INL/MIS-14-31953-Revision-10

AGR-5/6/7 Fuel Fabrication, Process Documentation, and Disposition

Douglas Marshall

September 2016

The INL is a U.S. Department of Energy National Laboratory
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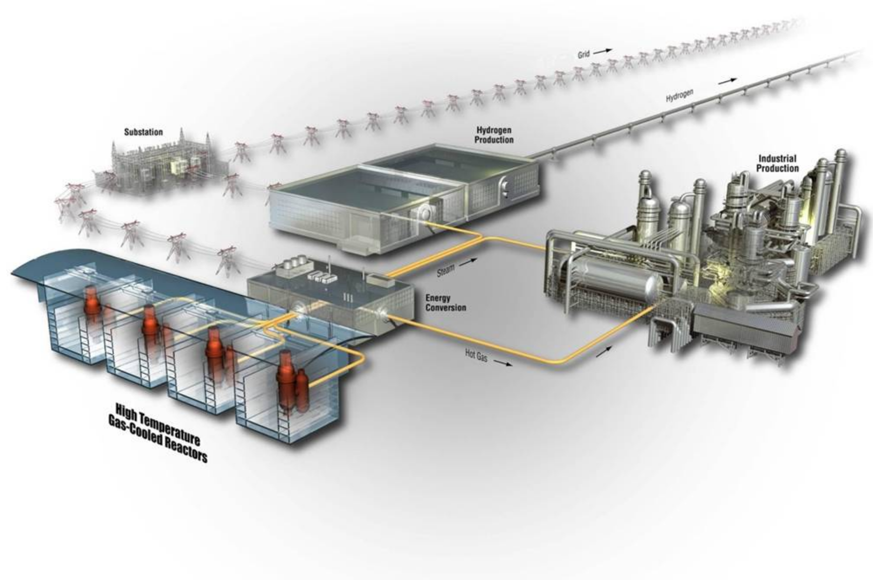
AGR-5/6/7 Fuel Fabrication, Process Documentation, and Disposition



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Signatures

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P For Preparer of the document.

A For Approval: This is for non-owner approvals that may be required as directed by a given program or project. This signature may not be applicable for all uses of this form.

C For documented review and concurrence.

Note: Applicable QLD: MSA-000065

REVISION LOG

Rev.	Date	Affected Pages	Revision Description
0	05/22/2014	All	New document.
1	06/12/2014	7-11	Revised to incorporate comments and exceptions contained in the Subcontractor proposal.
2	07/16/2014	7,9	Deleted references to compacting and cleanup in work scope description to avoid confusion.
3	04/08/2015	All	Add work scope for overcoating and compacting development for compacts with a nominal 25% packing fraction.
4	07/06/2015	6,7-9,13	Include uranium loading to nominal packing fraction statements. Revise estimated completion dates for kernel forming, blending, and sintering activities.
5	10/01/2015	All	Updated subcontractor name to BWXT; updated references to latest revisions; clarified that Carbonization Schedule B Revision 1 is to be used in development; and incorporated AGR-5/6/7 TRISO coating of approved AGR-5/6/7 LEUCO kernels in work scope.
6	11/5/2015	9	Allow compacting development work to be conducted using either low-enriched or natural UCO kernels. Increase allowable pre-burn leach defect fraction (still below the fuel specification) so that kernel batch blending will not be required. Clarify that available resinated graphite matrix will be used.
7	01/18/2016	All	Add AGR-5/6/7 final fuel compacting for 25% and 40% packing fraction compacts, documentation of fuel fabrication processes to be prepared, and requirement for BWXT to prepare a disposition plan for residual materials, waste, and government-furnished equipment.
8	04/05/2016	All	Incorporate changes to the document based on revised completion dates for the various described work scope as a result of issues encountered during TRISO coating.
9	04/27/2016	6-7, 8-9, 12-14, 16-18	Added reference to changes made in Revision 9 to SOW. Added task to conduct preliminary work activities supporting finalization of a disposition plan. Updated deliverable and milestone dates. Minor clarifications.
10	09/09/2016	6, 8, 9, 14, 16, 17	Updated reference document revision information. Revised the delivery date of AGR-5/6/7 fuel compacts and certification package. Deleted redundant revision history.

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1. INTRODUCTION

1.1 Background

The need for United States (U.S.) energy self-sufficiency dictates the development of new low-cost, environmentally-safe forms of energy generation, hydrogen production and industrial heat systems using high temperature gas-cooled reactor (HTGR) technology. Efficient fabrication of ultra-high quality, tristructural isotropic (TRISO) coated particle fuel is a central requirement for implementing gas reactor technology.

