HTGR Technology Course for the Nuclear Regulatory Commission

May 24 – 27, 2010

Module 8

Fuel Performance
Outline

• Fuel operating experience in HTGRs
  • Fuel irradiation and post-irradiation examination (PIE)
  • Safety criteria and performance limits
  • Fuel performance modeling
  • Fuel cycle issues
Reactor Operation Experience for Fuel Has Been Good

• Four experimental and three power reactors using coated particles
  – UK, US, Germany, Japan, China

• Commercial-scale production and reactor operation (and supporting R&D) have lead to
  – Understanding of fabrication
  – Understanding of irradiation behavior and limits
  – Fuel quality and performance improvements

.....coated particles w/~50,000 kg HM fabricated
## Coated Particle Fuel Has Been Used Internationally In Seven Gas-Cooled Reactors

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Fuel</th>
<th>Fuel Enrichment (%)</th>
<th>Temp (°C)</th>
<th>Burnup (% fima)</th>
<th>Fast neutron fluence ($10^{25}$ n/m²)</th>
<th>Average Power Density (w/cc)*</th>
<th>Power/particle (milliwatt/part)</th>
<th>Packing Fraction (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Pebble Bed</td>
<td>TRISO (UO₂)</td>
<td>7.8</td>
<td>1048</td>
<td>8.75</td>
<td>2.4</td>
<td>10</td>
<td>55</td>
<td>7</td>
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<tr>
<td>Typical Prismatic</td>
<td>TRISO (UCO)</td>
<td>14 or 20</td>
<td>1250</td>
<td>26</td>
<td>4.5</td>
<td>31</td>
<td>40</td>
<td>23</td>
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<tr>
<td>Dragon</td>
<td>BISO/TRISO Various</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Peach Bottom I</td>
<td>BISO (U/Th)C₂</td>
<td>93</td>
<td>1400</td>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVR</td>
<td>BISO/TRISO Various</td>
<td>93</td>
<td>1100-1280</td>
<td>16</td>
<td>7</td>
<td></td>
<td></td>
<td>40</td>
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<tr>
<td>THTR</td>
<td>BISO (U/Th)O₂</td>
<td>93</td>
<td>1100</td>
<td>10</td>
<td>4</td>
<td>17</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Fort. St. Vrain</td>
<td>TRISO (U/Th)C₂, ThC₂</td>
<td>93</td>
<td>1200</td>
<td>16</td>
<td>4</td>
<td>29</td>
<td></td>
<td>60</td>
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<tr>
<td>HTTR</td>
<td>TRISO UO₂</td>
<td>3 to 10 (6 ave)</td>
<td>1490</td>
<td>~1</td>
<td>&lt;1</td>
<td>24</td>
<td>35</td>
<td>28</td>
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<tr>
<td>HTR-10</td>
<td>TRISO UO₂</td>
<td>17</td>
<td>1200</td>
<td>~1</td>
<td>&lt;1</td>
<td>6</td>
<td></td>
<td>35</td>
</tr>
</tbody>
</table>

* Power density in volume where there are coated particles (compact and fueled region of pebble)
Operated 1965 to 1976 developing many new fuel designs – Tested BISO and TRISO with many fuel forms including Pu fuels – important early fuel developments were almost all made at Dragon
Peach Bottom I (40 MWe), Delta, Pennsylvania

- Used BISO (U/Th)C₂ fuel particles no longer proposed for use in HTGRs
- First core experienced failures
- Corrected in the second core

Fuel element – cylinders with outer sleeve, annular compacts, inner graphite filler, internal purged sweeps fission products to trapping system
AVR (Arbeitsgemeinshaft Versuchsreactor), Hanau, Germany

BISO and TRISO pebble fuels of various qualities tested over 21 years – total of 2 million pebbles
Operated with hot helium temperature up to 950 °C
THTR (Thorium High Temperature Reactor), Hamm-Uentrop, Germany

**BISO** (U/Th)O₂ fuels tested during 5 (1983 – 1988) year operation
Power reactor operated on the power grid – steam cycle with 750 °C hot helium - ~1 million spheres
Operating with TRISO UO₂ pebble fuel since 2003

