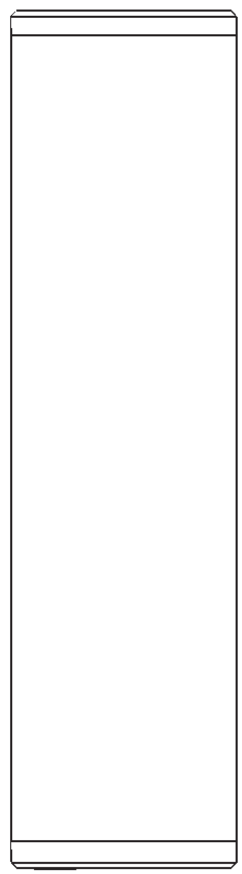
Watt/g	Initial	0	0.1	5	10	15	20	30	40	50	60
Light Elements	4.28E-15	4.28E-15	4.28E-15	4.28E-15	4.28E-15	4.28E-15	4.28E-15	4.28E-15	4.28E-15	4.28E-15	4.28E-15
Actinides	5.18E-07	5.18E-07	5.19E-07	5.22E-07	5.22E-07	5.22E-07	5.22E-07	5.21E-07	5.21E-07	5.21E-07	5.20E-07
Fission Products	4.69E-09	4.69E-09	2.07E-08	1.65E-08	1.44E-08	1.27E-08	1.12E-08	8.79E-09	6.90E-09	5.43E-09	4.27E-09
Total	5.22E-07	5.22E-07	5.40E-07	5.38E-07	5.37E-07	5.35E-07	5.33E-07	5.30E-07	5.28E-07	5.26E-07	5.25E-07
					5.36E-04	**Watts/kg**					

Appendix B

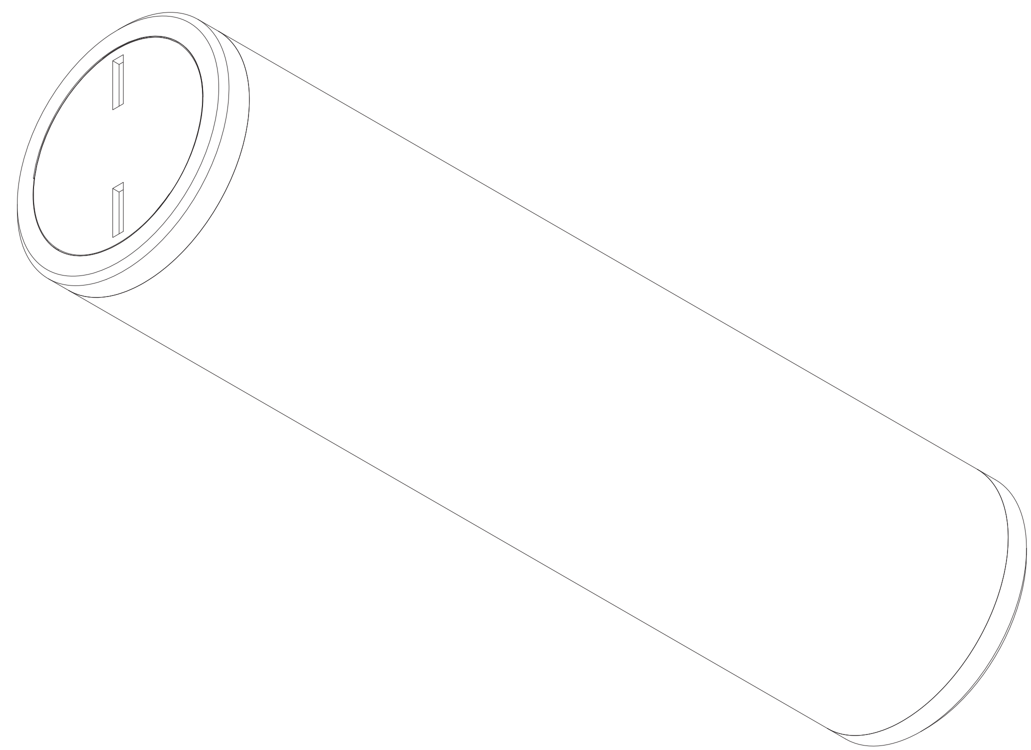
Drawings

5x19 Canister

Side View



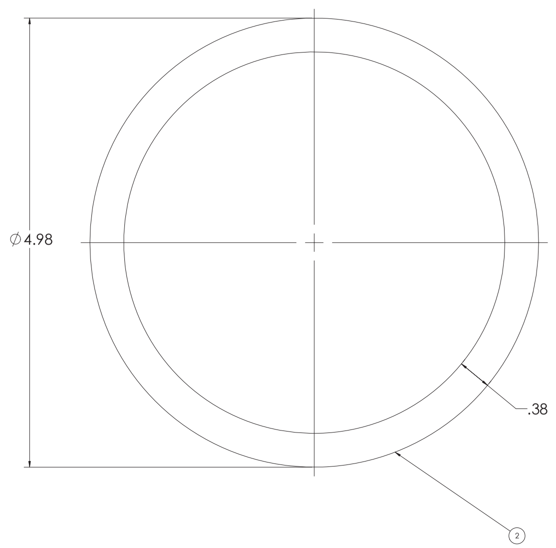
Isometric View



ITEM NO.	DESCRIPTION	Material	QTY.
1	5x21 bottom lid	Stainless Steel	1
2	5x21 body	Stainless Steel	1
3	5x21 top lid	Stainless Steel	1
4	5x21 top lid cover	Stainless Steel	1
5	o-ring size 040	PERFLUOROELASTOMER 75 (Parker)	1
6	o-ring size 043	PERFLUOROELASTOMER 75 (Parker)	1
7	contents		1