BWX Technologies (BWXT) is uniquely qualified in the U.S. with the institutional knowledge, access to equipment, and a Nuclear Regulatory Commission (NRC) license to produce TRISO coated particle nuclear fuel above 5 wt% ^{235}U.

1.2 Purpose/Objectives

The ultimate purpose of this work scope is to produce low enriched uranium carbide/oxide (LEUCO) TRISO coated particle fuel to be fabricated into compacts that are approximately 25 mm (1-inch) long by approximately 12.3 mm (1/2-inch) in diameter for the AGR-5/6/7 experiments. The objectives of the AGR-5/6/7 set of experiments are to qualify the TRISO fuel for future use in an HTGR, establish the U.S. domestic capability to fabricate this fuel, and provide a "margin" test for the AGR TRISO fuel under irradiation conditions.

The AGR Fuel Development and Qualification program has devoted significant resources to define equipment, processes, and operating parameters to fabricate quality nuclear fuel at a near industrial scale. Challenges have been met and overcome, nuances of the fabrication processes have been discovered, and process parameters have been defined.

Surrogate, natural uranium, and LEU fuel forms have been processed to various stages of the fuel fabrication namely, kernels, TRISO coated particles, overcoated TRISO coated particles, and fuel compacts.

The knowledge and understanding of fuel fabrication processes need to be preserved for eventual use in designing and operating a fuel fabrication facility to produce the initial and replacement cores for future HTGRs. This will be accomplished by thorough documentation of the fabrication, upgrading, and analytical processes and methods; including documentation of what has and what has not worked well, strengths and limitations of the current processes, proposals for improvement, corrective actions, etc. INL recognizes that some sections of the documentation may describe equipment and processes that were not funded by the AGR program, which BWXT considers proprietary and business sensitive. Proprietary and business sensitive information as agreed to by both parties shall remain under the control of BWXT and shall not be made available to other parties without BWXT approval.

A disposition plan will be written for GFE procured expressly for the AGR program to preserve essential process capabilities, minimize cost to the U.S. Department of Energy, and minimize encumbrance of BWXT processing facilities. Additionally, a disposition plan for residual chemicals and uranium bearing materials (natural, low enriched, and highly enriched) will be prepared. Consideration must be given to possible future interest in kernels, TRISO coated particles, and fuel compacts by the AGR program, other national laboratories, universities, and/or international collaborators.

1.3 Anticipated Benefits

Completion of this work scope will result in a tested and characterized LEUCO TRISO coated particle fuel type, as submitted by an applicant, suitable for use in either a prismatic or pebble-bed small modular reactor; once fully qualified and approved by the NRC. The fuel form will be available for private entities interested in commercializing nuclear power development for electrical energy, process heat, and/or hydrogen production use. Initial presentations and discussions have been held with the NRC regarding the safety and efficiency of this fuel form for possible use by future applicants to the NRC for reactor licensing.

Documenting the fabrication processes will facilitate the design, commercialization, and operation of a future fuel fabrication facility. Many pitfalls can be avoided by preserving “lessons-learned” information and details on equipment and process weaknesses that can be addressed during the design of a new, full-scale facility. The duration of process startup and process parameter refinement can be shortened by inclusion of information on what worked well and which process parameters successfully fabricated fuel compliant with fuel specifications.

Proper disposition of equipment and uranium-bearing materials will:

A. Minimize storage space and costs for equipment and fuel materials

B. Preserve valuable resource materials for future use, study, and/or irradiations

C. Make residual enriched materials available for use by others.

2. APPLICABLE CODES AND REFERENCES

- American Society of Mechanical Engineers (ASME) NQA-1-2008/-1a-2009 addenda.
- PLN-3662, "Fuel Characterization Plan in Support of NGNP Industrial Fuel Fabrication and Development"
- SPC-1352, "AGR-5/6/7 Fuel Specification"
- SPC-1363, "AGR-5/6/7 Fuel Fabrication Feedstock Chemical Purity Specifications"
- PLN-4352, "Statistical Sampling Plan for AGR-5/6/7 Fuel Materials"
- TFR-831, "AGR Compact Post-Qualification Verification Test Requirements"

3. SCOPE

3.1 Work to Be Performed

The tasks to be performed under this SOW are summarized below:

3.1.1 Uranium Source Material - Completed

INL has identified high-purity, highly-enriched uranium (HEU) oxide source material from within the DOE inventory and secured the transfer of ownership of the source material for down blending with natural uranium to produce LEU feed stock sufficient to produce at least 12 kg of LEUCO fuel kernels.