27,000 spheres

Small experimental reactor bringing HTR technology to China

HTR-10, Beijing, China
Fort St. Vrain, Platteville, Colorado

Operated on power grid for ~13 years (1976-1989) – reduced power

TRISO (U/Th)C₂ fissile and ThC₂ fertile fuel

2450 fuel assemblies, 7.5 million compacts, 33,000 kg HM in fuel

Fuel performed well
Currently operating with first core TRISO UO₂ fuel to 2014

Operating with 950°C helium temperature

Excellent fuel performance – low measured fission gas release
Improved Equipment and Fabrication Procedures Provided Substantial as-Manufactured Quality Improvement

But some fuel has not performed well under irradiation
In-Pile $^{85m}$Kr Release Measurements in FSV Indicate Good Coated Particle Fuel Performance

![Graph showing In-Pile $^{85m}$Kr Release Measurements in FSV](image)

- Cycle 1
- Cycle 2
- Cycle 3
- Cycle 4

FSV FSAR "Expected" Value

Kr-$^{85m}$R/B $^*$

- Measured
- Predicted, total
- Predicted, Cont. only

HTTR $10^{-8}$

THTR

AVR

Operating Time, Days

*R/B rate of gas release/rate of gas creation
Outline

• Fuel operating experience in HTGRs

• Fuel irradiation and post-irradiation examination (PIE)

• Safety criteria and performance limits

• Fuel performance modeling

• Fuel cycle issues
CP Irradiation & PIE Procedures and Equipment are Well-Developed Tools for Understanding CP Fuel

- **Fuel irradiations**
  - Test units – compacts, pebbles, particles
  - Test reactors and test equipment
  - Irradiations are conducted to
    - Determine fission product barrier failure mechanisms, rates, limitations, and margins
    - Design information on irradiated fuel materials
    - Demonstrate performance of evolving fuel developments
    - Validate fuel performance and fission product transport methods
  - Irradiation test measurements
    - Temperatures, neutron spectra and fluence, fission gas release

- **Post-irradiation examinations (PIE)**
  - PIE facilities and equipment extract quantitative data
  - Results contribute to understanding and quantification of fuel performance
Irradiation Facilities at INL – ORNL & Worldwide

Advanced Test Reactor
INL

Russia: IVV-2M
Pebbles
SM-3/RBT-6
Compacts

High Flux Isotope Reactor - ORNL

High Flux Reactor
Petten, Netherlands

Many other reactors have been used for Coated Particle Irradiations
Irradiation Facilities Measure Irradiation Conditions and Coating Integrity via in-Reactor Fission Gas Release

**AGR-1 Experiment Block Diagram**
Six (6)-Capsule Test Train Design for AGR-1

Individual Cell Features

- Thermocouples
- Graphite
- Flux Wire
- ATR Core Center
- Hf Shroud
- Fuel Compact
- Gas Lines
- SST Shroud

AGR-1 test train assembly
6-individual instrumented capsules

Twelve, 0.5” diam, 1” long compacts/cell
Capsule Irradiations Envelope Far Exceeded NGNP Operating Envelopes

All Coated Particle Irradiations

- Earlier irradiations most Coatings survived
- But performance did not meet modern standards in all cases
  - 1400°C
  - $12 \times 10^{25}$ n/m²
  - 60% PF
  - 100 w/cc (fuel region)
  - ~90% FIMA
AGR-1 Irradiation Conditions Closely Match Expected Prismatic NGNP Service Conditions

And satisfied performance requirements (based on in-pile fission gas release measurements)

- 1300°C
- 4.5 x 10^{25} \text{ n/m}^2
- 28\% \text{ PF}
- 32 \text{ w/cc (fuel region)}
- \sim 26\% \text{ FIMA}
Outstanding Coated-Particle Fuel Performance Observed in Most Recent US Irradiation

AGR-1 Reactor Cycle

In-Pile R/B

Capsule 1 ↑
Capsule 2 ↓

Typical AGR-1 Fuel Temperatures

Time-ave fuel temp (calc) °C

MAX
AVE
MIN

Kr85m
Kr88
Xe135
Summary – Fuel Irradiations

• TRISO - extensive irradiation testing
  – Exceeding NGNP operating envelope
  – German (pebble) and recent US (compact) irradiations demonstrate required performance