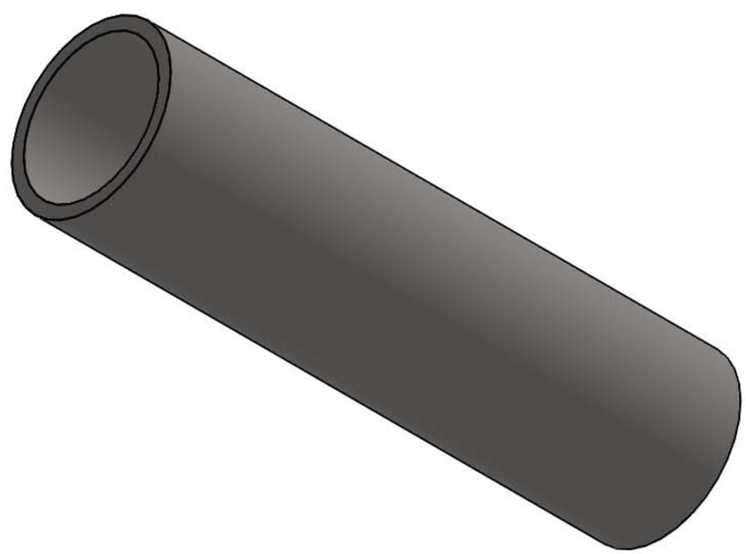
5x19_canister A0

Top View



Side View

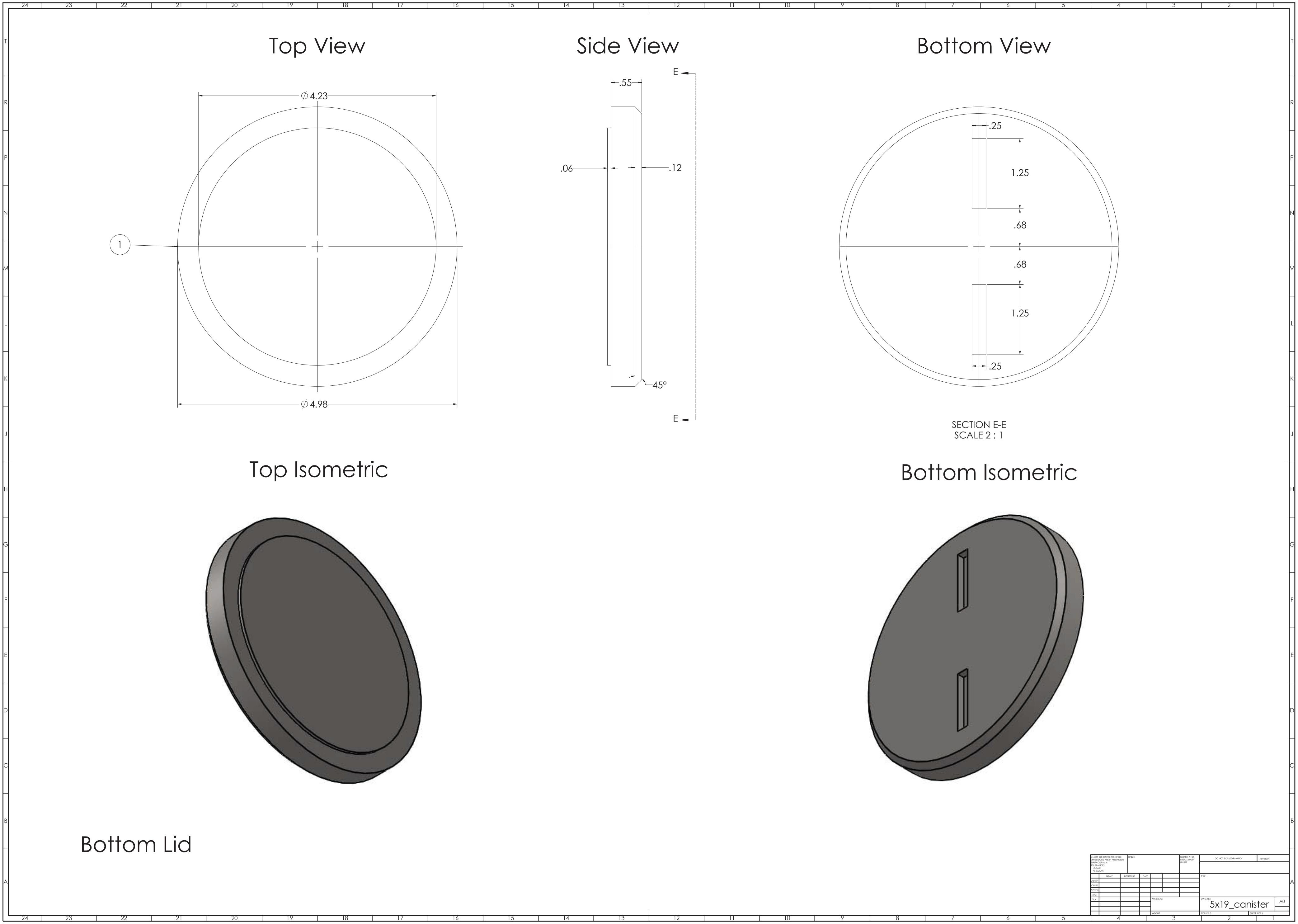
Isometric View

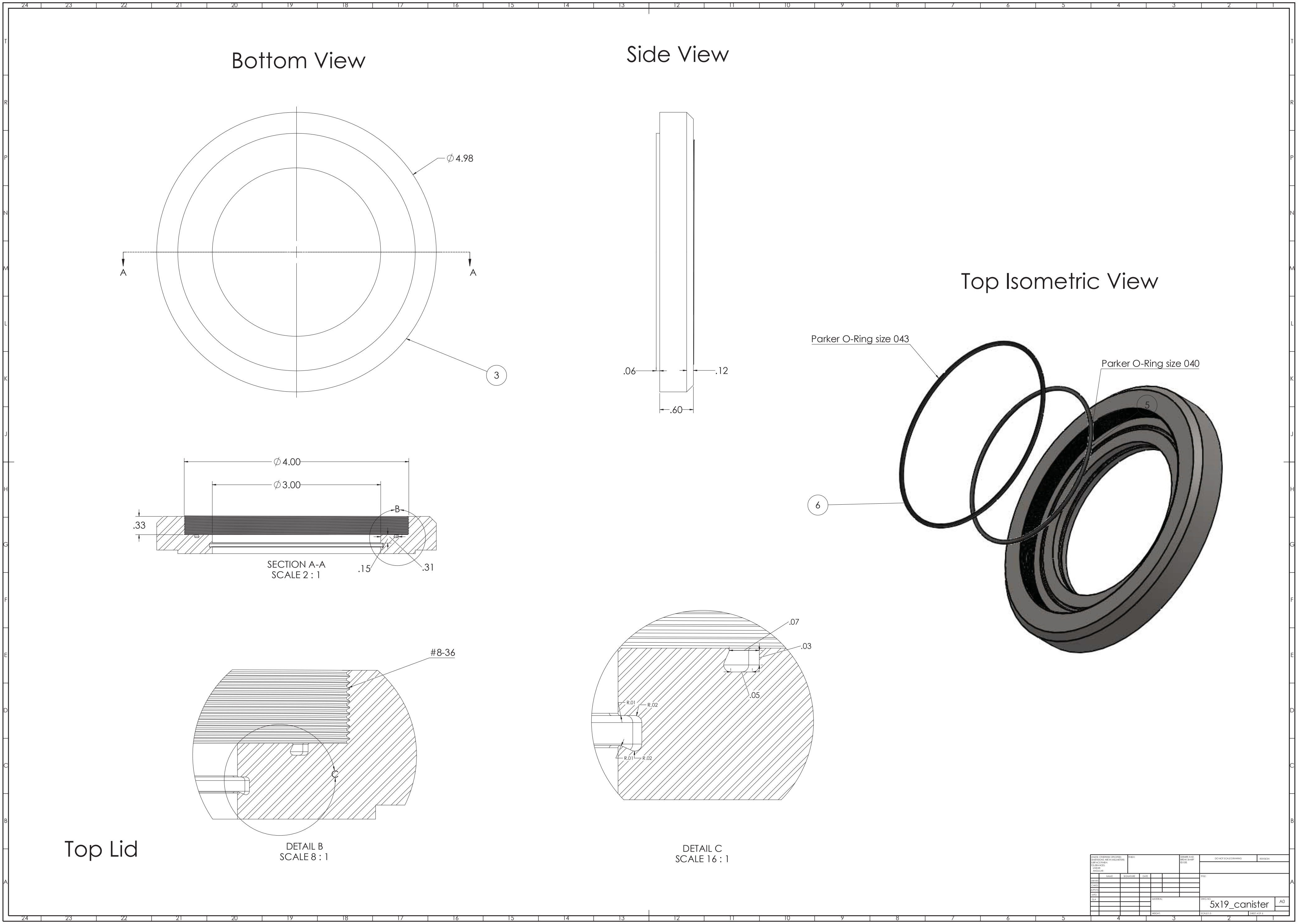


Canister Body

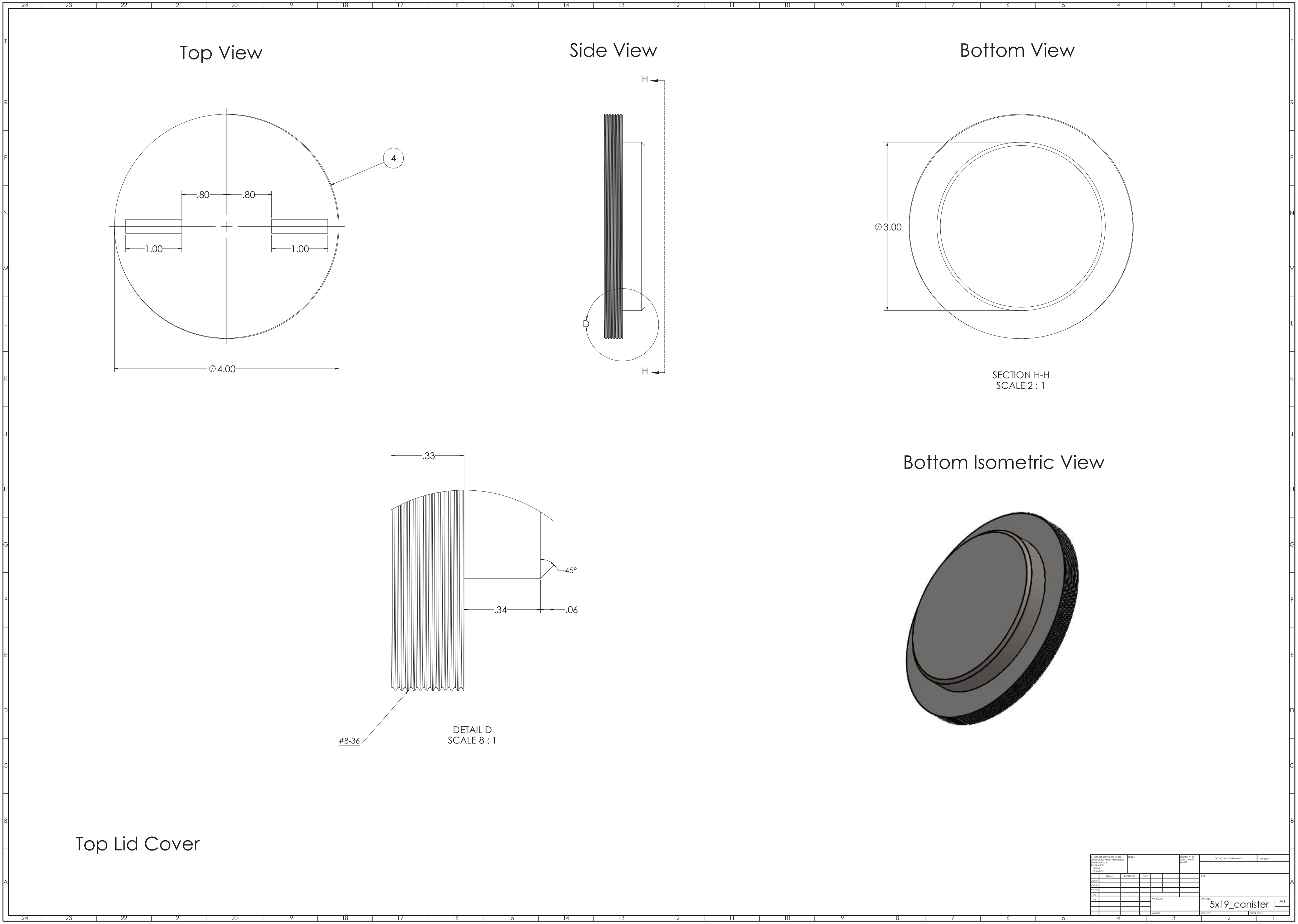