BWXT shall perform all necessary conditioning required to get the material into an ADUN solution for the kernel forming process.

In order to obtain the 12 kg of LEUCO fuel kernels specified above, a quantity up to 30 kg of starting material will be provided for BWXT to use for training, process start-up, and final fuel fabrication.

3.1.2 LEUCO Kernel Manufacture - Lot J52R-16-69317 Complete, J52R-16-69318 in progress.

BWXT shall fabricate at least 12 kg of 425-µm diameter LEUCO kernels for use in AGR-5/6/7 experiment fuel fabrication.

A. Complete production and characterization of approximately 10 ADUN batch solutions, and approximately 16 kernel forming runs to produce approximately 12 kg of LEUCO kernels.

B. Prepare blend plans to composite these into one or more kernel lots. Following acceptance of the blend plan(s) by INL, BWXT shall composite the kernels and shall prepare summary tables showing compliance of the kernel lots with the specifications given in SPC-1352.

C. Mount and section a minimum of 1,000 kernels from the kernel lot (or pooled batch data) to quantify the surface-connected fissure (a.k.a., lenticular void) fraction. The target surface-connected fissure fraction is less than 2.0e-2 at 95% confidence (based on kernel lot G73AG-NU-69311 results and rounded up) unless modified by mutual agreement between BWXT and INL.

Definition: *A surface-connected fissure is any fissure extending into the carbide-rich interior that has an oxide-rich phase along the fissure perimeter; regardless of visual evidence on the metallographic mount for surface connectivity.*

D. Prepare a data package for the LEUCO kernels, including the input chemicals' certificates, process parameters, and characterization data from kernel batches and composite lots. BWXT shall retain 3 to 5-g samples from each of the individual kernel batches and the blended lots.

3.1.3 Preparations and Testing for Compacts with Nominal 25% Packing Fraction – Complete

The AGR-5/6/7 experiment design requires compacts to be fabricated with nominal 40% and 25% packing fractions to meet the test objectives. Compacts with a nominal 40% packing fraction have been previously fabricated successfully. The second set of compacts requires a nominal 25% packing fraction (0.91±0.06 gU/compact)[1]. This will involve defining a matrix overcoating scheme targeting the lower uranium loading in the fuel compacts and forming compacts.

BWXT shall devise a method of overcoating TRISO coated fuel particles in Freund-Vector Lab-3 Granuex® equipment, compacting the overcoated particles, and heat treating the compacts targeting the nominal 25% packing fraction.

Demonstrating the ability to overcoat TRISO coated fuel particles at a nominal 25% packing fraction will show that the equipment is capable of being used for fuel fabrication that supports a zoned fuel loading scheme for the first core of a prismatic HTGR.

[1] The uranium loading specification was changed to 0.90 ± 0.08 gU/compact in SPC-1352 Rev. 7 after this work was completed.

A. Overcoat a batch of UCO TRISO coated particles that have an exposed kernel defect fraction (pre-burn leach) less than 4e-5 (95% confidence) with matrix material. The nominal packing fraction shall be determined using kernel and TRISO particle properties to target 0.91±0.06 gU/compact[1].

B. Sieve the overcoated particles to reject particles with compound kernels.

C. Perform a compacting test matrix consisting of one compacting schedule (Table 3 of TFR-831, Section 4.4.4.3; k_{eff} = 5.4 W/m·K) in combination with three ram force setpoints of 4.0, 4.5, and 5.0 kN (respectively corresponding to nominal forming pressures of 8, 9, and 10 MPa). Produce ~84 compacts for each combination (totaling ~ 252 compacts) using a common overcoated particle batch.

D. Characterize the green (non-heat treated) compacts for length, diameter, and weight. Visually examine the compacts for indications of adverse processing conditions. Ensure compact traceability during the measurements.

E. Carbonize each compact set using Carbonization Schedule B Revision 1 in TFR-831 (Section 4.5). Heat-treatment of the compacts shall be a continuous, combined cycle with carbonization.

F. Characterize the compacts in task 3.1.3.E for length, diameter, and weight. Visually examine the compacts for surface flaws and document photographically. Ensure compact traceability during the evaluation.

