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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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TRANSFORMATIONAL CHALLENGE REACTOR

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

To obtain valuable data that will help in the design and commissioning of the Transformational Challenge Reactor, a series of graded, increasingly complex irradiation tests are planned that will demonstrate the feasibility of advanced manufactured reactor core components. In the first irradiation test, conventionally-fabricated uranium nitride tristructural isotropic (UN TRISO) fuel kernels will be embedded into compacts that are fabricated using advanced manufacturing methods. These compacts are to be irradiated at Massachusetts Institute of Technology's Nuclear Reactor Laboratory and Idaho National Laboratory's Transient Reactor Test Facility. This report presents the characteristics of the proposed samples and experiments.

1. INTRODUCTION

Neutron irradiation experiments are considered critical for assessing the robustness of emergent fuel concepts for the Transformational Challenge Reactor (TCR) Program. To comprehensively document valuable data for commissioning the TCR and to satisfy the associated licensing modalities, a graded testing approach is adopted in which a series of increasingly complex irradiation tests will be designed and performed. The first step will include neutron irradiation experiments performed at Massachusetts Institute of Technology's Nuclear Reactor Laboratory (MIT-NRL) and Idaho National Laboratory's Transient Reactor Test Facility (INL-TREAT) in FY 2020. While MIT-NRL data will be used to test the normal neutronic behavior of the fuel, INL-TREAT data will facilitate the assessment under the anticipated reactivity insertion accidents via transient testing. Both tests are designed to evaluate advanced manufactured (AM) silicon carbide (SiC) compacts containing conventionally-fabricated UN-TRISO fuel [1–3]. This report describes the selection and identification of relevant samples for these tests and provides a brief description of the experiments.

2. DESCRIPTION OF THE TCR FUEL FORM

The fuel form for the TCR consists of conventionally-fabricated UN TRISO fuel particles embedded inside a silicon carbide (SiC) matrix [2, 3]. These integrated fuel forms are fabricated using AM methods, specifically binderjet printing followed by chemical vapor infiltration [4]. The specifications for TCR fuel are listed in Table 1. The final geometry of the homogenized container is still in its evolutionary stages and is expected to be finalized in mid FY 2020.

Table 1. Typical fuel parameters for the TCR

Composition	UN
Enrichment	~19.5%
Fuel type	TRISO, spherical, fully encapsulated ceramic fuel
TRISO configuration	Kernel, buffer, inner pyro carbon (IPyC), SiC, outer PyC (OPyC)
Nominal TRISO dimensions*	800 μm (kernel), 90 ± 15 μm (buffer), 35 ± 5 μm (IPyC), 35 ± 3 μm (SiC), 35 ± 4 μm (OPyC)
Matrix	SiC
Fuel compact	Fully ceramic SiC cannister integrated with TRISO and SiC matrix
TRISO packing fraction	~62 %

**ORNL UN TRISO specification*

3. IRRADIATION TESTS AT MIT-NRL

The main objective of these tests is to assess the preliminary neutronic behavior of the fuel forms produced under the TCR Program. The fuel test articles consist of conventionally-fabricated UN TRISO encapsulated in SiC matrix and fabricated using AM. These samples will be provided by Oak Ridge National Laboratory (ORNL) and irradiated at MIT-NRL. Two facilities: Pneumatic tube and the Graphite reflector positions, at MIT-NRL will be used to obtain irradiation behavior data.

The pneumatic irradiation facility (PH) provides a thermal flux of up to 5.6×10^{13} n/cm^2-s and is ideal for short-duration, low-temperature, un-instrumented irradiation tests, which are key for ascertaining fuel coating integrity (i.e., the nonfailure of the SiC coating). Samples will be placed in sealed metal or quartz capsules and packed into a polyethylene or titanium pneumatic sample holder called a "rabbit." The maximum encapsulated sample size for a 1 in. pneumatic facility (1PH1) is 1 in. diameter and 3.24 in. long, and the maximum encapsulated sample size for a 2 in. pneumatic facility (2PH1) is 1.375 in. diameter and 6.25 in. long. The maximum recommended rabbit payload mass is 50 g. Nuclear heating within the sample and packaging could also limit the maximum allowable mass.

