INL/MIS-17-41472-Revision-1

POST-IRRADIATION EXAMINATION AND SAFETY TESTING OF AGR-2 PEBBLE BED MODULAR REACTOR FUEL AT OAK RIDGE NATIONAL LABORATORY

David Laug

Changing the World's Energy Future

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-17-41472-Revision-1

POST-IRRADIATION EXAMINATION AND SAFETY TESTING OF AGR-2 PEBBLE BED MODULAR REACTOR FUEL AT OAK RIDGE NATIONAL LABORATORY

David Laug

December 2018

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

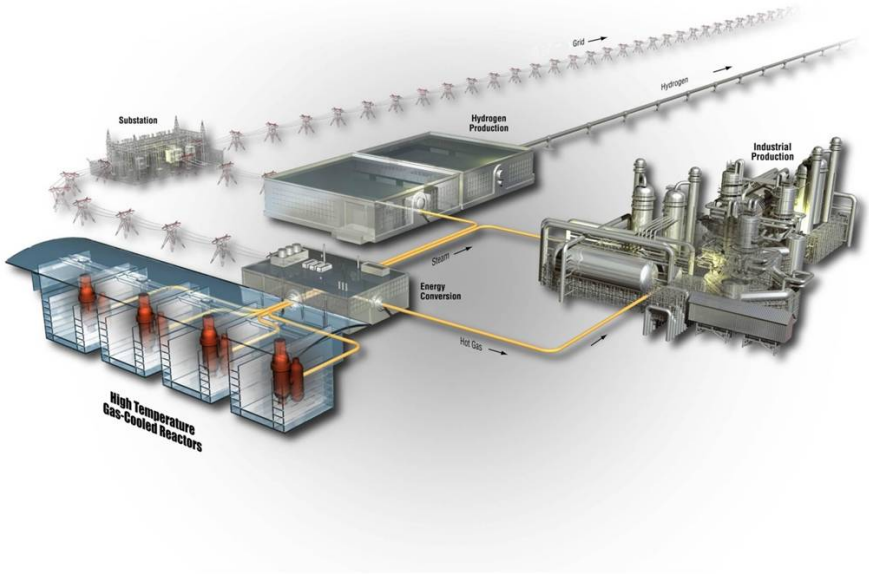
Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract Unknown

Document ID: SOW-13882
Revision ID: 2
Effective Date:12/03/2018
INL/MIS-17-41472

Statement of Work

Project No(s): 23841, 29412

Post-Irradiation Examination and Safety Testing of Pebble Bed Modular Reactor LTD Fuel at Oak Ridge National Laboratory



The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

Idaho National Laboratory

SIGNATURES

Signature and Typed or Printed Name	Signature Code	Date (mm/dd/yyyy)	Organization/Discipline
David V. Laug	P	11/30/18	C600/INL Fuels PIE Technical Lead
John D. Hunn	A	11/30/18	ORNL, AGR PIE Technical Lead
Paul A. Demkowicz	A	12/3/18	C600/INL ART TRISO Fuel Director
Michelle T. Sharp	C	12/3/18	H330/INL Quality Engineer

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.

C For documented review and concurrence.

Note Quality Level 3 (QL3)

REVISION LOG

Rev.	Date	Affected Pages	Revision Description
0	04/11/2017	All	New document
1	4/24/2017	11	Delete section 3.3.1 and renumber subsequent subsections
2	12/03/2018	All	Updated with FY19 work scope and schedule

CONTENTS

1. INTRODUCTION 6

1.1 Background 6

1.2 Purpose/Objectives 6

1.3 Anticipated Benefits 7

2. APPLICABLE CODES AND REFERENCES 7

3. SCOPE 7

3.1 Work to Be Performed 7

3.1.1 Provide Oversight and Technical Support 7
3.1.2 Training and Qualification 8
3.1.3 Compact Receipt and Inspection 8
3.1.4 Deconsolidation and Leach-Burn-Leach 9
3.1.5 Particle Analysis and Irradiated Microsphere Gamma Analyzer 9
3.1.6 Sample Preparation and Microanalysis 9
3.1.7 CCCTF Operations 10
3.1.8 CCCTF Deposition Cup and Component Analysis 10
3.1.9 Waste Handling 10
3.1.10 Project Reporting 10