5x19_canister

A0

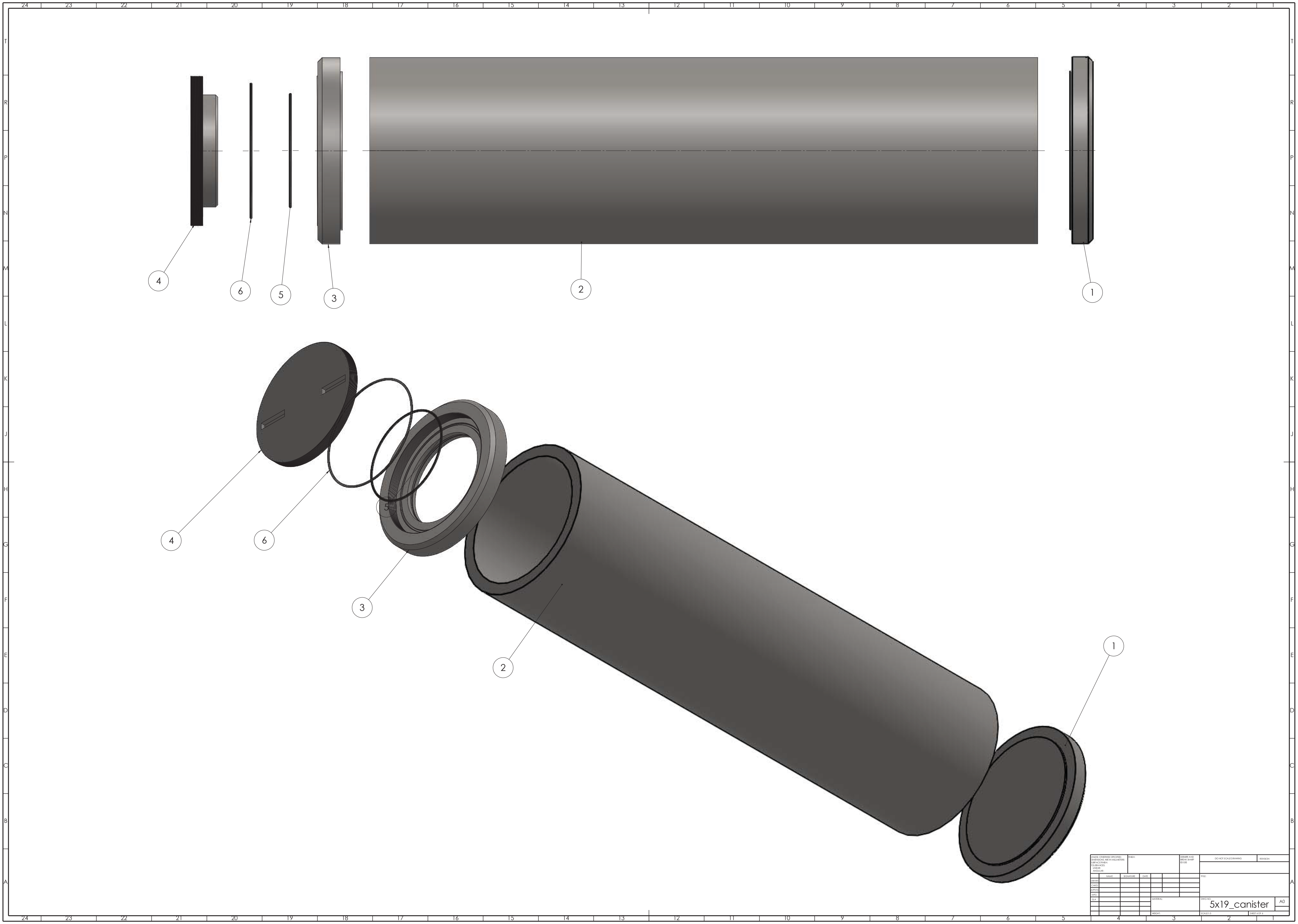

Top View
Side View
Bottom View
⌀4.23
⌀4.98
1
.55
.06
.12
45°
E
E
.25
1.25
.68
.68
1.25
.25
SECTION E-E
SCALE 2 : 1
Top Isometric
Bottom Isometric
Bottom Lid
5x19_canister
A0