Vertical graphite reflector (GV) positions provide a thermal flux of up to 1.2×10^{13} n/cm^2-s. The 3GV positions are manually loaded vertical tubes that provide access to the MIT Nuclear Research Reactor (MITR) graphite reflector region at the same height as the core. Irradiations in this facility require custom encapsulation and neutron/gamma shielding but allow for instrumented irradiations up to high temperatures. The maximum encapsulated size for this facility is approximately 2.5 in. diameter and 18 in. length. The outer encapsulation will be designed to maintain a target temperature via nuclear and/or in situ electrical heating and will be monitored by thermocouples.

The experiments are currently planned as two phases. In Phase 1, bare UN kernels sealed in a quartz container will be irradiated in the reactor's pneumatic test facility (1PH1 or 2PH1) for short durations (1–2 days). After irradiation, the NRL-provided encapsulation will be punctured, and the gas drawn from around the fuel's primary encapsulation will be analyzed via gamma spectroscopy (i.e., HPGe detector) to determine the identity and activity of any gaseous radioactive isotopes. This benchmark data will be used to determine fuel (i.e., coating) failure in Phase 2 experiments. In Phase 2, UN TRISO fuel particles embedded in a SiC matrix will be irradiated in the PH and GV positions. Following the irradiation, gas sampling and analysis will be performed using gamma spectroscopy, and the resulting data will be compared with the benchmarking data obtained in Phase 1 to evaluate the behavior of the AM SiC encapsulated samples.

The test matrix for the MITR experiments are shown in Table 2.

Table 2. MIT-NRL irradiation matrix

Fuel ID	Pneumatic tubes (1PH1/2PH1)	Reflector positions (3GV)	
	<5 W/cc	<5 W/cc	<50 W/cc
Bare UN kernels	x		
UN TRISO	x		
AM TRISO compact	x	x	x

4. TRANSIENT TESTS AT INL-TREAT

The objective of these tests is to assess the behavior of AM fuel compacts under highly conservative reactivity insertion events (RIEs). To obtain valuable data, samples fabricated at ORNL will be tested at INL-TREAT. The INL-TREAT pulses will be shaped to introduce thermomechanical stresses via energy deposition in the AM SiC encapsulated samples that would result during an equivalent RIE in the TCR. The main outcome of these experiments will determine the energy deposition thresholds that thermo-mechanically damage the matrix and TRISO coatings due to transient energy deposition. Several experiments are planned for FY 2020 and early FY 2021 in which varying amounts of energy will be deposited into the fuel. The experimental flowchart is described in Figure 1. In each experiment, miniaturized TCR compacts will be subjected to transient neutron pulses generated at INL-TREAT and will be evaluated for different damage modalities with a post-irradiation examination.