• Additional testing needed
  – Establish repeatability – statistical confidence
  – Fuel fabricated on production-scale equipment
  – Obtain additional design data, limitations, margins
  – Validate fuel and fission product design methods
Techniques for Coated Particle PIE are Well Developed

Coated particle post-irradiation examinations performed at well-equipped hot cells, TRIGA reactor, accident testing facilities at:

- Oak Ridge National Lab
- Idaho National Lab
Specialized Methods Have Been Developed for Coated Particle Fuel Examination

• Examine irradiated compacts and pebbles
  – Dimensions, visual, metallographic, thermal/mechanical properties
  – Fission gas release (R/B) - reactivation
  – Solid fission product release
  – Accident behavior
• Examine irradiated individual particles
  – Compact & pebble deconsolidation
  – Individual microsphere gamma analyses (IMGA)
  – Exposed or uncoated heavy metal
  – Metallography
  – Scanning electron microscope/microprobe
Metallography Reveals Condition of Particles w/SEM – Microprobe – Distribution of Elements (variety of irradiations)
Individual Particles Can be Gamma-Counted and Isolated for Examination

- IMGA gamma counts a large number of individual particles and tallies results.
- Automated handling & counting.
- Pick out problem particles for detailed examination.

Graph showing data distribution with normal and experimental distributions.
Accident Testing of Irradiated Fuel

- Furnace configuration

Test Compacts, Spheres, Particles (ORNL, INL, Worldwide)
FG Data Indicates Coating Failure Initiated above 1600 °C
Satisfying the Accident Criterion is Achieved by Reactor Design

- Fuel temperature stays below the damage limits during complete loss-of-coolant incident
- Heat removed passively during loss-of-coolant events - annular core

Fractional release of $^{85}\text{Kr}$

- Coated particles stable to beyond maximum accident temperatures

Fuel temperature stays

$\text{Heating time (days)}$

$\text{Time After Initiation (days)}$

Depressurized

Pressurized

To Ground
PIE Reveals Details of Coating Response to Accident Conditions – Determine Mechanisms & Rates

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Duration</th>
<th>Cs$_{137}$ Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600°C, 500h</td>
<td>F$_{Cs137}$ &lt;1%</td>
<td></td>
</tr>
<tr>
<td>1800°C, 200h</td>
<td>F$_{Cs137}$ 4.5%</td>
<td></td>
</tr>
<tr>
<td>2000°C, 30h</td>
<td>F$_{Cs137}$ 22%</td>
<td></td>
</tr>
<tr>
<td>2100°C, 30h</td>
<td>F$_{Cs137}$ 69%</td>
<td></td>
</tr>
<tr>
<td>bis 2500°C</td>
<td>F$_{Cs137}$ 99%</td>
<td></td>
</tr>
</tbody>
</table>

SiC Coating

Kernel-buffer interface

Kernel

Ceramographic sections through UO$_2$ TRISO particles
Summary – Post Irradiation Examination

• Irradiation testing of CP fuels can realistically simulate reactor conditions

• Irradiation facilities can measure and control irradiation conditions and collect in-pile data

• Specialized PIE tools have been developed for coated particle fuel to obtain quantitative performance and design data

• Accident conditions can be simulated and data on fission product barriers and fission product release collected
• Fuel operating experience in HTGRs
• Fuel irradiation and post-irradiation examination (PIE)
• Safety criteria and performance limits
• Fuel performance modeling
• Fuel cycle issues
Fuel Safety Approach

