INL/RPT-23-74753-Revision-1

Final CRADA Report: Accelerated Burn-up Accumulation Test of Clean Core Thorium Energy Designated ANEEL Fuel

September 2023

Michael Jason Worrall, Nicolas E Woolstenhulme, Christopher Glen Turner

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Idaho National Laboratory

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract 22SP810

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PROJECT INFORMATION

CRADA No.: 20CRA22 Completion Date: 09/30/2023

Participant(s) and Point of Contact(s): Clean Core Thorium Energy, LLC
Mehul Shah, President & Chief Executive Officer

INL Point of Contact(s): Stefanie Johnston, Agreements Management, Stefanie.Johnston@inl.gov
Michael Worrall, Principal Investigator, Michael.Worrall@inl.gov

Scope and Objective

Clean Core Thorium Energy (CCTE), LLC, located in Oak Brook, Illinois, is committed to the development of alternative nuclear fuels. CCTE focuses on leveraging the inherent benefits of thorium to create a novel nuclear fuel solution for our world's growing power demand. Unlike certain other fuel cycles that propose to use thorium in advanced reactors, CCTE is focused on deploying solid fuel designs (ceramic pellets in metallic cladding) in existing pressurized heavy-water reactors and Canada deuterium uranium (CANDU) reactors. CCTE's fuel design, referred to as Advanced Nuclear Energy for Enriched Life (ANEEL), uses mixed thorium-uranium oxide ($[Th,U]O_2$) to enhance reactor operational strategies while producing significantly low attractiveness material in terms of nuclear proliferation.

The overall project objective is to investigate the performance of high-burnup ANEEL fuel via an irradiation experiment to be performed in the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL). The scope of work for Cooperative Research and Development Agreement (CRADA) 20CRA22 was specifically aimed at performing the conceptual design and analysis for developing an irradiation test rig as well as a fuel fabrication process for the experiment pellets, fabrication and qualification of the pellets, and shipment of the pellets to INL for use in constructing experiment rodlets.

Project Accomplishments

This section lists all the tasks outlined in CRADA 20CRA22, along with how each was satisfactorily completed.

Task 1. *INL will conduct conceptual design activities to support development of an appropriate irradiation test rig. The conceptual design will include mechanical design to support development of notional irradiation hardware; nuclear and thermal analyses to support irradiation test position selection, fuel sample enrichment selection, and hardware configurations; and structural analysis to establish rodlet burnup limits.*

Completion statement: The conceptual design for the CCTE-ANEEL-1A irradiation experiment was completed in October 2022 with the issuance of the Phase I data package. The conceptual experiment design consisted of a standard design in which a stack of experimental pellets are encapsulated in an inner rodlet. This rodlet is then encapsulated in an outer capsule and placed into a standard ATR basket. As part of the conceptual design process, a set of functional and operational requirements for the irradiation test were generated and transmitted to CCTE as INL document FOR-634.

Task 2. *INL will consult with CCTE's fuel fabricator at Texas A&M University (TAMU) during the fuel fabrication development process. INL support will include the review and ultimate approval of the*

CCTE/TAMU fabrication control plan as it relates to reactor safety and engineering quality assurance requirements.

Completion statement: TAMU successfully developed a fabrication control plan used to fabricate the CCTE experiment pellets.

Task 3. *CCTE/TAMU will develop and demonstrate pellet fabrication processes that meet CCTE design specifications.*

Completion statement: TAMU successfully fabricated fuel pellets that met the design specifications. The fuel fabrication process consisted of blending UO_2 and ThO_2 powders in varying quantities, pressing the powder mixture into the desired pellet form, then sintering the pellets to achieve the desired density.

Task 4. *INL will prepare and deliver uranium oxide (in pellet form) from existing INL stock so that TAMU can use it for producing pellets for irradiation. Based on the conceptual design, INL will determine and inform TAMU of the enrichment levels required to meet the desired heating rates.*

Completion statement: Stock uranium oxide pellets were delivered by INL to TAMU in support of the fuel fabrication efforts. The material was mixed with thorium oxide procured by TAMU in order to create the CCTE experiment pellets.

Task 5. *The processes developed in Task 3 will be applied by CCTE/TAMU under a formal fabrication control plan so as to produce fuel pellets that meet INL standards. A fuel specification will need to be in place prior to fuel fabrication.*

Completion statement: The fuel specification was developed and transmitted to CCTE/TAMU as INL document SPC-2987. CCTE experiment pellets were successfully fabricated via TAMU's fabrication control plan.

Task 6. *CCTE/TAMU will conduct the pre-irradiation pellet characterization studies necessary to provide reference data during the post-irradiation examination activities. Typical examinations include compositional analysis, dimensional inspection, immersion density, and microstructural analysis.*

Completion statement: Each pellet's bulk properties (mass, physical dimensions, density) were measured as part of TAMU's quality inspections. A description of how each pellet batch was created was included in the quality documentation.

Task 7. *INL will work with CCTE/TAMU to develop and specify all quality inspections required for formal acceptance of the fuel in preparation for subsequent fabrication into rodlets by INL for irradiation in ATR. Upon being granted approval, CCTE/TAMU will ship the fuel to INL.*

Completion statement: The fabricated pellets were successfully shipped to INL.

Task 8. *Qualification of the fuel pellets will be required upon being received at INL. Typically, such qualification includes a combination on non-destructive inspections, fabrication documentation review, and destructive analysis of representative pellets in order to verify chemistry and isotopic data.*

Completion statement: Upon receipt of the pellets, INL performed bulk property measurements (e.g., mass, physical dimensions) on each pellet to confirm TAMU's measurements. Destructive analysis of a representative sample of pellets was deferred from this CRADA work scope to a follow-on Strategic Partnership Project agreement (SPP 22SP810) that is funding the rest of the irradiation campaign.

Task 9. *INL will provide an updated project execution plan, including cost and schedule estimates for the next phase of the project.*

Completion statement: An updated cost estimate and project plan was provided as part of establishing SPP 22SP810.

Benefit to DOE

This work provided an opportunity for INL to collaborate with a small business as well as a well-respected university on a conceptual design of an irradiation experiment for a novel fuel system that could provide a stable, more efficient, and more economical means of powering pressurized heavy water/CANDU reactors worldwide, which benefits the DOE as well as the entire global nuclear industry.

Economic Viability

CCTE is still in the pre-licensing phase for ANEEL fuel, but if this fuel type is ultimately approved and implemented into the existing global reactor fleet, domestic production of ANEEL fuel would represent a large, and constant, demand for high-assay, low-enriched uranium (HALEU).

Generated Data and Reports

Document	Responsible party	CRADA protected information?
Fuel pellet specification	INL	Y
Fuel pellet fabrication control plan	TAMU	Y
Fuel pellet quality documents	INL/TAMU	Y
Functional and operation requirements for the CCTE-ANEEL-1A irradiation experiment	INL	Y
Conceptual design for the CCTE-ANEEL-1A irradiation experiment	INL	Y

Project Status and Summary

The work performed under this CRADA represented the conceptual design and analysis phase for the CCTE-ANEEL-1A experiment, as well as fabrication of the experimental pellets. SPP 22SP810 is currently in place and being executed to complete the final design and analysis, fabricate the experiment hardware, assemble the experiment test trains, irradiate the test specimens in the ATR, and perform post-irradiation examinations on the irradiated specimens.