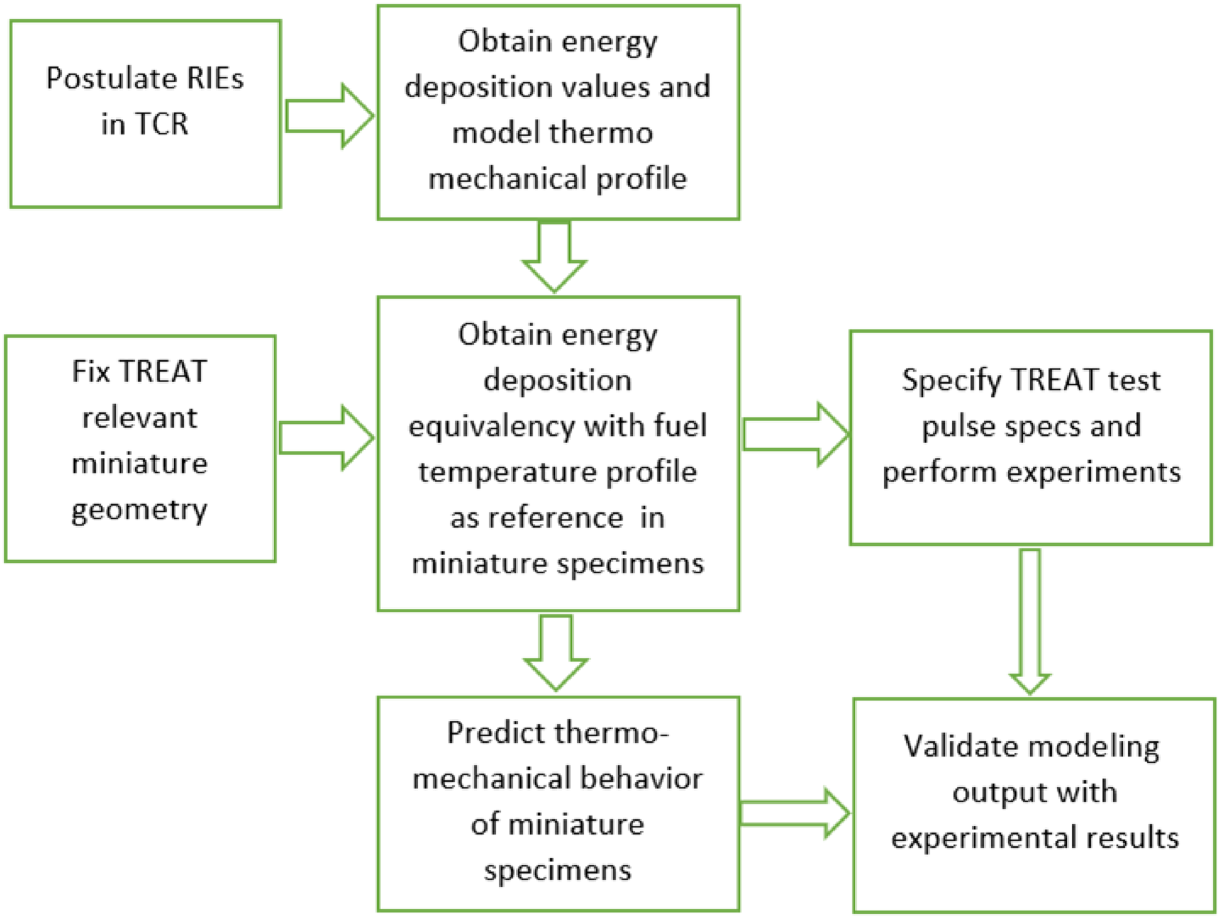

Figure 1. INL-TREAT test flowchart.

Preliminary energy deposition estimates of TCR-relevant postulated RIE were completed at ORNL. The Cp (Specific heat) method was used to estimate the energy deposition in the fuel using RELAP. Simulations were conducted for both hot-zero and hot-full power conditions, with 1$ and 0.75$ postulated reactivity insertions. The simulation results and the associated fuel temperatures are shown in Figure 2.