- Fuel safety criteria are related to the fuel fission product barriers – coatings
- Based on meeting plant top-level dose limits with margin
- Coating failure allowance allocated to as-manufactured and in-service performance
- Testing established service environment where performance requirements are achieved
- Coating integrity during operation is protected by Operational Technical Specifications
  - Parameters are monitored and limited to meet safety criteria and stay within performance limits
  - Coating integrity monitored by primary coolant radioactivity
- Coating failure limitation during accidents is achieved by reactor design – passive, conductive heat loss
### Estimated Maximum Service Conditions for Pebble & Prismatic NGNP Fuel (not Limits)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Maximum Value* (PBMR-CG)</th>
<th>Maximum Value* (Prismatic NGNP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum fuel temperature–normal operation, °C</td>
<td>1048</td>
<td>1400</td>
</tr>
<tr>
<td>Maximum time averaged fuel temperature, °C</td>
<td>1048</td>
<td>1250</td>
</tr>
<tr>
<td>Fuel temperature (accident conditions), °C</td>
<td>1483</td>
<td>1600</td>
</tr>
<tr>
<td>Fuel burnup, % FIMA</td>
<td>8.75</td>
<td>17**</td>
</tr>
<tr>
<td>Fast neutron fluence, 10^{25} n/m^2 (E &gt; 0.18 MeV)</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

*Anticipated max. temperatures are not design limits. These temperatures may be exceeded for a limited time (days or weeks) without resulting in fuel failure and can be exceeded by a small fraction of the fuel for longer periods without resulting in excessive fission product release.

*These do not represent “cliffs” where if exceeded failure will result

**Estimated FIMA for 14% enriched reference fuel particle under development by NGNP/AGR Fuel Program
Comprehensive Fuel Qualification Program
Being Conducted by NGNP/AGR Fuel Program

- Process development
- Test sample fabrication
- Irradiation testing & PIE
- Accident testing
- Validate fuel performance models
- Fuel product and process specifications
- Technology for commercial fuel fabrication
- Reduce market risk
- Qualify fuel for NGNP
NGNP/AGR Fuel Program Overview

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Irradiation</th>
<th>Safety Tests &amp; PIE</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early lab scale fuel Capsule shakedown Coating variants German type coatings</td>
<td>AGR-1</td>
<td>AGR-1</td>
<td>Update &amp; Fuel Performance And Fission Product Transport Models</td>
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<tr>
<td>Large scale fuel Performance Demonstration</td>
<td>AGR-2</td>
<td>AGR-2</td>
<td>Validate Fuel Performance And Fission Product Transport Models</td>
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<tr>
<td>Failed fuel to determine retention behavior</td>
<td>AGR-3&amp;4</td>
<td>AGR-3&amp;4</td>
<td></td>
</tr>
<tr>
<td>Fuel Qualification Proof Tests</td>
<td>AGR-5&amp;6</td>
<td>AGR-5&amp;6</td>
<td></td>
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<tr>
<td>Fuel and Fission Product Validation</td>
<td>AGR-7&amp;8</td>
<td>AGR-7&amp;8</td>
<td></td>
</tr>
<tr>
<td>Fission Product Transport/Retention</td>
<td>Lab Tests</td>
<td>Integral Loop Validation*</td>
<td>requirement TBD</td>
</tr>
</tbody>
</table>

* Integral Loop Validation TBD
Outline

- Fuel operating experience in HTGRs
- Fuel irradiation and post-irradiation examination (PIE)
- Safety criteria and performance limits
- Fuel performance modeling
- Fuel cycle issues
Role of Fuel Performance Modeling

• Guide current and future particle designs
• Assist in irradiation and safety experiment planning
• Predict observed fuel failures
• Predict fission product transport through particles and matrix
• Interpolate fuel performance for core design assessments

......INL leading US model development - PARFUME
Coating Failure Mechanisms to be Modeled

- Coating Stresses
  - Internal gas pressure
  - Irradiation induced dimensional changes
  - Interactions between coatings
- Fuel kernel thermo-chemistry
  - Oxygen management
  - Fission product compounds and phases
- Carbon Transport in temperature gradient
  - Kernel migration
- Chemical reactions with coating
  - CO/CO$_2$, palladium, lanthanides, impurities and other fission products
  - SiC decomposition at high temperature
- Inter-relationships between failure mechanisms
Coating Stress Modeling Requires Large Quantities of Detailed Data

- Linear Viscoelastic Constitutive Equation for Coatings

Coating properties depend strongly on:
- Fabrication process that affects coating structure
- Exposure to fast neutrons
- Temperature
- Imposed stress