3.2 Work Excluded 11

3.3 Requirements 11

3.3.1 Environmental 11
3.3.2 Safety and Health 11
3.3.3 Quality Assurance 11

3.4 Place of Performance 11

3.5 Interfaces 11

3.6 Miscellaneous 11

4. RESPONSIBILITIES 11

4.1 INL 11

4.2 ORNL 12

5. DELIVERABLE SCHEDULE 12

6. COMPLETION CRITERIA AND FINAL ACCEPTANCE 12

7. APPENDICES 12

8. ATTACHMENTS..... 12

1. INTRODUCTION

1.1 Background

A cooperative research and development agreement (CRADA) has been established between Pebble Bed Modular Reactor (PBMR) State Owned Company (SOC) Ltd. of the Republic of South Africa and Battelle Energy Alliance, LLC (BEA), the managing and operating contractor of Idaho National Laboratory (INL). The objective of this agreement is to conduct safety tests and destructive post-irradiation examination (PIE) on compacts containing tristructural isotropic (TRISO) coated particle fuel that was provided by Necsa (for PBMR and title transferred to the Department of Energy) and irradiated in the Advanced Test Reactor in Capsule 4 as part of the Advanced Gas Reactor (AGR)-2 experiment performed under a previous CRADA (08-CR-12). The proposed safety testing and post-test examination will assist with assessing fuel performance during high-temperature reactor accident conditions.

Due to different capabilities, some work will be performed by Department of Energy's Oak Ridge National Laboratory (ORNL) under a separate agreement. This statement of work describes the work scope to be performed by ORNL in support of the CRADA. Based on consultation with PBMR and ORNL, INL may modify the scope of work to be performed at ORNL. In particular, data from initial tests and examinations may result in scope modification as necessary.

1.2 Purpose/Objectives

The PBMR PIE work at ORNL includes:

1. Providing management support and oversight to planned activities
2. Making preparations for and performing compact receipt, offloading, and initial inspection following shipment from INL to ORNL
3. Performing irradiated fuel compact deconsolidation and leach-burn-leach (DLBL) analysis
4. Performing visual inspection and irradiated microsphere gamma analysis (IMGA) of individual irradiated particles
5. Performing microanalysis of particles using various techniques, including optical and electron microscopy, elemental analysis, and x-ray microtomography, followed by focused ion beam milling of specimens for electron microscopy at Nelson Mandela University.
6. Performing safety testing using the Core Conduction Cooldown Test Facility (CCCTF) and post-test analysis
7. Performing waste handling and disposition.

Experiments on irradiated fuel compacts will be performed as described in individual Compact Examination Plans transmitted from INL to ORNL. These will include specific data requirements and testing necessary for each compact and will be prepared in coordination with INL and ORNL staff prior to the start of PIE on the fuel specimens.

1.3 Anticipated Benefits

The primary objective of these activities is to better understand low-enriched uranium dioxide TRISO fuel performance—in particular, fission product release behavior during irradiation and during high temperature accident simulations, and the effects of neutron irradiation and temperature on properties of the TRISO fuel, such as particle coating layer microstructures.

2. APPLICABLE CODES AND REFERENCES

ASME NQA-1-2008/1a-2009, Part I is applicable to the work scope performed.

Stevenson-Wydler (15 USC 3710a) Cooperative Research and Development Agreement (CRADA) No. 16-CR-05.

3. SCOPE

3.1 Work to Be Performed

Four compacts have been selected for testing and analysis in consultation with PBMR. The compacts are listed in Table 1, along with a brief description of the proposed use for each. Figure 1 presents a simplified flow chart describing the tentative work flow for the four compacts selected for this activity. Note that some decisions involving this plan (including safety test temperature for several of the compacts, and selection of safety-tested compacts for post-test destructive examination) are to be determined (TBD) at a later time based on results from earlier tests.

