Development of TRU-TRISO Fuel for Deep Burn

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On Actinide and Fission Product Partitioning and Transmutation

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Outline

• TRISO fuel fabrication
• Deep Burn TRISO
• Deep Burn - LWR
• Summary
Coated Particle Fuel Manufacturing Steps

235\textsuperscript{U} < 20\% U\textsubscript{3}O\textsubscript{8}

Dissolution

Ammonia Donor

$\text{U}$\textsubscript{3}O\textsubscript{8}

Gel-Sphere

Water-Wash

Carbon for UCO

Gelation

Furnaces

dry-calcine-sinter

200 – 800 – 1600\°C

Kernel

Fluidized Bed Coater

(1300-1500\°C)

Pyrocarbon, SiC Layers

TRISO Particle

Blend

Graphite + Resin

Press-Cure

Furnaces
carbonize - densify

800 – 1800\°C

Compact
“Fuel Stick”

Block Fuel Element

Managed by UT-Battelle
for the U.S. Department of Energy

11\textsuperscript{th} Info Exchange Mtg on P&T
In-Core Release-to-Birth Rate Ratio is a Performance Metric for TRISO Fuel

- AGR-1 demonstrated very low gas release
- No indication of any particle failures
- Currently undergoing PIE
- TRISO based fuel is expected to ensure low fission product release, independent of kernel composition

Figure courtesy of M. A. Feltus
TRISO Particle Fuel and Deep Burn

- TRI-structural ISO-tropic (TRISO) particle fuel is a key element for high temperature reactors, initially developed for high temperature gas-cooled reactors.

- Good performance of TRISO fuel has been demonstrated over the last 5 decades, most recently in the DOE/NE Advanced Gas Reactor program’s AGR-1 irradiation test.
  - 19.7% enriched UCO kernels coated (50-mm lab scale coater) and compacted at ORNL were irradiated in INL’s Advanced Test Reactor.
  - After 3 years of irradiation to 19.6% peak burn-up, $4.4 \times 10^{25} \text{n/m}^2$ peak fast fluence, and 1038-1121°C average temperature, no fission product release due to fuel particle failure was detected.

- The high temperature and high burn-up fission product retention capability of the TRISO coating can also be applied to transuranic fuel for fuel cycle application.

- “Deep Burn” refers to the large fractional TRU burnup that can be achieved in a TRISO fueled gas-cooled reactor.

- DB-LWR refers to new concept of TRISO in a SiC matrix.
Destruction of LWR Fleet Transuranic Waste Inside TRISO Fuels

- Fuel recently developed at ORNL and irradiated in ATR at INL under Next Generation Nuclear Plan Program
- Global performance record for particle fuel: ~19% of LEU consumed, zero fuel failures
  - More than 2× the previous record
  - More than 3× current LWR fuel
  - Not a single TRISO fuel particle failure
- Significant step for TRISO nuclear fuel particles for use in HTGRs

Fluence achieved at 19% burnup with fertile fuel is similar to that expected for Deep Burn TRU TRISO fuel at > 60% burnup
LWR TRU Can be Effectively Destroyed in a Single Deep Burn irradiation

- LWR TRUs can be effectively destroyed in thermal reactors using TRISO fuel form
- Pu239 – 240 – 241 sequence produces a very steady reactivity behavior
Single-irradiation High Burnup is Critical to Effective TRU Disposal

Repository Capacity is strongly determined by decay Heat Load

DB Integral Heat Load relative to OT

- Optimized Fuel mgt
- Or enriched fuel

2.5x Repository Capacity

Range of DB-LWR TRU fuel Burnup

- 3.5 yr
- 4.0 yr
- 4.5 yr
- 5.0 yr
- 5.5 yr
- EFPY

DB-TRU Burnup (MWd/kg)

6x Repository Capacity
Deep Burn Fuel Development Goals

• Establish a framework to support a path forward for Deep Burn fuel development, production and testing

• Modify the lab-scale fuel fabrication methodology and equipment used to make the high performance UCO-TRISO AGR-1 fuel to establish the capability to fabricate TRU-TRISO fuel
  – Develop methods for fabrication of TRU kernels and TRU-TRISO coated particles, initially using surrogate material
  – Transition to glove box operations and redesign some fabrication components to allow for work with transuranic elements
  – Establish QC capability for kernels, coated particles and compacts containing transuranic elements