Failure by Brittle Material Statistical Model - Weibull

\[ P_f = 1 - \exp\left( \int_V \left( \frac{\sigma}{\sigma_0} \right)^m dV \right) \]

...the coating properties constitute the largest uncertainty in predictions of coated particle performance
TRISO Coatings Are Complex Structures with Complex Interactions Between Coating Layers

- Pyrocarbons shrink
- Keep SiC in Compression
- SiC does not fail

PyC shrinks under fast neutron irradiation
  - PyC structure \((BAF_0)\)
  - Temperature
INL PARFUME – Integrating First-Principle Treatment of Failure Mechanisms for General Applications

Past Failure Mechanisms Observed in PIE

Reactor Service Conditions:
- Neutron Flux
- Power Density
- Fast Neutron Fluence/Damage Temperature

Dimensionality, failure modes to be considered, key material properties

- Thermal Response
- Structural Behavior Module
- Failure Evaluation (Weibull)
- Fission Product Release

Pieces of the Model

Fuel Attributes

Boundary Conditions and Geometry

Constitutive Relations

Physio-chemical Properties
- Corrosion attack rates of SiC
- Thermo-mechanical Properties
- Fission Product Transport Properties

Thermo-mechanical Properties

Thermal Behavior
Accident Modeling

• Initial empirical separate effects treatments used in the past
  – Pressure vessel, chemical attack, amoeba
  – Thermal decomposition depending on accident temperature and state of irradiation

• 1-D performance codes being upgraded and integrated for applications during accidents

• Covered in Module 15
Summary – Fuel Performance Modeling

• 1-D fuel particle performance codes are being developed in many countries
  – Codes have different levels of capability
  – Goal to integrate failure mechanisms
  – Most still under development moving toward a common goal of universal applicability

• Uncertainties in performance predictions arise mainly from properties of irradiated coatings

• Multi-dimensional codes are used to predict non-spherical effects
Outline

- Fuel operating experience in HTGRs
- Fuel irradiation and post-irradiation examination (PIE)
- Safety criteria and performance limits
- Fuel performance modeling
- Fuel cycle issues
Fuel Cycle Issues

• **Sustainability**
  – Resource utilization
  – Enrichment
  – Thorium

• **Proliferation**
  – Reprocessing of coated particles

• **Fuel cycle economics**

• **Ultimate disposal of coated particle fuel**
Once-Through LEU Fuel Cycle being Considered for NGNP - Good Proliferation Resistance

10% enr. UO₂
15% enr UCO

Many other cycles possible
Selection depending on economics and waste management policy

Ultimate Disposal
## Fuel Cycle Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>PBMR-CG (LEU)</th>
<th>GT-MHR (LEU)</th>
<th>PWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>HM loading</td>
<td>MT/GW(th)</td>
<td>11.2</td>
<td>7.5</td>
<td>36</td>
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<tr>
<td>Ore utilization</td>
<td>U3O8/GW(e)-Yr</td>
<td>183</td>
<td>182</td>
<td>212</td>
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<tr>
<td>Conversion Ratio</td>
<td>new fissile/used fissile</td>
<td>0.46</td>
<td>0.4</td>
<td>0.5</td>
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<tr>
<td>Discharged Pu</td>
<td>kg/GW(e)-Yr</td>
<td>147</td>
<td>96</td>
<td>338</td>
</tr>
<tr>
<td>Heat load - discharge@ 10 years</td>
<td>kw(th)/GW(e)-Yr</td>
<td>25</td>
<td>24</td>
<td>26</td>
</tr>
</tbody>
</table>
Summary

• Coated particle fuel has been manufactured in commercial quantities and successfully used in power reactors

• Substantial experience with fuel irradiation, examination, and testing → strong database on fuel performance

• Performance modeling is continuously improving – additional data and validation needed
Suggested Reading

• Fuel Operating Experience in HTGRs
  – Nuclear Technology, 35, No. 2 206-573 (1977) entire volume

• Fuel Irradiation and PIE
Suggested Reading

• **Fuel Performance Modeling**

• **Fuel Cycle Issues**