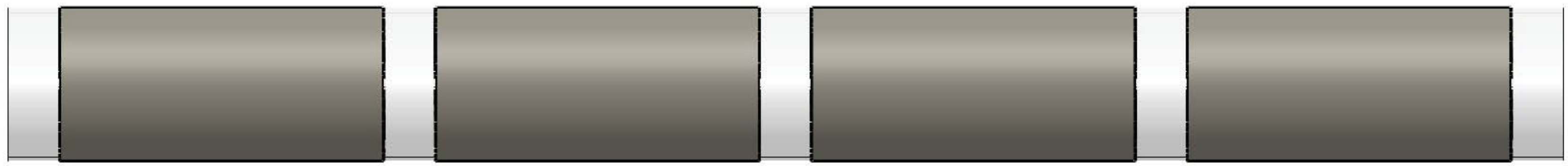


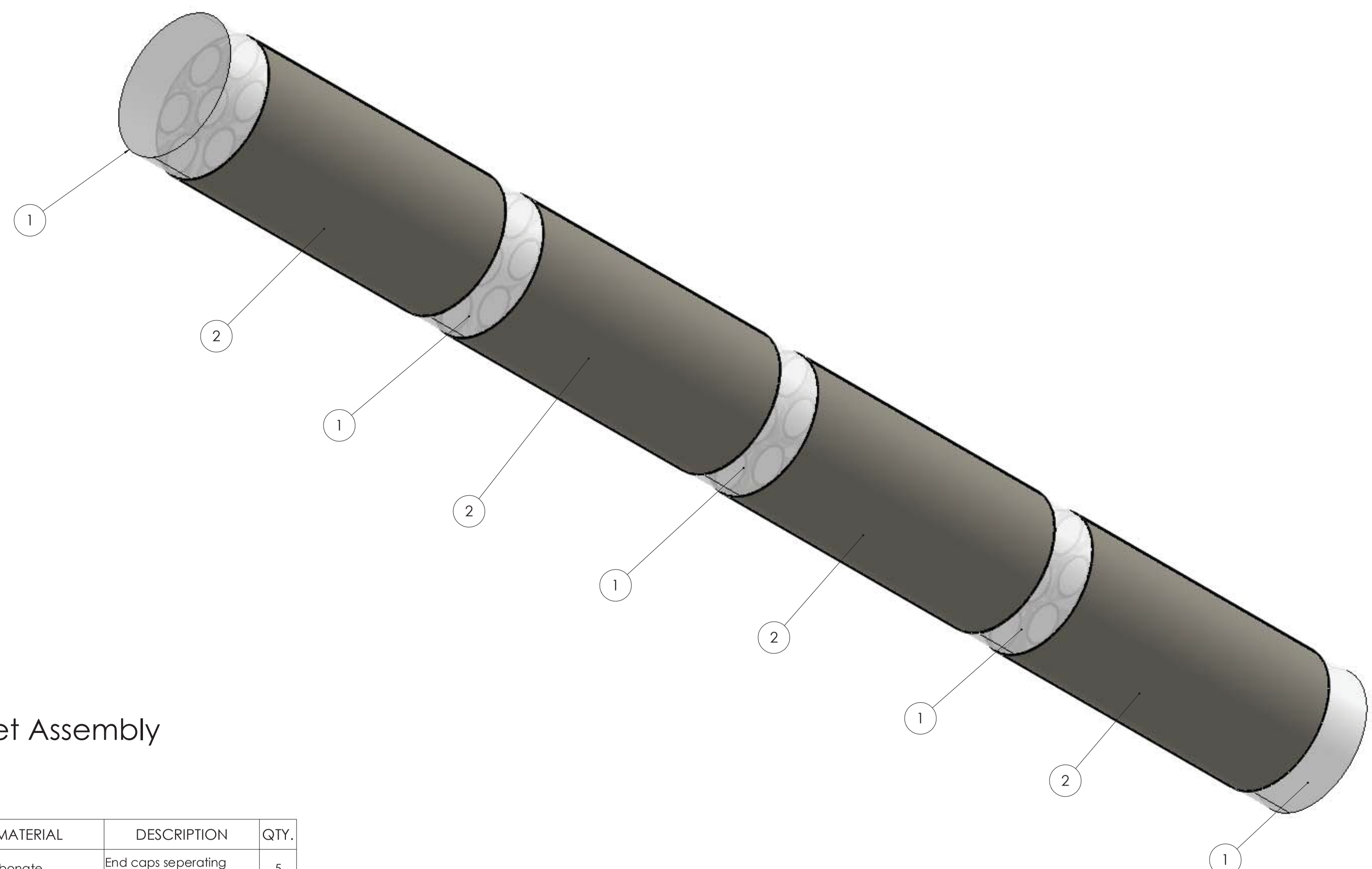
Bottom View
Side View
Top Isometric View
∅4.98
A
A
3
.06
.12
.60
Parker O-Ring size 043
Parker O-Ring size 040
5
6
∅4.00
∅3.00
B
.33
.15
.31
SECTION A-A
SCALE 2 : 1
#8-36
C
DETAIL B
SCALE 8 : 1
.07
.03
.05
R.01
R.02
DETAIL C
SCALE 16 : 1
Top Lid
5x19_canister
A0



Top View
Side View
Bottom View
.80
.80
1.00
1.00
4
∅4.00
H
H
D
∅3.00
SECTION H-H
SCALE 2 : 1
.33
45°
.34
.06
#8-36
DETAIL D
SCALE 8 : 1
Bottom Isometric View
Top Lid Cover
5x19_canister
A0


1
2
3
4
5
6
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
5x19_canister
A0
WEIGHT:
SCALE:1:5
SHEET 6 OF 6