• Develop a ZrC coating capability and investigate feasibility of ZrC as a fission product barrier

• Demonstrate Fully Ceramic Microencapsulated (FCM) fuel form
  – Optimize fully dense SiC matrix for TRISO compaction
  – Demonstrate irradiation stability of FCM fuel to high burnup
Major Accomplishments to Date

• Secured approval for TRU Kernel fabrication – operational approval expected February 2011

• Developed and demonstrated fabrication methods for Deep Burn kernels using ZrO$_2$ as a surrogate for the transuranic oxides
  – Developed a new wash procedure to solve a historic fabrication problem involving kernel integrity (flaking and cracking)
  – Developed equipment for high yield production of $<300$ µm diameter kernels
  – Developed equipment for production of kernels with an internal getter

• Produced quality ZrC coating
  – Produced coated particles with high quality ZrC coatings in place of the standard SiC TRISO layer
  – Completed initial parametric study to identify appropriate ZrC deposition conditions

• Demonstrated and patented SiC matrix compacting for TRISO fuels
  – No open porosity, near full density, no apparent damage to TRISO particles
Kernel Development

• After studying and reporting on issues and techniques for fabrication of TRU kernels using the sol-gel approach, several internal gelation systems (including two new methods) were developed to optimize production of high quality ZrO$_2$ surrogate kernels with a high process yield.

Vibrating Needle

288 ± 11 µm
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Pneumatic Delivery

250-330 µm
ZrC Coating Development

• ZrC is of interest as a replacement or supplement to the SiC layer in TRISO

• Existing coating equipment was modified to deposit ZrC
Good ZrC Coatings Have Been Obtained

- Fine, equi-axis grain structure similar to ideal SiC coatings has been demonstrated.
A series of reactor irradiation of ZrC indicate good performance.
TRU-TRISO Fabrication

• Assessments and approvals for TRU glove box operations are well underway
  – Not a simple or quick process
  – Safety analysis with possible accident scenarios
  – Identification of applicable codes
  – Readiness review level determination
  – Modification of nuclear facility safety basis documentation
  – Several levels of approval

• Coating equipment has been designed, components are on order, and some parts have been received. Coating furnace assembly to be completed this year

• Particle classification glove boxes have been ordered and being a custom glove box to house the coating equipment has been designed

• Goal is to be ready to fabricate TRU kernels in early FY11 and coat these kernels in late FY11 or FY12
Glove Box Kernel Fabrication Facility

- Internal Gelation Station
- Sintering Furnace
- Characterization Boxes
- Packaging
Glove Box Coating Facility

Top bag port for furnace chamber installation and removal

Furnace exhaust
HEPA then to process exhaust (TBD)

Glove box designed with a removable panel/side for maintenance access when actinide particles are not present. This allows significant reduction in glove box volume, thus minimizing impact of postulated explosion scenario.

Glove box exhaust
HEPA then to exhaust header

Furnace and scrubber/soot filter contained within single glove box

Glove box size ~30 x 30 x 48 inches or ~25 cubic feet

Bag port for injector removal

Floor level

Cooling water, electrical, instrument, and purge gas penetrations

Process gas inlet

HEPA air inlet
Deep Burn Kernel Performance

- Control of O/Pu ratio appears to be important for preventing kernel migration
- TRISO-coated PuO$_{2-x}$ kernels were irradiated to ~70% burn-up in 1970’s Peach Bottom HTGR irradiation test (FTE-13)

PuO$_{1.84}$ kernels showed amoeba effect

PuO$_{1.68}$ kernels looked better
Demonstration of Likely Effect of SiC or ZrC Getter On CO and Total Pressure

Reduced oxygen potentials, and therefore CO pressures, from gettering phases observed to mitigate kernel migration

**Internal Gettering of Kernels**

\[ \text{SiC} + \text{O}_2 = \text{SiO}_2 + \text{C} \]

- SiC will be added to TRU kernels for reduction of O/Pu ratio to prevent kernel migration and possibly sequester Pd in the kernel as PuPd$_3$Si$_3$C$_5$
- Approximately 0.6 moles SiC per mole heavy metal atom is required
- Internal dispersion of SiC has been successfully demonstrated in zirconia surrogate kernels (Journal of Nuclear Materials 410, 2010)
Science of TRU Kernel Development and Fabrication