Table 1. PBMR compacts selected for examination

Compact ID	Testing and Analysis
4-3-1	Safety testing at 1600°C and post-test examination
4-2-1	Safety testing at 1600°C and post-test examination
4-1-2	Safety testing up to 1800°C; post-test analysis not planned
4-3-2	As-irradiated destructive examination

3.1.1 Provide Oversight and Technical Support

ORNL will support the INL ART PBMR PIE effort by performing PIE work scope as identified in Figure 1 and discussed below; providing technical input, analysis, and expertise; and preparing detailed reports based on experimental results. This work scope includes the general oversight of the ORNL PIE activities identified below and reporting on a bi-weekly and monthly basis as requested. Milestones related to completion of work on certain high priority activities have been established between INL and ORNL with deliverables prepared to provide the objective evidence of having completed the activities.

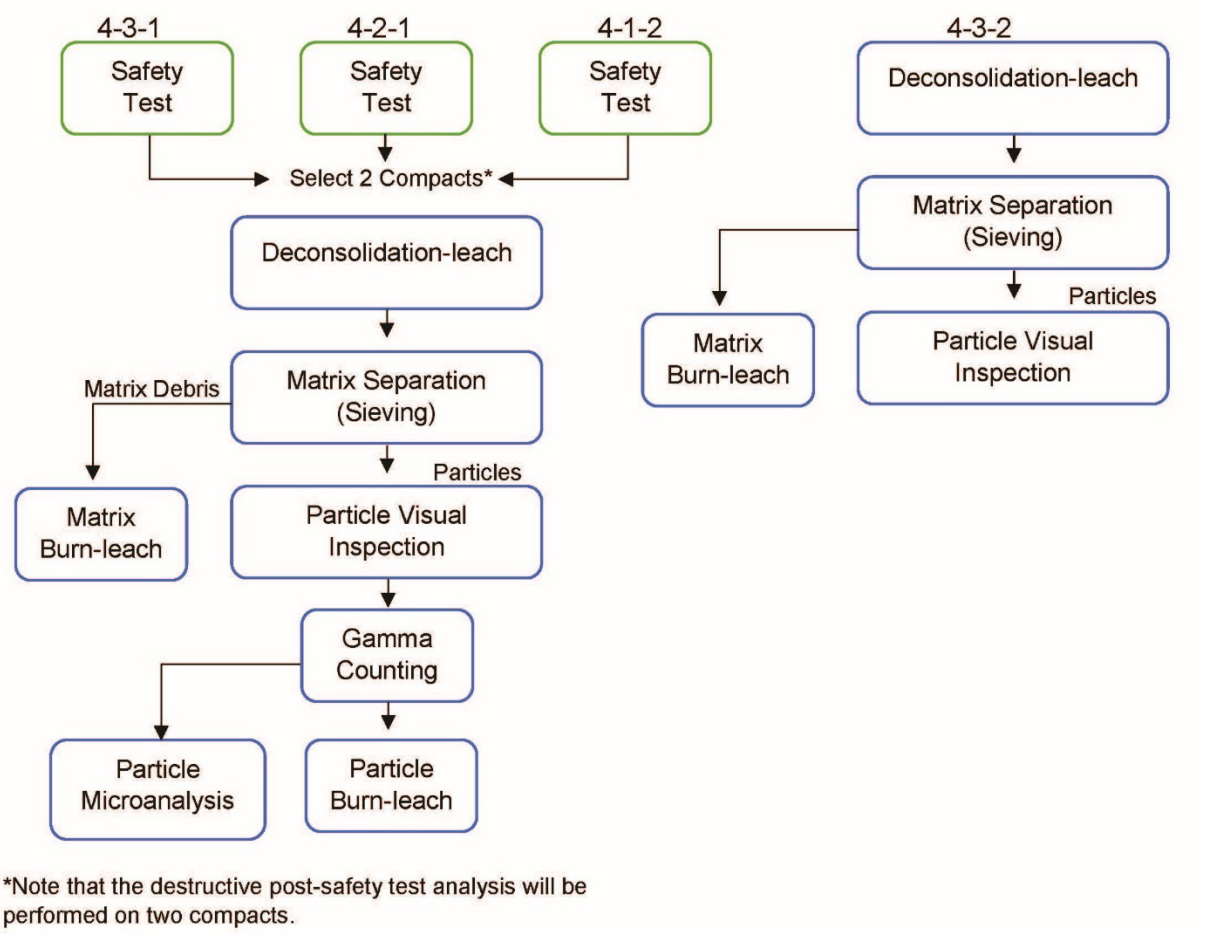


Figure 1. Proposed safety testing and analysis work flow on four PBMR Compacts (note that Gamma counting has been deleted for Compact 4-3-2.