TN-LC Basket Assembly

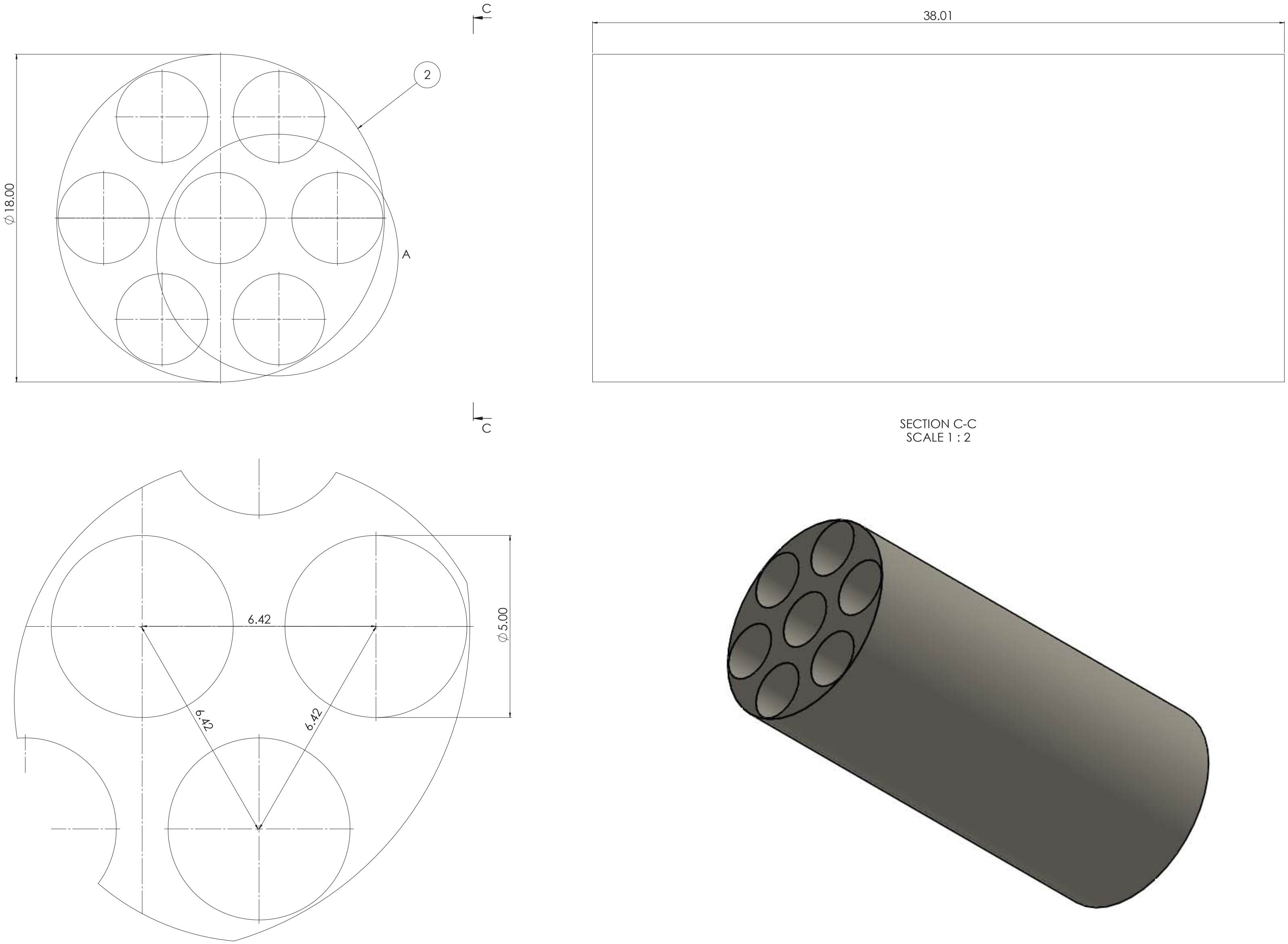
ITEM NO.	PART NAME	MATERIAL	DESCRIPTION	QTY.
1	Central Polycarbonate Base	Polycarbonate	End caps seperating foam sections	5
2	Central Foam	Rigid Polyurethane Foam	Central foam sections with canister tube slots	4