G. Quantify the matrix density and packing fraction for each compact set in tasks 3.1.3.C.

H. Using the data from tasks 3.1.3.D, 3.1.3.E, and 3.1.3.F, select one forming force for further investigation and characterization. The objectives are to minimize axial growth of the compact during carbonization while keeping matrix density above 1.70 g/cc.

I. Select and install, as necessary, a loader insert with a cavity volume designed to attain an acceptable compact length for the nominal 25% packing fraction compacts (SPC-1352).

J. Sieve the overcoated particles to reject particles with compound kernels. Sample the overcoated particles for pre-burn leach analysis (if deemed necessary).

K. Press, carbonize, and heat-treat at least 400 compacts from the parameter combination selected in task 3.1.3.H. Characterize the compacts in the “green” and heat-treated states for length, diameter, and weight.

L. Perform a deconsolidation and pre-burn leach analysis on compacts from task 3.1.3.J. Refer to PLN-4352 for the statistical sample size.

M. Determine the mean packing fraction and mean matrix density of the compact population.

N. Perform a pre-burn leach on the residual population of overcoated particles if a sufficient sample size remains. Methodology for this testing shall be mutually agreed upon between INL and BWXT as no standard method currently exists for this material type.

3.1.4 Readiness Review – Completed in February 2016

BWXT shall allow INL personnel to conduct a readiness review prior to AGR-5/6/7 production LEUCO TRISO coated particle fabrication runs. BWXT shall make a reasonable effort to provide access to unclassified data and processing areas associated with TRISO coated particle fabrication.

3.1.5 AGR-5/6/7 TRISO Coating of Certified LEUCO Kernels – Upon successful completion of readiness review in Section 3.1.4

BWXT shall fabricate, blend, and certify a quantity of TRISO coated LEU fuel particles using certified LEUCO kernels as follows.

A. A minimum of five TRISO coating batches shall be produced.

B. At least three TRISO coating batches shall be blended into a certified lot for AGR-5/6/7 compact fabrication.

C. The mass of certified TRISO coated fuel particles shall exceed 8 kg.

BWXT shall submit a TRISO particle certification data package to INL.

3.1.6 AGR-5/6/7 Pressing of 25% and 40% Packing Fraction Compacts

BWXT shall use the certified AGR-5/6/7 coated particle fuel described in Section 3.1.5 and process parameters selected from compacting development work performed for 25% and 40% packing fraction compacts to fabricate the compacts that will be used in the AGR-5/6/7 irradiation at INL. Not less than 100 compacts of nominal 25% packing fraction and 140 compacts of nominal 40% packing fraction, from certified batches, shall be packaged and shipped to INL for use in the test train. A similar quantity will be used for quality assurance purposes, and the remainder will be shipped to INL for archive purposes.

Compact sets shipped to INL for irradiation shall originate from two or more compact batches of the respective packing fraction. Compacts shall be individually packaged with an identification code on the container linked to the production batch, packing fraction and the measured physical dimensions (size and mass) of the individual compact.

3.1.7 Fuel Fabrication Process Documentation

BWXT shall document the processes developed during the AGR fuel fabrication campaign over the past 12 years to make it possible for the processes to be duplicated in the future when a reactor operator chooses to design and construct an HTGR that utilizes TRISO fuel. The parts of the processes that have been established as proprietary to BWXT are to be documented but shall be retained by BWXT for at least 25 years after end of program. The intent of this documentation is to provide a comprehensive description of the equipment, processing parameters used, lessons learned, known weaknesses and proposed enhancements as related to fabrication of the AGR program fuel.

3.1.8 Preparation of Disposition Plan

BWXT shall prepare and submit a disposition plan for disposition of the residual materials, wastes, and GFE that remain from the AGR fuel fabrication processes that have taken place at BWXT. The disposition plan and strategy will be agreed to by both parties and a subsequent revision to this SOW will incorporate the final quantities, disposition paths, pricing, and completion dates. Preference is given to established disposition paths.

3.1.9 Preparations to Execute the Disposition Plan

BWXT shall conduct preliminary activities to facilitate preparation of the disposition plan and timely execution of the disposition plan. At the discretion of BWXT, this may include detailed inventories of materials and equipment, co-location of materials with similar disposition paths, and obtaining any necessary descriptions, approvals and authorizations for waste streams, etc.

3.2 Informal Process Documentation and Teleconferences

BWXT shall hold weekly teleconferences with INL personnel to report status of tasks and discuss weekly progress and future plans.