3.1.2 Training and Qualification

ORNL will perform training and qualification of operators and staff as necessary, develop or revise PIE procedures as required, maintain and upgrade the ORNL Quality Assurance Plan to include any new PIE activities, and maintain and update as necessary the ORNL Software Quality Assurance Plan.

3.1.3 Compact Receipt and Inspection

This task includes receipt and unloading of one planned compact shipment. Four irradiated compacts will be sent from INL to ORNL, packaged in DOT Type A transportation packages. After receipt and unloading, the compacts will be visually inspected, decontaminated as necessary, and the shipping packages will be returned to INL.

3.1.4 Deconsolidation and Leach-Burn-Leach

Designated irradiated compacts will undergo DLBL analysis using equipment installed in the shielded hot cells at the Irradiated Fuel Examination Laboratory. This activity is used to deconsolidate the compact matrix to liberate individual particles, quantify the isotopic inventory outside of intact SiC coatings, and help determine if any particles with a defective SiC layer are present in the compact by performing analysis (gamma-ray and mass spectrometry) of the leaching solutions. It is expected that a total of three compacts will be subjected to this procedure (see Table 1 and Figure 1).

3.1.5 Particle Analysis and Irradiated Microsphere Gamma Analyzer

Individual irradiated particles (generated from compact deconsolidation as described above) will be visually inspected using the Particle Micro-Manipulator, with specific particles selected for subsequent analyses as needed. Particles from selected compacts will then be gamma counted using the advanced irradiated microsphere gamma analyzer (IMGA) device to quantify the inventory of gamma-ray-emitting radioisotopes. This activity will help to identify particles that may have damaged coating layers causing abnormally high fission product release and provide information on the extent of diffusive release of selected fission metals.

3.1.6 Sample Preparation and Microanalysis

This activity will include materialographic sample preparation of individual particles using methods established previously at ORNL. If warranted, selected particles will be characterized by non-destructive x-ray tomography prior to this step in order to examine the interior kernel and coating morphology, with particular emphasis on defective particles identified by IMGA. Materialographic specimens will be characterized using a number of techniques, as appropriate, including: optical microscopy, scanning electron microscopy with elemental analysis (energy dispersive x-ray spectroscopy, and wavelength dispersive x-ray spectroscopy). Other advanced techniques, such as transmission electron microscopy may also be used to characterize the particles, determined based on consultation with INL staff. In addition to particles from the irradiated compacts, materialography will also be performed on unirradiated AGR-2 PBMR particles.

Specimens will be micromachined with a focused ion beam from some of the materialographic specimens and shipped to Nelson Mandela University for thinning and transmission electron microscopy.

The goals of this activity are to investigate the detailed microstructures of particle kernels and coating layers, identifying any coating degradation that may have occurred during irradiation or safety testing and identifying the location of fission products or actinides within the coating layers. This will provide a better understanding of the effect of irradiation on particle microstructures, the mechanisms of fission product transport through the coating layers, and possible particle failure mechanisms. This activity will also include the maintenance and repair of the associated analytical instruments as needed.

3.1.7 CCCTF Operations

This activity includes performing high-temperature safety testing on as-irradiated PBMR compacts. A safety test includes heating the fuel compact in the CCCTF furnace to the specified target temperature (typically 1600 to 1800°C) for the specified time (typically 300 hours), while monitoring the time-dependent release of fission gas Kr-85 and condensable fission products collected on hot-swapped deposition cups. The work will involve maintenance and repair of the CCCTF furnace, operation of the furnace during safety testing, monitoring of the CCCTF fission gas collection system for Kr-85, and change out and initial gamma analysis of the deposition cups.