TN-LC Basket

DWG NO. 1

A0

Central Foam Section

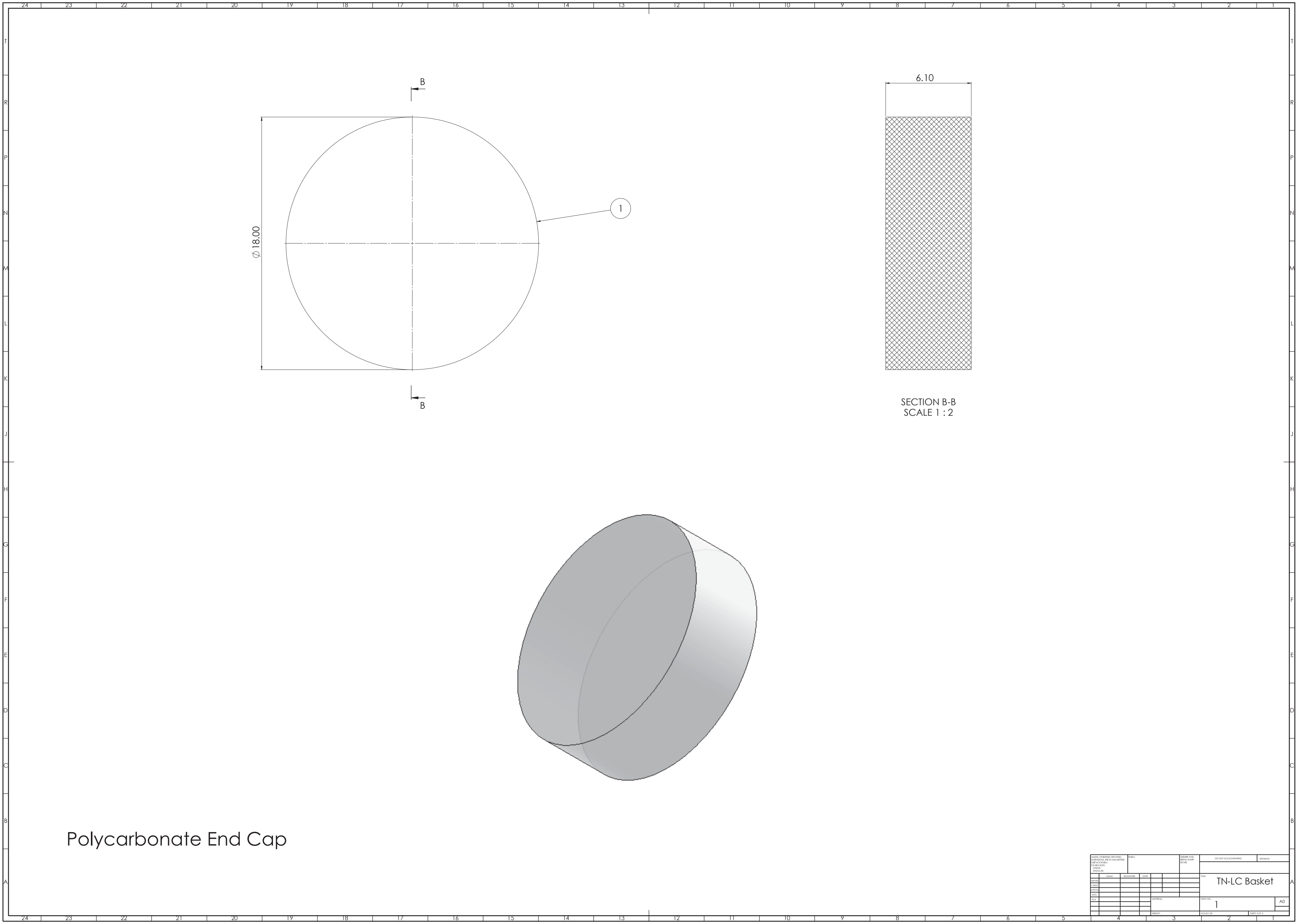


DETAIL A
SCALE 1 : 1

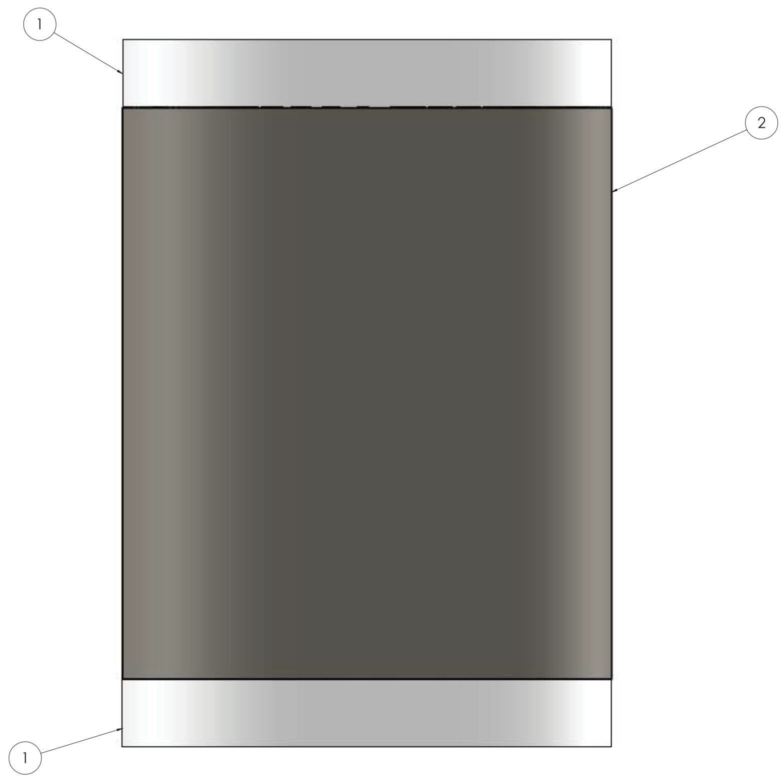
TN-LC Basket

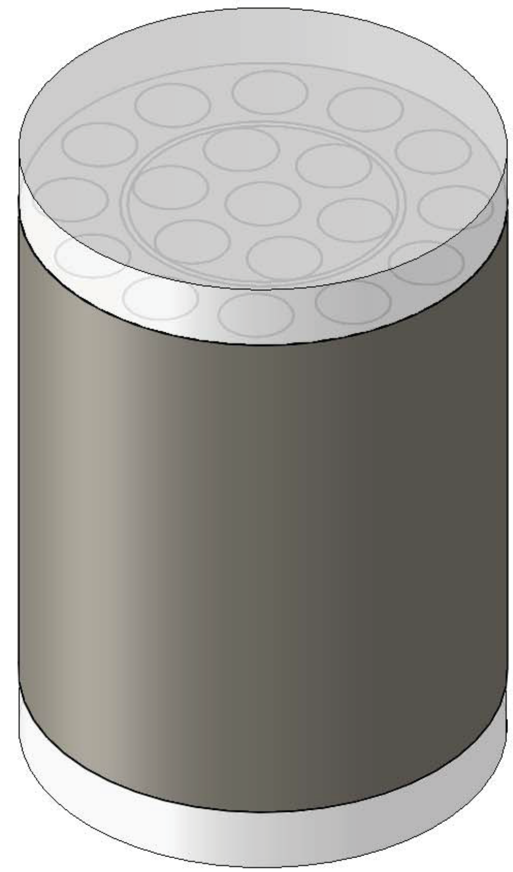
1

A0


B
B
∅18.00
1
6.10
SECTION B-B
SCALE 1 : 2
Polycarbonate End Cap
TN-LC Basket
1
A0

Optimus-L Foam Basket Assembly



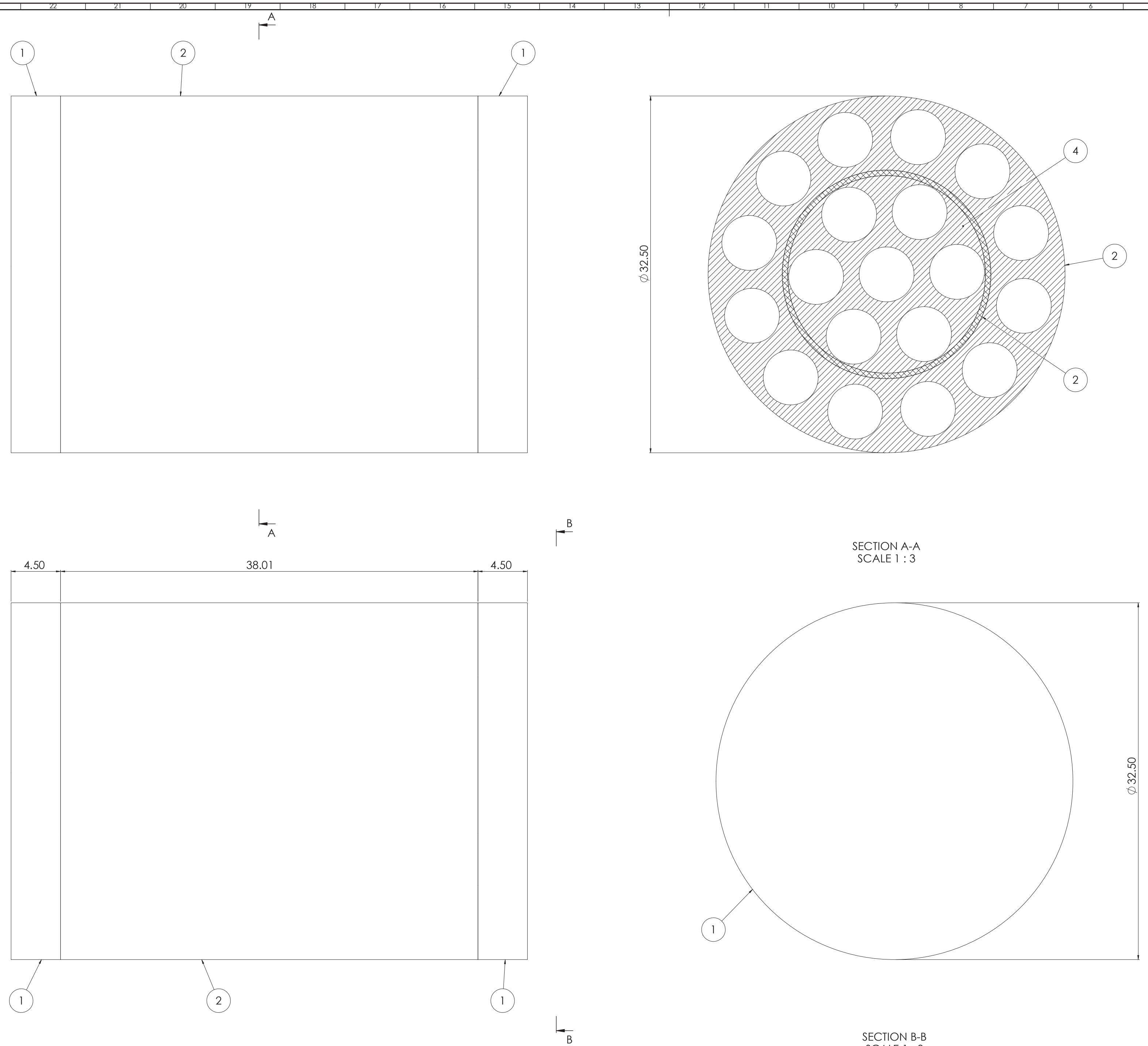


ITEM NO.	PART NAME	DESCRIPTION	MATERIAL	QTY.
1	polycarb base	Polycarbonate end cap	Polycarbonate	2
2	outer foam	Outer foam region	Rigid Polyurethane Foam	1
3	polycarb liner	Polycarbonate liner in between central and outer foam regions	Polycarbonate	1
4	Central_foam	Central foam region	Rigid Polyurethane Foam	1