3.3 Responsibilities

3.3.1 Chemical Feedstock Purity

BWXT shall ensure that feedstock chemicals meet the requisite purity specification (SPC-1363) prior to use for the work described in this SOW or obtain prior approval from INL to use a feedstock chemical that is not fully compliant with the specification.

3.3.2 Kernel Fabrication

BWXT is responsible to down-blend HEU from the DOE NGNP inventory with natural uranium to achieve the specified LEU enrichment per SPC-1352.

BWXT is responsible to characterize LEU fuel material properties and attributes in accordance with the sampling plan, PLN-4352.

BWXT shall perform all process design, development, upgrades, testing, manufacturing, and quality control testing to fabricate the kernels required for fuel fabrication, qualification and manufacturing activities as described in Section 3.1.1 and 3.1.2.

3.3.3 TRISO Particle Fabrication

BWXT is responsible to fabricate, blend, and characterize TRISO coated fuel particles for AGR-5/6/7 experiment as described in Section 3.1.5.

3.3.4 Overcoating and Compact Pressing

BWXT is responsible to overcoat TRISO coated fuel particles, press and characterize them into compacts with nominal 25% and 40% packing fractions as described in Section 3.1.6.

3.3.5 Process Documentation

BWXT is responsible to thoroughly document the fuel fabrication processes, steps, lessons learned, and identify those parts of the fuel fabrication where particular care must be taken to achieve the fuel specifications. It is understood that certain steps in the fuel fabrication process are susceptible to operational skill and should be specifically noted.

3.3.6 Disposition Plan for Residual Materials, Wastes, and GFE

BWXT is responsible to develop a disposition plan for the residual materials, wastes, and GFE remaining at the BWXT facility after completion of the fabrication and shipment of AGR-5/6/7 experiment compacts.

INL is responsible to work with BWXT to develop the disposition plan, approve the disposition paths as determined to be in the best interests of the U.S. government, and provide the funding needed to complete the approved dispositions prior to shipment of the AGR-5/6/7 compacts to INL.

INL is responsible to identify locations for storage of residual materials retained by the AGR program, approve the disposition of waste per available BWXT waste streams, and establish a disposition for each piece of GFE located at BWXT. GFE may be abandoned in place and ownership transferred to BWXT, transferred to another DOE-Nuclear Energy program at BWXT, or removed from the BWXT facility for disposal or repurposing.

3.4 Risk-Based Process Control and Management

BWXT shall employ a risk management scheme and plan for the purpose of identifying and resolving foreseeable process failure modes, consequences of those failures, and managing the associated risks to worker safety, process reliability, and product quality as they apply to the production of TRISO coated particle fuel and compacts for the AGR Fuel Fabrication program. BWXT shall determine root causes and corrective actions including replacement schedules for implementation of fabrication runs that are aborted.

3.5 Work Excluded

The final disposition of waste, residues, and GFE is excluded from this work scope until the waste disposition plan described in Section 3.3.6 is approved by both parties and included in a subsequent revision to this Statement of Work.

3.6 Requirements

Additional technical and functional requirements are given in TFR-831, "AGR Compact Post-Qualification Verification Test Requirements." Sampling shall comply with the requirements given in PLN-4352, "Statistical Sampling Plan for AGR-5/6/7 Fuel Materials." Fuel shall comply with specifications given in SPC-1352, "AGR-5/6/7 Fuel Specifications."

3.6.1 Environmental Requirements

BWXT shall comply with its internal environmental requirements.

3.6.2 Safety and Health

BWXT shall comply with its safety and health requirements.

3.6.3 Radiological Requirements

BWXT shall comply with its radiological requirements as applicable to operations, equipment maintenance, and waste management.

3.6.4 Quality

All work shall be performed under an ASME NQA-1-2008/-1a-2009 compliant quality assurance program including any contractually granted waivers.

Operating personnel shall be trained in the use of the equipment and the operating procedures prior to performing process operations. BWXT shall make reasonable efforts to utilize technical and operations personnel who are experienced with the unit processes and applicable procedures.

3.6.5 Security

BWXT shall comply with its security requirements.

3.7 Place of Performance

All work will be performed at the BWXT facility in Lynchburg, Virginia.

3.8 Interfaces

None

4. DELIVERABLES

4.1 Preparation of LEUCO Kernels

BWXT shall prepare approximately 12 kg of LEUCO kernels with full characterization data for INL review and approval. BWXT shall prepare and provide blend plans to INL for review and approval prior to commencement of kernel batch blending into a single lot. BWXT shall provide a data package characterizing the LEUCO kernel lot.