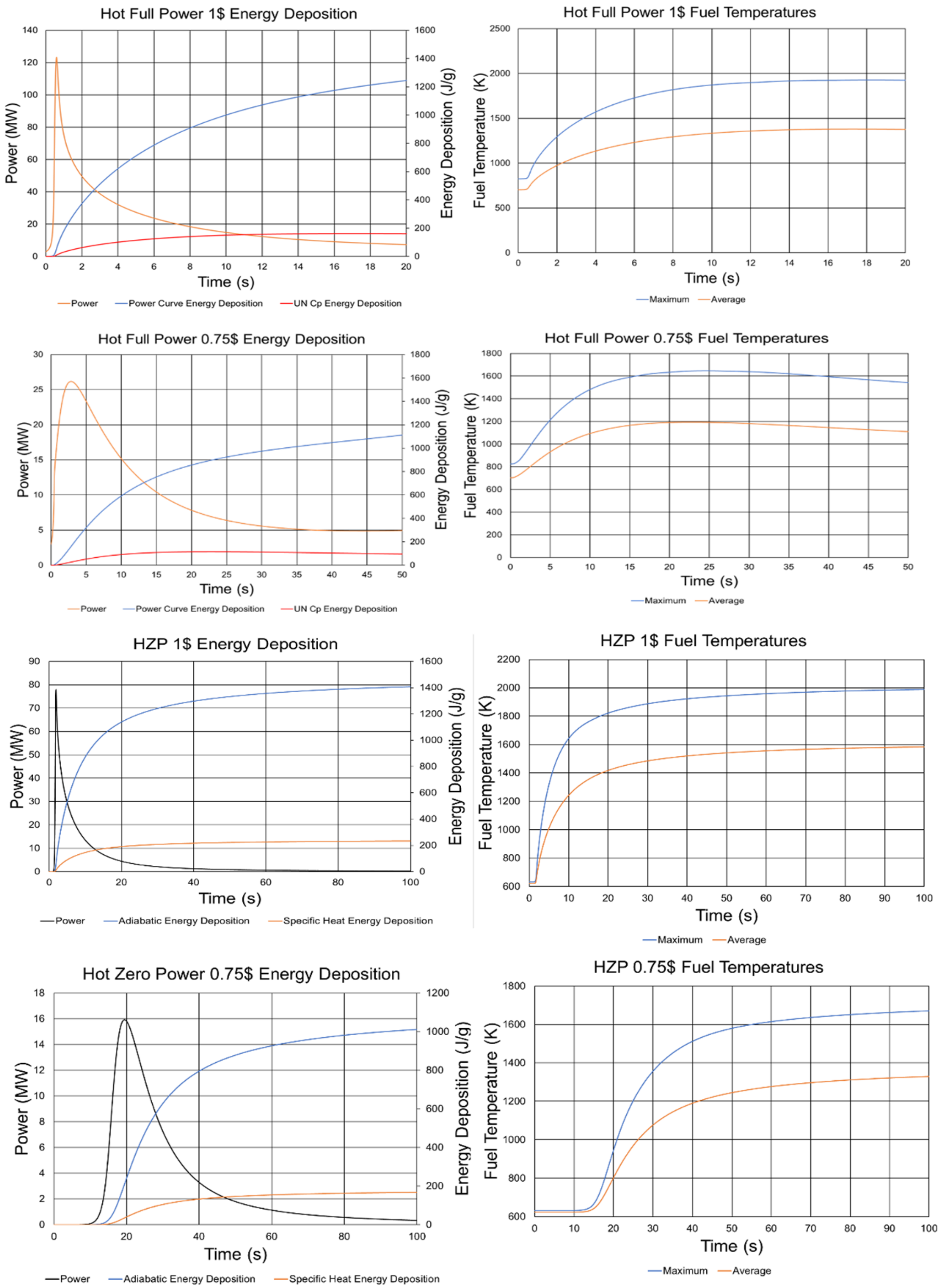

Figure 2. Simulation results of postulated RIEs in the TCR.

5. TEST SAMPLES

5.1 MIT-NRL IRRADIATION SAMPLES

ORNL has identified depleted UN kernels for the MIT-NRL experiments. Both bare UN kernels and UN TRISO batches were identified for the experiments.

At the time of this report's submission, ORNL has transferred 40 bare kernels of UN-containing depleted uranium (DU) and 20 bare kernels of UN-containing low enriched uranium for Phase 1 experiments. The kernels were selected from three existing batches prepared under the advanced fuel campaign (AFC-UN) program [5]. The details of the samples delivered to MITR are shown in Table 3. These bare kernels will be irradiated at MIT-NRL by the end of CY 2019 and subjected to fission gas release measurements to obtain benchmark data. Additionally, ORNL will transfer 20 low enriched UN (~7.3% enrichment) kernels to MIT-NRL for irradiation experiments.