Optimus-L Basket

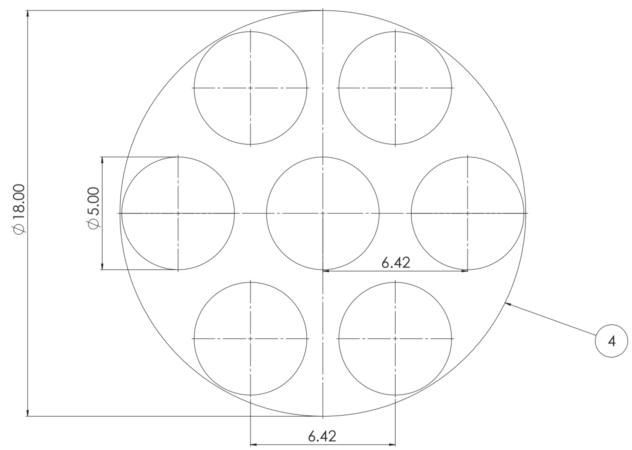
1

A0

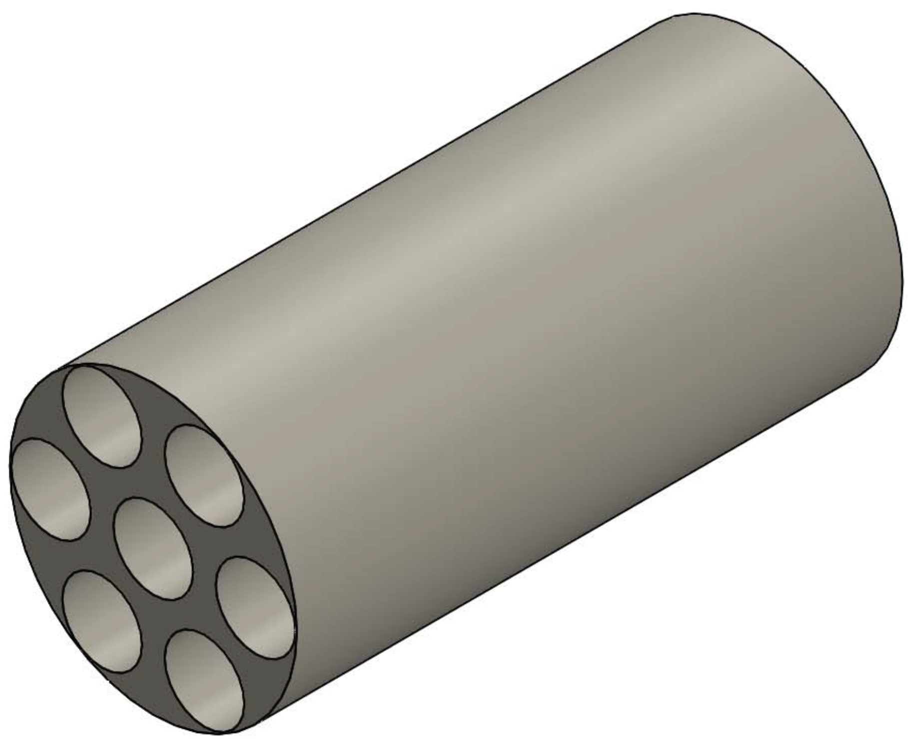


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE	TITLE: Optimus Basket		
DRAWN	B.M. Ham					
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. 1	A0
				WEIGHT:	SCALE:1:5	SHEET 2 OF 6