- Science products starting to flow
  - "Pneumatic Drop-on-Demand for Production of Metal Oxide Microspheres by Internal Gelation" by Valmor F. de Almeida, Rodney D. Hunt, and Jack L. Collins (accepted by the Journal of Nuclear Materials)
LWR Application of Deep Burn Fuel
Fully ceramic micro-encapsulated (FCM) fuel

- SiC: High conductivity, radiation stable
  - Replaces graphite matrix of HTR fuel with high-conductivity, repository friendly, radiation-stable SiC
  - Produces very clean interfaces and high density (~3% porosity)
  - Less hostile compacting process than used for HTR fuel
  - Low centerline temperature in LWRs should eliminate Fission Product migration issues
  - Recently patented

![Diagram showing UO₂ and SiC volume changes with temperature](image)

- UO₂ ΔV/V = 10%
- SiC ΔV/V = 1%

![Images of AK2S14 AGR Surrogate Fuel and 0.5 μm SiC](images)
Deep Burn of TRUs in LWRs: Effect of Burnable Poisons

FCM fuel compact (pellet)
In fuel pins

EFPD

K_{\text{\infty}}

0.9

1.0

1.1

1.2

1.3

Type 1 (Er_{2}O_{3})
Type 2 (Gd_{2}O_{3})
Type 3 (Gd_{2}O_{3})

Fuel compact

Outer PuC coatings
SiC coating
Inner PuC coating
Buffer (C)
Coated Burnable Poison particle (BISO)
PuC coating
Buffer (C)

Coated fuel particle (TRISO)

Fuel

Cladding
Gap
Gap
Fuel

Coolant

Burnable poison (Gd) can also be manufactured in fuel kernel

Fuel density
500–1000 TRISO particles/cm

Power production
0.2–0.3 W/particle

Code: McCARD - Monte Carlo depletion calculation, Nuclear library: ENDF-B/VII
Temperature: fuel pin (including cladding) 600°K, coolant 300°K
Creep-Down of FCM in Zircaloy Pin

- Understanding performance of FCM Fuel within standard LWR Fuel Rod
- FRAPCON was altered to incorporate FCM fuel containing 40% TRU-TRISO with equivalent heat loading as MOX or conventional LWR fuel

- Incorporation of nominal 3.5 mil gap is closed near end of fuel lifetime
- Centerline temperature using as-irradiated properties of FCM increase from ~700°C to ~500°C, well within the operating temperature range of SiC
- No surface reaction between SiC and zircaloy clad is expected in this temperature range
Integrity of TRISO in FCM Fuel

• A series of compacts were made with temperatures pressures higher and lower than assumed optimal.

• Interface chemistry, grain size, and optical image analysis was carried out.
Integrity of TRISO in FCM Fuel

Analysis of Interface for High Pressure High Temperature Processing

Resolvable sintering aids reside at OPyC boundary
Relatively small grains within matrix. Fully dense OPyC partially infiltrated
SiC layer apparently unmolested
Summary

• Demonstrated methods for TRU kernel fabrication using ZrO₂ surrogate
  – Developed special multistage washing process to eliminate kernel cracking/flaking
  – Introduced SiC into the kernel to enable deep burn
  – High yield fabrication of small diameter kernels

• Developed coating equipment and fabrication process to produce fine grained ZrC with equiaxed microstructure as potential replacement for SiC in standard TRISO coated particle. Irradiation studies indicate good performance of ZrC

• Installation of kernel fabrication equipment into glove boxes in Bldg 7920, Lab 109 is complete
  – Completed shakedown testing using ZrO₂ as a surrogate
  – Demonstrate fabrication of Zr/Y surrogate kernels in glove box in September 2010
  – Operational approval for TRU operations expected Feb 2011

• TRU Coating capability installation underway and will be operational in 2012

• A new fuel form, the SiC matrix fully ceramic microencapsulated fuel has been fabricated with surrogate TRISO. More complete optimization of the fuel form including neutron irradiation and clad compatibility to be carried out in 2011.
## Supplementary Information

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