Table 3. Bare kernels for irradiation at MIT-NRL

Sample ID	Description	Comments
FCM-4A-UN31K-07-FG	UN 0.23% enriched bare kernels	As fabricated (~87% density) [5]
FCM-4A-UN31K-1-HIP-FG		As fabricated, sintered (~92% density) [6]
FCM-LEU-UN-1-C	UN ~7.351% enriched bare kernels	As fabricated (~87% density) [5]

For Phase 2 experiments, loose UN TRISO particles and UN TRISO-bearing SiC compacts will be delivered to MITR. Two batches of UN TRISO particles were identified for this purpose. In FY 2020, fuel compacts will be fabricated using AM methods in the form of cylindrical specimens (~5 mm diameter × 5 mm height) containing either DU or low enriched UN TRISO particles. Several compacts will be irradiated in GV3 positions at MIT-NRL for durations ranging from a day to weeks. A 62.5% TRISO fuel packing fraction will be maintied in these samples to mimic the anticipated TCR packing fractions.

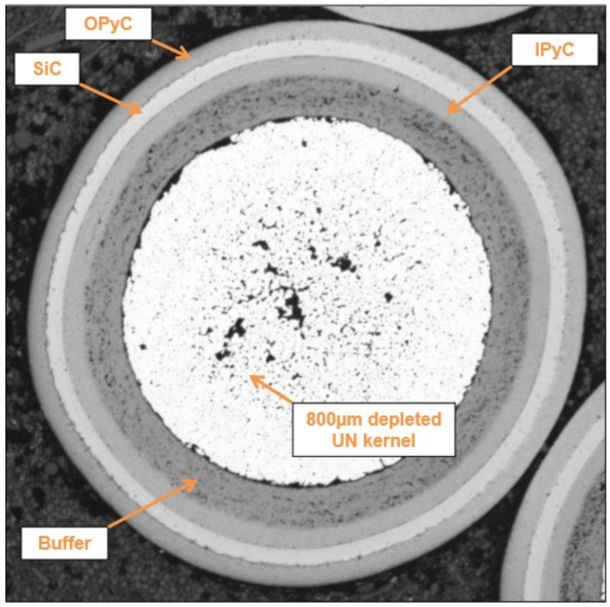

Figure 3. UN TRISO from batch FCM-4A-UN31K-02T [5].

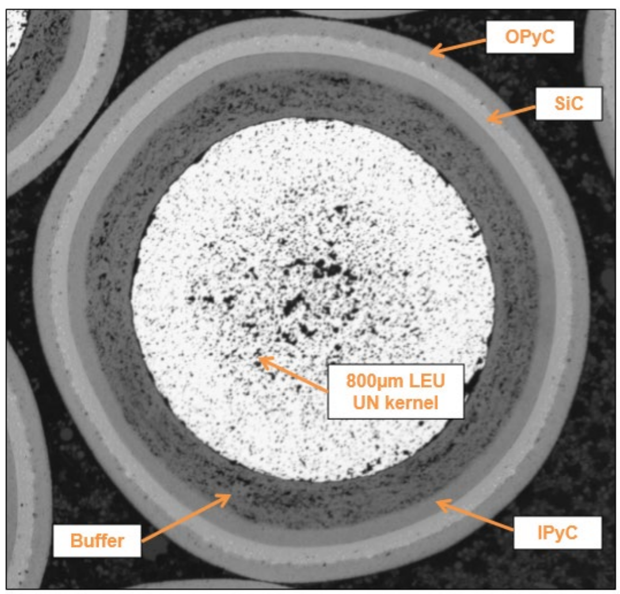

Figure 4. UN TRISO from batch FCM-LEU-UN-1-C-01T [5].