Top/Bottom View



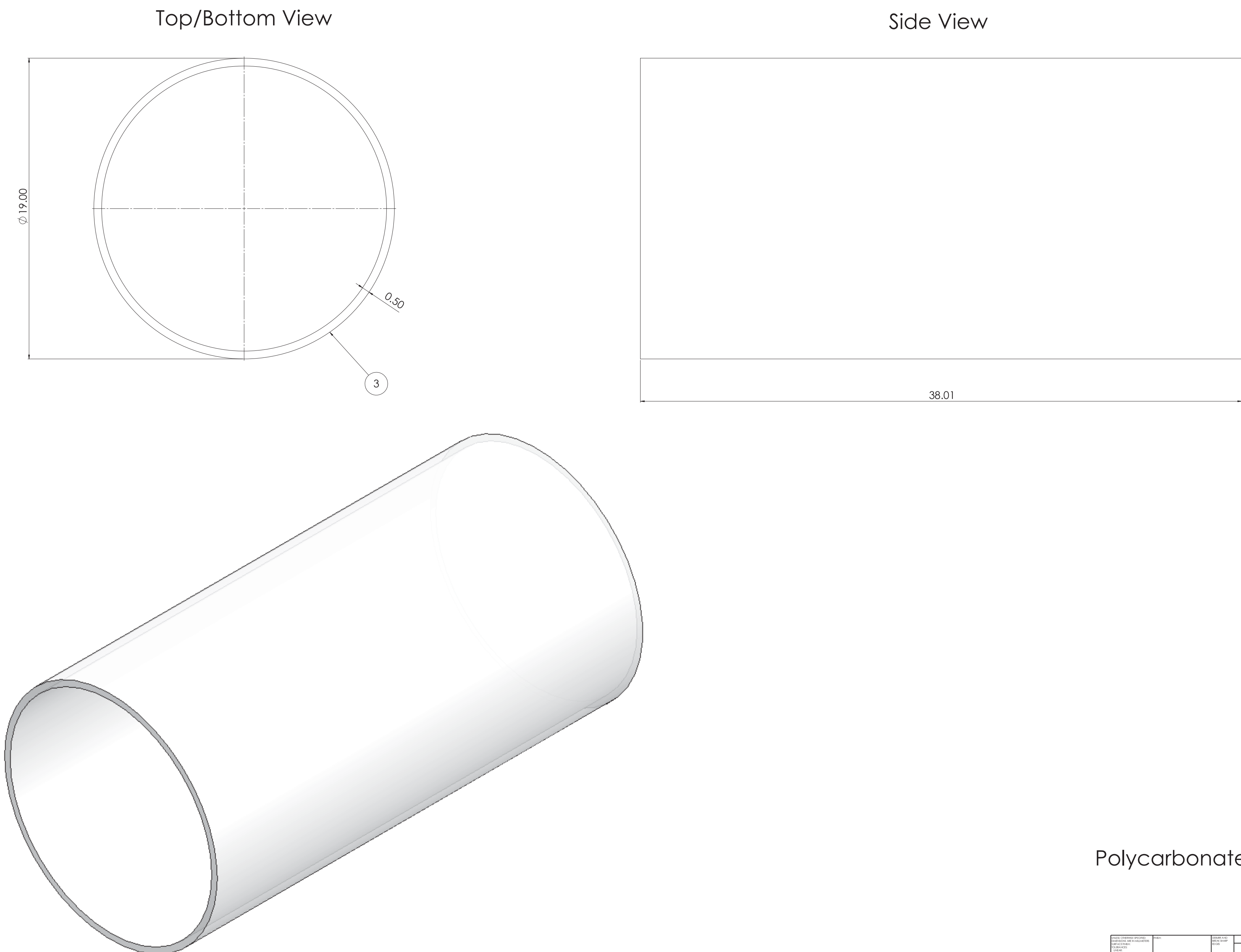
Side View



Central Foam

Optimus-L Basket

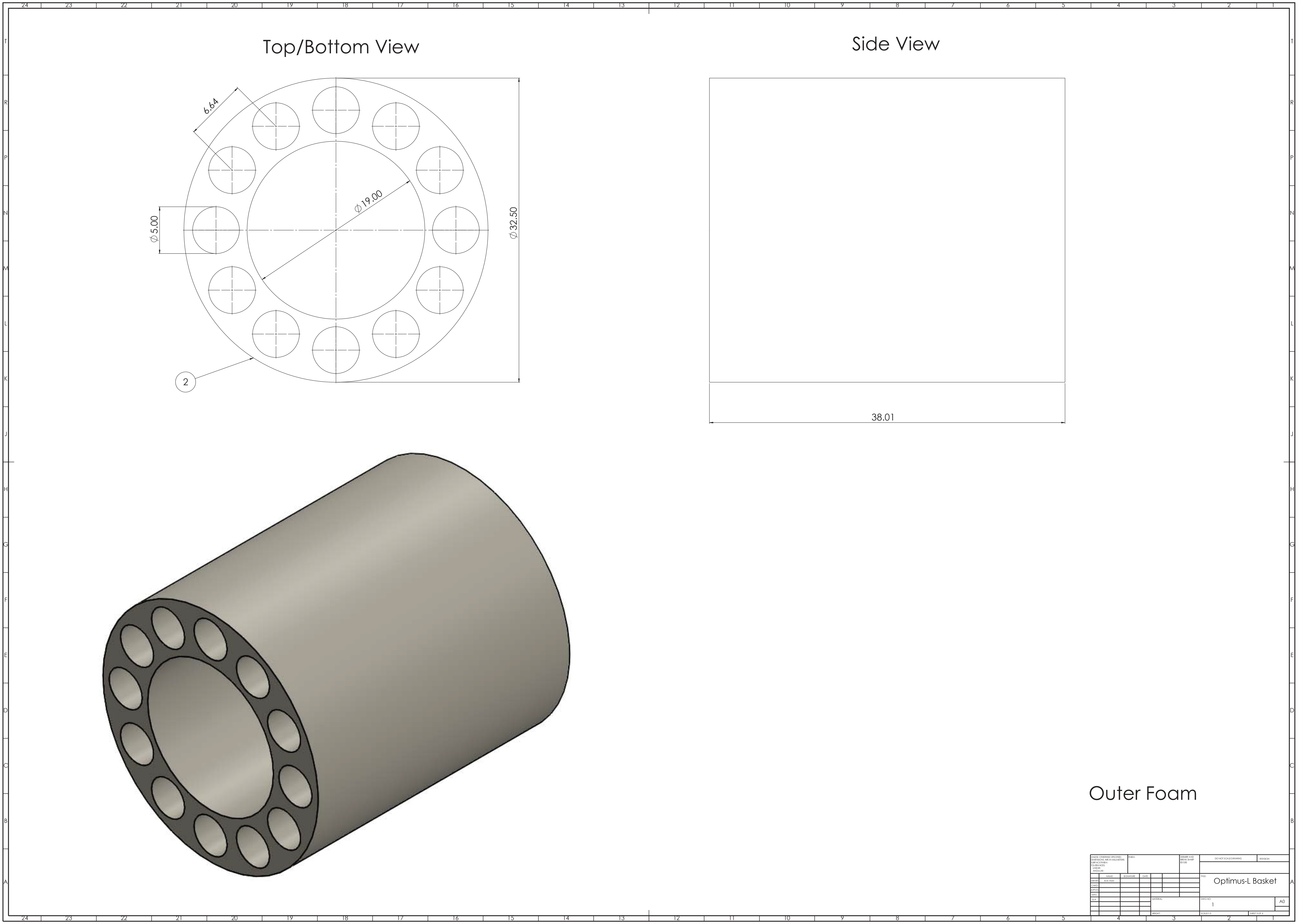
A0

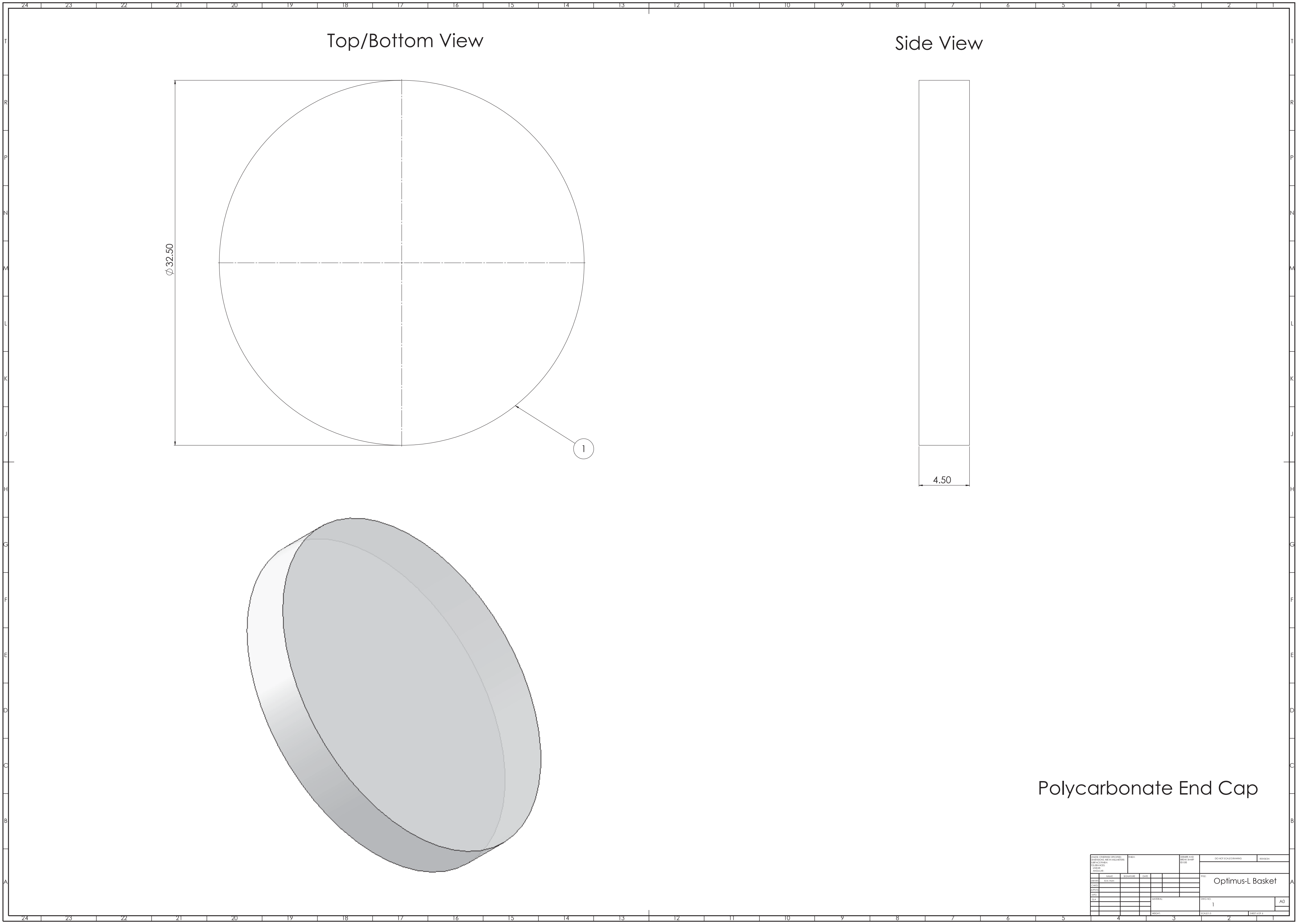


Polycarbonate Liner

Optimus-L Basket

A0


Top/Bottom View
6.64
∅19.00
∅5.00
∅32.50
2
Side View
38.01
Outer Foam
Optimus-L Basket
1
A0


Top/Bottom View
Side View
⌀32.50
1
4.50
Polycarbonate End Cap
Optimus-L Basket
A0
1