4.2 Overcoating and Compact Development for Nominal 25% Packing Fraction Compacts

BWXT shall issue a report documenting the overcoating and compacting development and qualification work performed including photographs and characterization data as well as non-proprietary process parameters. This report shall be issued within 45 days of completion of the compact characterization.

4.3 LEUCO TRISO Coated Fuel Particle Lot

BWXT shall issue a report certifying the LEU TRISO coated fuel particles to SPC-1352 and documenting the mass of fuel particles in the certified lot. This report shall be issued within 30 days of completion of the fuel particle lot certification.

4.4 Compact Batches

BWXT shall issue a report certifying the nominal 25% and 40% packing fraction compacts to SPC-1352 and documenting the qualification of the compacts in the certified batches for each packing fraction. This report shall be issued within 30 days of completion of the compact certifications.

5. SCHEDULE AND MILESTONES

5.1 Interim Schedule Dates

Forming of the Phase I LEUCO kernels was completed in January 2016. Sintering, upgrading of the Phase I LEUCO kernel batches, lot blending and certification were completed in May 2016. Phase II kernel forming, sintering, blending, upgrading, and certification will take place when time permits during the TRISO particle coating and compacting activities for AGR-5/6/7.

5.2 Schedule Development

Within 21 calendar days of receiving formal direction from INL to proceed with this work scope, BWXT shall provide a detailed schedule of the activities associated with these tasks for INL review and acceptance.

5.3 Milestones

BWXT shall participate in a review conducted by INL to assess BWXT readiness to commence LEU TRISO coated particle fuel fabrication by February 25, 2016. – Completed on February 25, 2016.

BWXT shall complete compacting process development for compacts containing 0.91±0.06 gU/compact and delivery of a summary report to INL by July 15, 2016. – Completed July 28, 2016.

BWXT shall prepare and submit a proposed disposition plan by April 28, 2016 for any residual materials, wastes, and GFE remaining at their facility upon completion of AGR-5/6/7 fuel fabrication efforts. INL will work with BWXT to finalize the disposition plan, establish locations for materials to be archived, and transfer or turnover of GFE as determined to be in the best interests of the U.S. government. – Completed April 27, 2016.

BWXT shall complete pressing of LEU fuel compacts at nominally 25% and 40% packing fraction, and ship the compacts for receipt at INL by March 16, 2017. The certification data package(s) for the two compact lots shall be transmitted to INL by August 16, 2017.

BWXT shall work with INL to complete disposition of uranium bearing materials and Government Furnished Equipment (GFE) by December 21, 2017.

6. COMPLETION CRITERIA AND FINAL ACCEPTANCE

6.1 LEUCO Kernel Fabrication and Characterization

The work will be completed when the LEUCO kernels have been fabricated and blended, with characterization performed and documented. The deliverables will be accepted after examination of the documentation by INL personnel and concurrence with the contents/results.

6.2 Compact Development and Qualification for Nominal 25% Packing Fraction

This work scope shall be complete when the compacts have been fabricated and characterized documenting successful completion and meeting the applicable specifications. The deliverables will be accepted after examination of the documentation by INL personnel and concurrence with the contents and results.

6.3 LEU TRISO Coated Fuel Particle Lot Certification

This work scope shall be complete when a LEU TRISO coated fuel particle lot has been fabricated, blended, and certified to the fuel specification in accordance with the SOW. The deliverable will be accepted after examination of the TRISO coated fuel particle certification document.

6.4 Compact Certification

This work scope shall be complete when 25% and 40% packing fraction compact batches have been pressed and certified to the fuel specification in accordance with the SOW. Deliverables will be accepted after examination of the compact certification documents.

7. EQUIPMENT PURCHASES

BWXT shall obtain approval from INL for purchases of equipment in conjunction with executing this SOW if the equipment meets either of the following criteria:

- Sensitive equipment (computers, cameras, and handheld electronic devices susceptible to personal use) individually valued over $1,000.

- Durable equipment individually valued over $5,000.

INL may provide BWXT with U.S. Government property identification/tracking stickers, which are to be applied to equipment meeting the criteria above.

Consumable materials, substances, and equipment (graphite furnace components, laboratory supplies, chemicals, etc.) are exempt from requirements for prior approval and tracking.

8. APPENDICES

None

9. ATTACHMENTS

None