5.2 INL-TREAT IRRADIATION SAMPLES

The INL-TREAT experiments are mainly conceptualized to evaluate the energy deposition threshold during a postulated RIE in the TCR. The planned experiments can be grouped into two classes:

- Class 1: a benign case in which the resultant experimental data will validate the simulations in terms of predicted and measured temperature profiles and thermomechanical stresses during a postulated RIE
- Class 2: a threshold/limiting case in which the specified INL-TREAT pulse will damage the fuel

To perform these experiments, INL proposes to use the SETH-DRIFT capsule. These capsules are equipped with instrumentation leads that will be used to accurately measure and monitor the sample temperature during the experiment. To satisfy the dimensional constraints of the current capsules, miniaturized hexagonal SiC specimens will be fabricated using AM methods for testing. The method of establishing equivalency between scaled TCR specimens and the miniaturized INL-TREAT specimens are described in Figure 1. The samples will consist of a hexagonal can or container with UN TRISO drawn from the depleted UN batches, as shown in Table 3. One sheet of axially stacked TRISO particles will be packed to achieve a packing fraction of 62.5%, as shown in Figure 5. The INL-TREAT sample characteristics are summarized in Table 4.

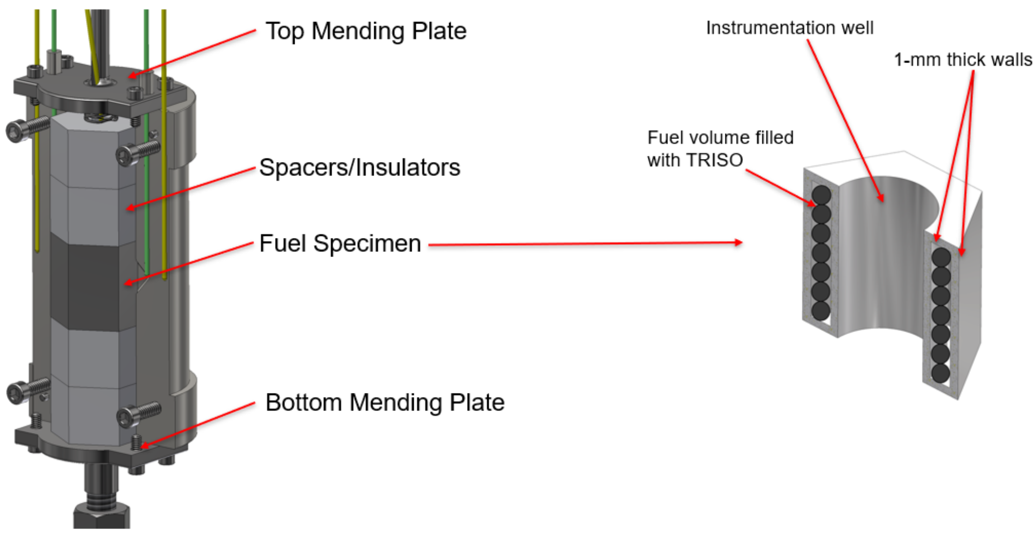

Figure 5. INL-TREAT fuel sample holder (*courtesy INL-TREAT*) and sample configuration.

Table 4. INL-TREAT sample characteristics

Fuel particles	Depleted UN TRISO
Compact geometry	Hexagonal
Compact height	1.905 cm
Compact wall thickness	0.1 cm
Compact vertex-vertex length	1.9688 cm
Fuel volume	1.165 cubic cm
Weight of TRISO/compact	~15 g

6. CONCLUSIONS

This report describes the first step for performing the irradiation experiments planned under the TCR Program. Various geometries will be irradiated at MIT-NRL and INL-TREAT with the adopted graded approach to obtain valuable irradiation data on TCR fuel. Bare UN kernels, UN TRISO particles, and TRISO fuel bearing SiC compacts will be irradiated at MIT-NRL to assess their response to neutron irradiation and the resulting temperature and stress gradients. Thin hexagonal samples consisting of depleted TRISO UN particles will be initially tested at INL-TREAT. Sample geometries and batches at ORNL were identified and are described in this report.

7. REFERENCES

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