3.1.8 CCCTF Deposition Cup and Component Analysis

Following safety testing, the internal components (in particular the graphite fuel holder, tantalum liner, and gas inlet tube) of the CCCTF furnace will be removed for radiochemical analysis for selected fission products. Deposition cups will also be subjected to supplemental gamma monitoring, if needed, followed by leaching for additional radiochemical analysis of the deposition cups to measure non-gamma-emitting isotopes.

Post-safety test PIE on the fuel compacts will be performed as detailed above, including DLBL, IMGA, and microanalysis as required based on discussion with the INL staff.

3.1.9 Waste Handling

This task includes the non-radiological and radiological waste handling and disposition from PBMR PIE and safety testing activities to be performed at ORNL.

3.1.10 Project Reporting

ORNL will participate in reviews of data, discussions with INL and PBMR staff, interactions with PBMR staff when visiting the laboratory to observe work in progress (schedule for such visits is still to be determined), and prepare technical reports on the results as agreed upon by INL, PBMR, and ORNL staff. Preliminary results from various stages of the work (e.g., safety testing results, deconsolidation leach/burn leach, and IMGA results) will be shared and discussed with INL and PBMR technical staff to make decisions on the path forward for subsequent analyses.

The final report, co-authored by INL and ORNL staff, will include the findings from all stages of the work and a description of the experiments performed and relevant data acquired. Overall data reported will include the following:

- Analysis results of furnace components for all three tests
- Compact fractional inventory of fission products released during the safety tests, based on as run inventory calculations
- Compact fractional fission product inventories outside of SiC, as determined by the deconsolidation leach burn leach and based on as run inventory calculations

- Results of particle inspection and gamma analysis of individual particles
- Discussion of particle microstructures, including any unusual particle, kernel, or coating behavior that may be linked to fission product releases.

INL or ORNL may, at the request of PBMR, host a meeting with members of the PBMR technical team following the preparation of a draft final report. The purpose will be to review all experimental results and discussion data and conclusions. The location of this meeting is still TBD. Discussions that take place at this meeting will be incorporated into the final report, as appropriate.

3.2 Work Excluded

Only work scope related to PBMR fuel PIE and safety testing is included. All other work scope is specifically excluded.

3.3 Requirements

3.3.1 Environmental

Work will be performed in accordance with applicable ORNL requirements.

3.3.2 Safety and Health

Work will be performed in accordance with applicable ORNL requirements.

3.3.3 Quality Assurance

ORNL will perform this work in accordance with its approved quality assurance program in compliance with ASME NQA-1-2008/1a-2009 criteria. INL ART Quality Assurance may elect to perform work inspections of selected processes. The INL and ORNL technical leads will identify the selected processes for inspection. INL will supply the inspection checklist to ORNL approximately three weeks prior to the inspection.

3.4 Place of Performance

The work scope identified in this statement of work (SOW) will be performed at various facilities at ORNL.

3.5 Interfaces

Interfaces will be between INL and ORNL technical representatives.

3.6 Miscellaneous

Preparations of presentations and reports, and travel will be included within this work scope in order to share the results found. This is expected and will be charged to the appropriate activity being supported.

4. RESPONSIBILITIES

4.1 INL

The INL is responsible to ship four PBMR compacts to ORNL for PIE and Safety Testing by 5/31/2017.

4.2 ORNL

ORNL is responsible for completion of the work scope outlined in Section 3. The deliverable schedule is defined in the next section.

5. DELIVERABLE SCHEDULE

Activity Description	Completion Date	Deliverable
ORNL to provide report of one PBMR safety test performed	12/15/2017	ORNL/LTR-2017/521 submitted to INL on 10/18/2017.
ORNL to provide a report on the destructive examination of the “as irradiated” PBMR compact	3/31/2018	ORNL/LTR-2018/488 submitted to INL on 3/27/2018.
ORNL to provide a report of the remaining two PBMR safety tests performed	8/15/2018	Report submitted to INL for review.
ORNL to provide a final summary report of all PBMR PIE, including results from any additional destructive examination of two PBMR safety tested compacts	8/31/2019	Report submitted to INL for review.

6. COMPLETION CRITERIA AND FINAL ACCEPTANCE

Review and acceptance of documentation provided by ORNL will be performed by INL.

7. APPENDICES

None

8. ATTACHMENTS

None